Following a Thread

Tracing technology and techniques along the Silk Road

Vol. I/II

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Abstract

The medieval silk trade has been the subject of substantial research. A key topic within this field is the origins of silk textiles traded over long distances, something particularly difficult to determine in silk textiles of simple construction, such as tabby (plain-weave).

This thesis combines experimental archaeology with microscopy to identify potentially diagnostic criteria for determining the provenance of often overlooked tabby silk textiles from medieval contexts. Silk reeling and processing experiments were conducted between August 2021 and January 2022 using specially constructed equipment based on historical and archaeological evidence. The resulting reference collection of silk filament and yarn samples were analysed using a combination of reflected and transmitted light microscopy, and Scanning Electron microscopy leading to the identification of a number of distinct visual characteristics indicative of processing methods. Two sets of early- to high-medieval silk tabby textiles, one from Coppergate, the other from Winchester Cathedral also underwent light microscopy and SEM analysis.

This research generated a number of new protocols for the analysis of silk textiles which support more accurate identification of plied silk yarn, and the differentiation of silk degumming processes. In addition to these key findings a number of observations were made regarding the different techniques employed to produce silk and transmission of knowledge related to both the technology and processes involved. These observations are relevant to the broader topics of medieval craft production and trade.

The comparison of the archaeological silk textiles with the experimental reference collection ultimately supported the identification of variations in processing steps across the textiles from both collections. These results provided an indication that the silk textiles may have been imported from a number of different regions that may have intersected at different stages of production which has important implications for our understanding of the medieval silk trade.

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Prefacing Note

In November 2023, the external advisor to this thesis, Penelope Walton Rogers, died unexpectedly while the author was on a leave of absence for health-related reasons. Penelope provided invaluable input on both research design and chapter drafts, but her passing occurred before a full draft of this thesis was completed and could be commented upon. This loss took an emotional toll during the final stages of writing-up, in addition to the loss of her expertise as a textile specialist.

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Author's Declaration

This thesis is a presentation of original work, and I am the sole author. This work has not previously been presented for a degree or other qualification at this University or elsewhere. Any support received during the preparation of this thesis has been acknowledged, and all sources are listed as references.

1 An Introduction to Medieval Silk Production

1.1 Introduction

Shiny, strong, smooth, and often colourful, silk tends to capture the imagination with its connotations of luxury, wealth, and far-off places. There is no question that in the medieval world, silk was frequently a symbol of power, status, and wealth. In an archaeological context, silk appears frequently in high status burials, or preserved in treasuries, while also appearing in more surprising archaeological contexts such as the urban landscapes of early-medieval Coppergate (Walton 1989), and London (Pritchard 1984). There is no evidence of a local silk-weaving industry in England during the Middle Ages (Crowfoot, Pritchard and Staniland 2006, 82), so the mere presence of silk in these contexts is an indication of far-reaching trade networks. The same can be said for the appearance of silk in Scandinavian archaeology and in the Hiberno-Norse context of early-medieval Dublin (Geijer 1938; Wincott Heckett 2003).

This thesis is concerned with the merging of the theoretical and the technical in relation to the medieval silk trade. The research undertaken combines experimental archaeology with macroscopic and microscopic analysis of both modern and medieval silk textiles to answer the question "Can the provenance of medieval silk textiles be determined through the technical analysis of thread structure and fibres?".

The vast trade networks that conveyed silk products and numerous other sought-after items across Eurasia from antiquity to beyond the Middle Ages was first dubbed "the Silk Road" by the 19th century German Geographer Ferdinand Freiherr von Richthofen. This term was later expanded to "silk roads" and the arguably more accurate "silk routes" (Figure 1.1) by other researchers (Manning 2014, 5). This shift in language acknowledges that these far-reaching trade connection were in fact, as Susan Whitfield(2019, 15) puts it " A system of substantial and persistent overlapping and evolving interregional trade networks across Afro-Eurasia by land and sea…".

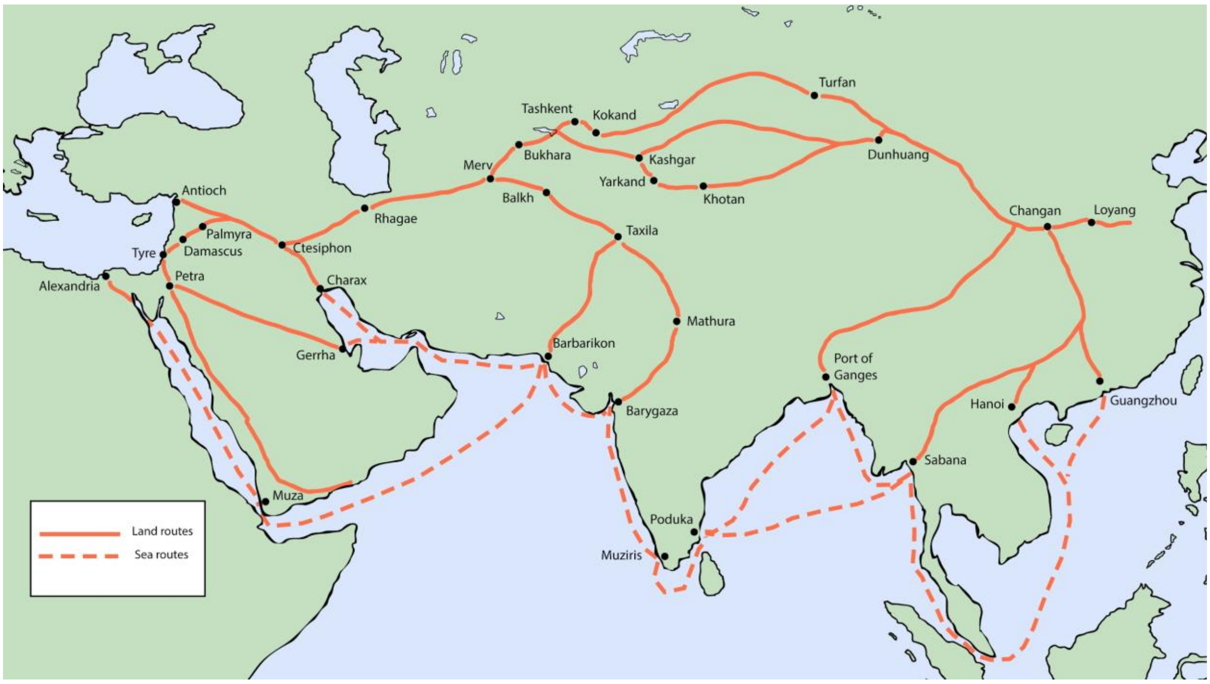


Figure 1.1: General sea and land trade routes stretching from China to the Mediterranean. No date specified (After Vollmer et al. 1983, 26)

Considerable research has been carried out on the silk routes themselves, and on the production and exchange of medieval silk textiles. Despite this wealth of research, it is still tremendously difficult to pinpoint the routes via which silk textiles travelled. Information is particularly limited regarding the origins of silk goods traded throughout northern Europe during the Early Middle Ages, although the probable role of Scandinavian trade networks has been emphasised in transporting these textiles to Britain (Walton Rogers 2020a, 109–110). As will be discussed in chapter 2.3, previous technical studies of silk textiles have identified characteristics of figured silk textiles (including motif and woven structure) that support identification of regions wherein these luxury textiles were woven. But this identification – while important to understanding the manufacture of medieval silks – can only provide a partial picture as it does not fully account for the various non-woven states in which silk was also transported, nor can these technical observations be applied to simple cloth structures such as tabby. The analysis of simple cloth structures and their components is a central concern of the research undertaken for this thesis and by the final chapter, the important connection between subtle silk textile characteristics and far-reaching trade networks will be made clear.

This chapter will establish the crux of this thesis –the provenance of silk textiles— first with an introduction to silk as a material, leading into a summary of the historical context of the medieval silk trade, including key centres of production, avenues of exchange, and a discussion of who was involved in silk production. This initial context will be followed by further explanation of the question of provenance in the field of silk research. The research question and aims of this thesis will then be discussed in further detail and the archaeological case studies will be introduced. A further explanation of the value of silk research will precede a breakdown of the overall thesis structure.

1.2 What is Silk?

Silk as a raw material has two components: Fibroin, which is the silk fibre itself, and sericin, which is a gummy protein that surrounds the fibroin(Shen, Johnson and Martin 1998, 8857). Silkworms extrude paired strands of fibroin, called brins. The brins are glued together with sericin, to form a single strand referred to as a bave. An individual silkworm constructs a cocoon from this continuous strand to protect itself during the metamorphosis from caterpillar, to pupa, to moth (Rayner 1903, 3,4).

The operational sequence of silk production will be discussed in detail within its historical context in Chapter 2. A key distinction to emphasise when discussing medieval silk production is that this thesis will focus on **silk-reeling**, a process which involves the unravelling of multiple silk cocoons to form smooth, strong continuous filament typically several hundred metres long, which can further be processed into yarn, with or without twist. The production stages involved in this process require different skills and specialist knowledge to those required for spinning discontinuous fibres such as wool. There are historical records that describe silk fibres being spun rather than reeled – this is particularly the case in Buddhist regions (Desrosiers and Debaine-Francfort 2016, 72) – and examples of spun silk have been found in some archaeological contexts such as Dunhuang and Turfan (Zhao and Wang 2013, 353). However, these examples are often discussed as an exception to the majority of surviving silk textiles, which appear to have been produced from reeled silk. It is for this reason that the establishment and spread of sites of sericulture and silk production throughout the Middle Ages is notable, as it provides a key to understanding the transmission of specialist knowledge, equipment, and potentially, the movement of people who possessed these skills.

1.3 An Introduction to Medieval silk Production and Exchange

In the context of the medieval European textile economy, “silk” generally refers to the fibre produced by *Bombyx mori* silkworm, a species of caterpillars initially domesticated in China. A wide variety of wild silk moths can be found all over the world, but the silk produced by these species exhibit different physical characteristics to *Bombyx mori* silk (Feltwell 1990, 123). While there are some potential examples of the use of wild silk varieties in medieval silk textiles that merit further exploration and research, the focus of this thesis is the processing of silk derived from Bombyx mori cocoons. Unless otherwise specified, the terms “silkworm” and “silk” when used throughout this thesis should be assumed to be referring to the Bombyx mori species and their products.

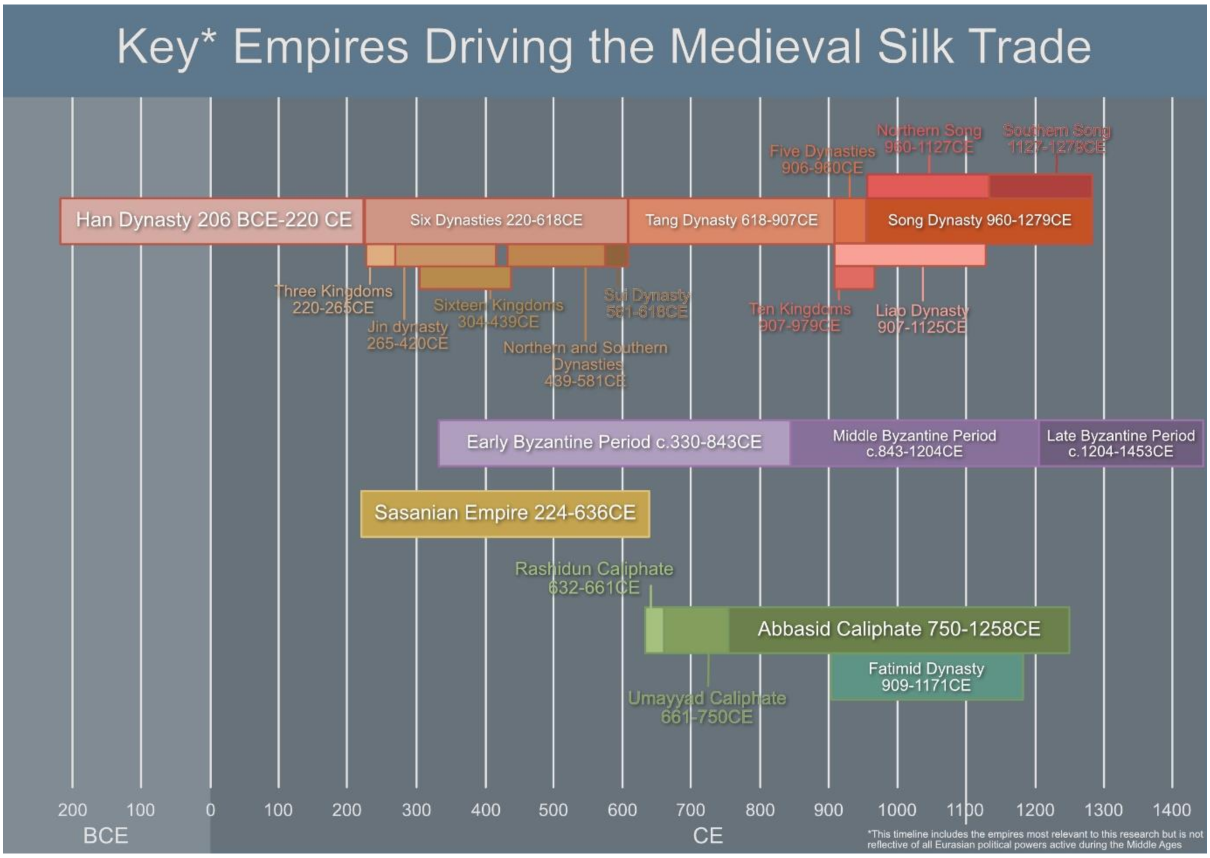


Figure 1.2: Timeline of key empires involved in the medieval silk trade (Source: the author)

1.3.1 Medieval centres of Silk Production and the spread of sericulture

Silk processing and weaving is understood to have originated in China, where archaeological silk textile fragments dating to the Neolithic have been found (Kuhn 1988, 272–273). The “opening” of the silk routes and subsequent trade of silk goods outside of China is generally attributed to Han (*206 BCE-220 CE*) Emperor Wu Di during the 2nd century BCE, although there are archaeological finds of silk outside of China predating this (Hao 2012, 112). Accounts vary slightly, but the general narrative is that emperor Wu aimed to either form an alliance with the peoples of *Xiyu* (the “Western Regions” outside of Han China) against their common enemy, the *Xiongnu* (Huns), or otherwise unite these small kingdoms using gifts of silk as a persuasive tool. Whatever the exact motivation, these initial diplomatic missions were ultimately unsuccessful, but they did result in the export of an increasing volume of silk and silk-processing methods from China in a more controlled and strategic manner (Mair

2014, 1–2; Wenying 2012, 119; Vollmer, Keall and Nagai-Berthrong 1983, 12). This state-controlled export of Han silk was interrupted by the dynasty’s collapse in the 3rd century CE. The resulting loss of strict regulation over silk exports has been credited with the spread of silk-production methods outside of China (Vollmer, Keall and Nagai-Berthrong 1983, 33).

By the start of the Early Middle Ages, production centres (Figure 1.3) had already been established in parts of central Asia, Egypt, Syria, Sasanian Persia, and Byzantium (Kuhn 1988, 419). Sericulture is said to have been established in Byzantium from the 6th century, when it is claimed that silkworm eggs were smuggled out of an unspecified eastern kingdom and brought to Emperor Justinian by Nestorian monks (Muthesius 1989, 136–137). The veracity of the details of this story are often critiqued, but this timeline for the establishment of Byzantine sericulture is frequently repeated, notwithstanding any debate (Zanier 2020, 18). Sericultural activities appear to have already been established in the Byzantine Empire by the 6th century (Muthesius 1989, 136–137), but records indicate a concentrated import and subsequent processing of Syrian silk during the 10th century, and Muthesius suggests that the imperial and non-imperial silk production sectors were supplied with both domestically produced and imported raw silk (Muthesius 1989, 141, 144). To the east, the Sasanians had established their own weaving centres in Susa, Jondishapur, and Shustar, further strengthening their command of the silk trade east of Byzantium (Daryaee 2010, 408).

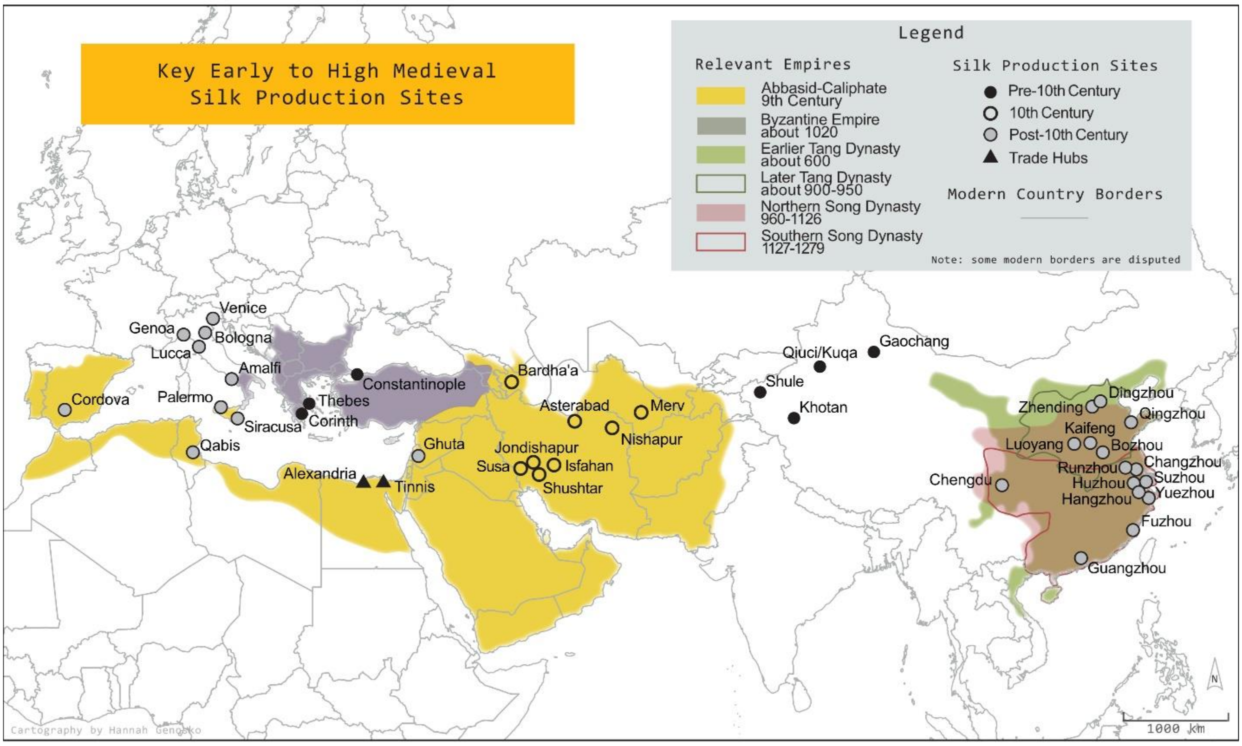


Figure 1.3: Key early- to high-medieval silk production centres with some relevant empires indicated (Map by Hannah Genosko, reproduced with permission)

Sericulture (and by extension silk-reeling) is claimed to have been introduced to Spain between the 8th and 9th centuries CE (May 1957, 3; Molà 2016, 205), in Sicily c. 827 CE following conquest by the Aghlabids (Jacoby 2004, 200), and in Lucca from the 12th century (Molà 2016, 206). Specific exporters of silk in its raw state are also noted in other contexts; according to a number of documents from the Cairo Genizah, Spain was a leading exporter of silk cocoons as well as raw reeled silk, both of which were apparently processed and/or woven in a number of countries including Egypt and Tunisia (Goitein 1967a, 102). This indicates the various stages at which silk products might be exported, and suggests a clear division of labour in the medieval silk industry.

Returning to the Byzantine Empire, specialised roles are described by the 10th-century *Book of the Eparch* (Also called the *Book of the Prefect*). Two examples are the roles of *Metaxopratai* (dealers in raw silk) and *Katartarioi* which varies in interpretation from silk reeler, to one who degums silk (Muthesius 1989, 145; Galliker 2017, 350–351). This further indicates clear divisions of labour between stages of silk import and production, even if the exact nature of each role is debated.

Equally important to our understanding of the trade of raw and finished silk products are restrictions placed on specific exports. Highly graded silk was an important means of marking rank and signifying authority in both ecclesiastical and imperial contexts in the Byzantine empire (Muthesius 2001, 38). Byzantium effectively wielded silk as a political tool between the 4th and 12th centuries through strategic trade agreements, the presentation of silk as diplomatic gifts, and as an expression of imperial wealth and power on the battlefield (Muthesius 1992, 100–104). Internally, rank and authority were not only demonstrated through sumptuary laws, but also through restrictions on silk production and export such as the prohibition of selling to Jewish traders or other merchants who intended to resell outside of Constantinople (as described in the *Book of the Eparch* (Goitein 1967a, 103). Restrictions on who was permitted to produce different qualities of silk further ensured a rigid hierarchy wherein only imperial workshops could produce "first quality silks", while private guilds were permitted to produce and sell "second quality silks" (Lopez 1945, 2–3). This approach was cemented through the strict control of exports meaning that while impressive Byzantine figured silks were in popular demand in the Mediterranean, raw silk was rarely if ever exported.

By the 7th and 8th centuries, the Byzantine and Sasanian silk monopolies were faced with a serious threat in the form of the Muslim caliphs. Islam was a new religion in the 7th century, but steadily grew in followers forming a significantly more unified identity under the leadership of Mohammed, the faith's founder and prophet, than had previously existed in the Arabian Peninsula. Following the death of Mohammed in 632, his first successors, the Rashidun caliphs expanded Muslim rule via a series of conquests (Kennedy 2016, 8–9). Between 633 and 639, the

Byzantine and Persian empires both lost important territories as Syria and Iran were invaded by the Rashidun Caliphate. Egypt was conquered by 643, meaning that Byzantium lost two key centres of silk production, while Persia fell completely under Rashidun rule by 644, meaning the Caliphate had not only gained control of key silk-production sites, but also trade routes from the east (Woodward Wendelken 2014, 67). Syria had been an important territory for Byzantium in regards to silk production, and this loss necessitated the establishment of new silk workshops further west in locations such as Corinth and Thebes (Ertl 2006, 251).

During the early 8th century, the Umayyad caliphate expanded the territory conquered by the Rashidun caliphs, conquering Spain. Silk weaving workshops were established in Córdoba, the "Western Caliphate's" capital from 756 (May 1957, 3). The new Muslim rulers of Persia had successfully adapted the silk production infrastructure established by the Sasanians, allowing for a swift and effective expansion of silk manufacture (Woodward Wendelken 2014, 68). While the expansion of Arabic rule was responsible for a significant increase of silk production in the mediterranean, a range of influences led to the development of silk production in Italy between the 9th and 11th centuries. In general some variant of "Arab, Greek, and Jewish" immigrants are credited, although there must also have been some degree of Byzantine influence (Molà 2000, 3; Kuhn 1988, 420).

Meanwhile, silk production intensified in the Tang and Song (Figure 1.4) dynasties during the 10th century, as silk became an increasingly demanded form of taxation (Zhao 2012, 209; Kuhn 2012, 15).

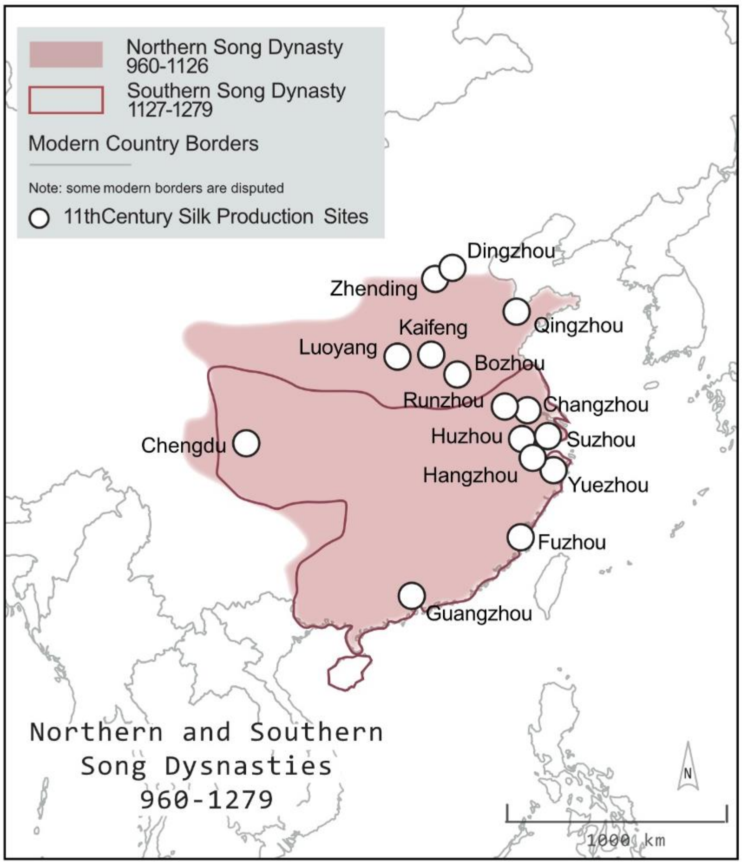


Figure 1.4: The Northern and Southern Song Dynasties with notable centres of silk production (Map by Hannah Genosko, reproduced with permission)

The time of the first 3 crusades played a large role in paving the way for a later Italian silk monopoly. Venice, Pisa and Genoa benefitted from significant trade privileges with the Byzantine empire during the late 11th and 12th centuries, to varying extents (Jacoby 1994, 349, 368). This was compounded by tremendous privileges granted to Italian merchants trading with Alexandria from 1173 on, as part of a strategy on the part of Saladin to strengthen the Egyptian economy (Day 1981, 161–162). The resultant control of the Mediterranean gained by Italian merchant fleets (Vollmer, Keall and Nagai-Berthrong 1983, 81) is one significant factor contributing to the rise of the late-medieval Italian silk monopoly.

The Italian silk industry came into its own during the late Middle Ages as the dominant supplier of silk for the European market (Molà 2016, 206). This can be attributed to the economic advantages listed above, and a series of threats that compromised the silk export of Italy's competitors, including Byzantium's preoccupation with the crusades and Mongol invasions of Persia (Kuhn 1981, 51). By the 13th century there were 4 primary silk weaving centres: Genoa, Venice, Bologna, and Lucca, each with particular specialisations (Molà 2000, 3).

1.3.2 Avenues of Silk Exchange

Silk products were exchanged via several mechanisms. As previously discussed, Sasanian Persia and the Byzantine Empire were key sources of silk for Europe during much of the Early Middle Ages. Byzantium was the key player in disseminating silk cloth westward, both for export via trade and as a powerful political tool, while Persia controlled the flow of silk from the east by land and sea despite Byzantine attempts to circumvent this (Oikonomidès 1986, 33; Vollmer, Keall and Nagai-Berthrong 1983, 33). The 8th and 9th centuries saw an increased sea trade initiative under Islamic rule (Ma 2002, 10) supported by the appropriation of established weaving workshops and establishment of new ones.

During the Song dynasty silk was frequently exchanged internationally as part of conditions of peace treaties (Kuhn 1988, 385). Silk was also transported internally via itinerant merchants who purchased silk produced in rural communities, and sold it on to urban centres (Kuhn 1988, 386).

Previously mentioned restrictions on forms of silk manufacture in the Byzantine Empire effectively created two spheres of Byzantine silk export: the strategic dissemination of imperial silks as diplomatic gifts to both foreign churches and states (Lopez 1945, 4), and the economic export of silk primarily produced by private guilds (Lopez 1945, 8–9; Muthesius 1989, 146). Imperial silks presented to churches and emperors on the European continent were often distributed further as "hand-me-downs" of sorts, at times being reworked (Walton Rogers 2020a, 109). It has been noted that many Byzantine silks reached Anglo-Saxon England as secondary gifts from popes and German emperors (Fleming 2007, 130). The reuse of fabrics was not just limited to Byzantine silks, as there are examples of repurposed silks such as a mantle belonging to a church in Valencia, made from fragments probably manufactured in Egypt and Syria (Jacoby 2004, 205). This practice undoubtedly contributed to the transfer of fabrics to multiple social classes across Europe and the Mediterranean.

The distribution of second-hand clothing in the Mediterranean and Near East is also discussed by Goitein. Sasanian and later Muslim rulers maintained a practice of giving new garments embroidered with their names, referred to as *khila* ‘robes of honour”, a practice that Goitein argues evolved into a trend of giving second-hand clothing to one’s social “inferior” amongst the court and bourgeoisie. There was also a practice of selling or exchanging clothing via a vendor of second-hand goods established in this region (Goitein 1967b, 184). It is notable that the trade and reuse of silk textiles is documented in multiple regions. The Byzantine empire certainly looms large in the medieval silk trade and it is perhaps for this reason that, even tabby silk textiles imported to Europe and Britain during the early Middle-Ages have frequently been assumed to be Byzantine in origin (Fleming 2007, 128, 130; Wåhlander 2016, 142). The results of this thesis will demonstrate that there is cause to believe that the silk textiles reaching early- to high-medieval Britain, are likely to have been produced in multiple different regions (see chapters 8 & 9).

1.3.3 Who tended the silkworms? Who reeled the silk?

So far, the overarching organisation of silk production has been discussed, but not much attention has been paid to the individual craft workers and their cultural contexts. It has been established that a broad network of exchange existed across Eurasia by the early Middle Ages which in part connected various silk workshops that operated within different regions. A key theory underpinning the connection between technical textile characteristics and their production locations is that craft techniques are inherently social productions (Lemonnier 2004, 3). The relationship between stages of craft production and the cultural framework of the craft producer supports the link between technical textile variations and where they were produced. It is also important to understand that this relationship does not operate in a single direction; Van der Leeuw (2013, p.240), for example, has argued that technical and social choices have a symbiotic relationship.

Who, then, were the medieval silk workers? Zanier (2007, 111) argues based on historical accounts that women have played a dominant role in silk production, globally. Zanier's focus is largely post-medieval, although he builds his case based on several medieval sources including the 10th-century *Calendar of Cordoba,* which links women to moriculture (Zanier 2007, 112; citing Dozy 1961, 48-49), Arab sources from the 13th-14th century that make the same connection (citing Chézy, 1805, p. 39; Bodenheimer, 1994, p. 305; Renaud, 1948, p. 34; and Jayakar, 1906, pp. 794-795) and the 13th-century Cantigas of Alfonso el Sabio, which mention a woman from Segovia who raises silkworms (citing Alfonso el Sabio 1979, cant. 18). A key argument made is that popular belief linked femininity with sericulture, and this excluded men from the practice, although this supposed exclusion was clearly not strict or universal, as Zanier also mentions "enclaves" of itinerant male silk workers in southern Italy and Spain (Zanier 2007, 114). Earlier historical events also indicate mixed gender silk work in Central and eastern Asia. In 829 CE the kingdom of Nanzhao (modern Yunnan) invaded Sichuan, capturing and forcibly moving tens of thousands of craftspeople back to Nanzhao. It is specified that the craftspeople were **male and female.** and that the textile arts flourished from that time, becoming competitive with 'China', presumably meaning the Tang dynasty (Zhao, 2012, p.207).

Despite at least some male involvement in silk production, the strong association with female labour means that it is worth considering the role of silk production in the construction of gender roles. Angela

Sheng discusses references in Confucian texts to women weaving, and specifies that the production of plain weave (*tabby*) textiles of silk (*bo*, *juan*) and plant fibres was the domain of women in rural areas. Importantly these accounts also connect to the topic of status as Sheng specifies this was the work of commoners, and that the women who wove plain silk cloth were used as an example of female virtue, as they not only clothed their families but also supported the state (this cloth was used as a form of currency and paid as tax as early as the 1st century BCE) (Sheng 2012, 12), this dates. In the Han dynasty texts Sheng discusses, the concept of textile production as women's work was enforced within a context of setting standards for humility, while setting out expectations that women should produce unembellished cloth (Sheng 2012, 15). From the Southern Song dynasty (1127-1279) on, weaving of simple cloth was increasingly commercialised; this echoes some shifts in the organisation of weaving in medieval Europe a century earlier, also linked to gender (Øye 2016). In the Song dynasty, this meant that poor women increasingly sold their textile products rather than retaining them for private use, and men joined weaving workshops. Ironically, this transition apparently only intensified the romantic ideal of virtuous women's work being weaving within the home (Sheng 2007, 18). All of this relates to a dictated ideal linked to state control of agriculture and textile production providing a clear example of the interrelation between socio-economic organisations and technical systems (Lemonnier 2004, 15).

The topic of gender in many ways intersects with the topic of status, which is frequently discussed in relation to the consumption of silk but is more complicated in relation to silk workers. In the context of the Song Dynasty, we see plain silk weaving used as part of a construction and reinforcement of gender roles, and arguably, a reinforcement of social class. Dorothy Ko argues that textile work was an instrument used to mark and reinforce a Confucian ideal of womanhood, while also marking class differences amongst women. This can be considered part of a process of performing and “becoming” one’s gender within the context of imperial Chinese textile production (Ko 2007, 172). Ko’s focus on the idea of “becoming” one’s gender through the performance of gendered work, acknowledges the differences between biological sex (which Ko also points out does not follow a rigid binary) and socially and culturally constructed gender roles (Ibid.). Citing examples of male laymen workers and monks producing embroideries of the goddess Guanyin in the Tang and Song Dynasties and male embroiderers in the 19th century, Ko points out that gendered labour division was clearly not so rigid as one might assume. Ko also suggests that belief systems such as Buddhism, or commercial motivations may have challenged Confucian authority and its influence on gendered divisions of labour (Ibid.). This is a helpful example of a transition in gendered labour being used to challenge established social hierarchies, underscoring the previously mentioned symbiotic nature of technical and social choices described by Van der Leeuw.

Sheng and Ko both highlight the concept of “women’s work” as a tool of the ruling class, influenced by Confucian philosophy. It may be argued that the reinforcement of these roles was built upon a pre-existing association, but it is equally important to note that the attempted enforcement of more rigid gender roles is likely to have influenced perceptions of silk production in relation to gendered labour throughout the subsequent Chinese dynasties. In contrast, in a European context, an argument can be made for sericulture as a means of acquiring independence and agency. There is substantial evidence that some of the few female-run guilds in medieval Europe were tied to silk production (Dale, 1933; Farmer, 2016; Bellavitis, 2018) and in this case silk processes provided a means of establishing agency and status amongst female workers.

The movement of diasporic people is also an important element of the silk trade, and this can be complicated to address. The role of Jewish artisans and traders has frequently come up in the research for this chapter. In some cases there is confusion as to the exact role that Jewish people were permitted to take in silk production, as is the case in pre 12th century Byzantium (Lopez, 1945, pp. 23–24; Muthesius, 1993, p. 10), in others it is simply a matter of referencing the role that Jewish traders or craftspeople played in introducing silk production to particular regions without much further contextualising information (Kuhn, 1988, p.420; Molà, 2000, p.3). In other cases, this sort of movement is tied to a single event. For a period from 1314 into the mid-14th century, political turmoil in Lucca caused many Lucchese weavers to flee to other silk producing centres in Italy. Seeing the advantage of this, the other cities welcomed Lucchese refugees, and the result was an overall strengthening of the Italian silk industries outside of Lucca (Molà, 2016, p. 207).

The transfer of skilled prisoners was another way in which rulers strengthened their own silk industries. A particularly well-known example took place in 1147 CE; Roger II, the Norman ruler of Sicily’s apparent disappointment in the quality of silks produced locally led him to transport captured artisans from Thebes and Corinth (Jacoby, 1992, pp. 463–65; Muthesius, 1993, p. 9). Connected to the previous topic of diaspora, Gil states that the captured artisans were Jewish (Gil, 2002, p. 33). The implication of this enforced transport of artisans is that it had the effect of improving upon the pre-existing practices of the Sicilian workshops that had been initially established under Muslim rule, in which case it would have been fascinating to observe how these different sets of weavers interacted with one another.

The capture of skilled workers was not always intentionally targeted; following the battle of Talas River in 751, the Abbasid Caliphate’s silk industry benefited when Chinese prisoners of war turned out to be silk weavers. The Chinese weavers were transferred to Abbasid workshops, resulting in an integration of 8th-century Chinese weaving methods with local production (Woodward Wendelken, 2014, p. 69).

Social hierarchies clearly influenced how silk production technology was transferred, while such instances were frequently used as a symbol of state power. These established hierarchies also likely influenced production processes on an individual level. For example, the influence of an overarching social structure on the technology used in silk production is demonstrated by a case made by Francesca Bray (1995, 122) that the basic materials required by a peasant household during the Song dynasty would incorporate a simple loom, trays and other equipment for raising silkworms, a basic reel, and a spindle-wheel, all of which would be made from cheap materials and repaired within the home or with the help of a local carpenter. In contrast, manorial households or large workshops could accommodate large complex looms and other equipment.

The above examples demonstrate that, while skilled workers were a key part of establishing the silk trade in many territories, these workers themselves do not appear to have occupied a privileged status within medieval societies. Certainly, in the examples of prisoners of war, silk workers seem to have had very little agency. This contrasts with the ways in which control of silk production may be considered a source of agency, particularly in the case of female-operated silk-working guilds in western Europe. There was clearly some social stratification across different sectors of silk production. For the purposes of this thesis, an awareness of the identities of those enacting the process of silk production provides some insight into how social values were reaffirmed or contested (Dobres 2000, 100) through the development, use and adaptation of silk processing technology across Eurasia.

1.4 The Question of Provenance

The medieval world was well-connected, and the proliferation of silk is strong evidence for this. The medieval silk trade serves as an excellent focal point from which to analyse the transmission of craft knowledge during this time-period. The spread of silk-reeling techniques is an understudied area of research that can shed new light on vital craft practices tied to the medieval silk industry.

In the field of silk research, provenance of materials is an important yet somewhat ephemeral topic. The Middle Ages saw tremendous growth in silk production (Jacoby 2004, page 198; Muthesius 2003, page 330) leading to the increased mobility of goods, materials and people along the Silk Road. The volume of exchange is reflected by the diversity of sources for raw silk imported into late-medieval European centres of trade including Lucca, Florence, Paris, and London (Farmer 2016, 45–47; Molà 2016, 209–210). However the full extent of the trade in raw materials throughout the Middle Ages is still uncertain, which causes difficulty in tracing the origins of raw silk imported by regional workshops in Europe and the Mediterranean (Vollmer et al. 1983, page 4). This issue is underscored by the writing of prominent ethnographer and historian S.D. Goitein on records of the silk industry from the Cairo Geniza:

> “Needless to say, the Geniza contains many records of merchants who traded that commodity [silk] as their main line and in quantities of over a hundred pounds. Nevertheless, the enormous popularity of dealings in silk and the subsequent profusion of references to them hamper the efforts to bring the entire material under control.” (Goitein 1967a, 223)

This research aims to explore the physical characteristics of silk produced in different regions as a reflection of the specialist knowledge of skilled silk workers, who often were themselves key to transmitting knowledge of silk production methods from one region to another (Schoeser 2007, page 36). The transfer of knowledge is an important topic of study and debate in contemporary archaeological and sociological research (Eerkens & Lipo 2005; Stark et al. 2008). Wendrich emphasises the multifaceted nature of knowledge transfer, which encompasses both physical and mental processes within a particular social context (Wendrich 2013, page 4). More particularly, the mobility of ideas is an important factor in the exchange and design of medieval silk textiles. By 1100 AD, an “international style” of patterned silk weaving had become prevalent, which Muthesius has noted can occasionally cause difficulty in differentiating between medieval Byzantine and Islamic silks (Muthesius 2003, page 327)

Attempts have been made to associate specific silk yarn characteristics such as degree of twist with particular geographic regions, but many gaps in information remain, precluding a concrete association of yarn types with specific production sites. While this subject has been partially approached by Desrosiers (2019), no theories on silk thread variations have been tested with experimental archaeology. Within the context of the medieval silk trade there are recorded variations in the processing methods associated with certain geographic regions, and these will be discussed in greater detail in Chapter 2. Despite access to this technical information, there is a significant lack of information on the specific impact these processing techniques have on the quality and appearance of the resultant silk threads and the fibres from which they are made. A study focussing on silk-reeling and processing techniques provides the ideal approach to address this gap in research. Using experimental archaeology to determine the impact of various methods and equipment on the quality of silk threads will enable a thorough analysis of the different styles of silk thread seen in medieval samples. The results of this experimental research have the potential to determine the provenance of silk textiles of previously unknown origin, and may provide crucial information on the quality (and therefore desirability) of raw silk produced in different regions, further informing our understanding of medieval trade networks.

1.5 The Research Question

The question at the core of this thesis is "Can the provenance of medieval silk textiles be determined through the technical analysis of thread structure and fibres?"

This research was designed with 3 key objectives:

1. To determine how the physical appearance and dimensions of silk fibres and threads are affected by different silk-reeling and processing techniques;
2. To establish a new methodology for determining the provenance of medieval silk fibres based on diagnostic morphological characteristics;
3. To use the resulting data to build a framework for analysing the extent of international and intercultural transfer of knowledge and technology connected to medieval silk production.

This research has aimed to identify diagnostic criteria for determining the equipment and production methods used in the manufacture of medieval silk threads through the combination of experimental archaeology and textile microscopy. The goal was to compare experimentally produced silk samples with archaeological silk textiles to provide insight into the conditions under which medieval textiles were produced. The ultimate aim was that the results of this analysis would establish a framework that aids in identifying the location of production and, if unknown, the time period during which surviving medieval silk textiles were produced.

1.6 Archaeological Silk Case Studies

> "It is interesting to note that this the most practical of all thread constructions is also the one most conductive to aesthetic elaborations…"
>
> (Albers 2017, 24)

Anni Albers' poetic description of tabby, or plain weave cloth structure touches on why tabby silk textiles make fascinating case studies. The precious material of silk woven in a deceptively simple structure demonstrates the potential for near infinite aesthetic variation, and yet the production of tabby silk during the Middle Ages is an under-explored area of research.

For the purposes of this research 2 groups of tabby silk textiles with pre-identified variations in appearance and yarn characteristics were selected for analysis.

The first group of textiles were uncovered during the 1976-1981 Coppergate excavations in York and date to the 10th century. The second group of textiles were recovered from a mortuary chest in Winchester cathedral as part of an ongoing research project. The Winchester silk textiles date between the 7th and early 12th centuries (Swire 2024).

The Coppergate and Winchester textile collections provide an excellent opportunity to compare early-to-high-medieval tabby textiles from different social and depositional contexts. The results of their analysis have the potential to provide new insight regarding the technical choices made during the production of these textiles. The provenance of the textiles prior to their use and deposition is unknown, apart from the fact that these textiles must have been imported from outside of Britain. This means that any new information regarding production technique also has the potential to illuminate the possible origins of these silk fragments.

1.7 Why Silk?

Beyond the specific concerns regarding the provenance of textiles and the “how” of production methods, the study of silk production provides an avenue for the exploration of broader concerns in the field of craft research. Adamson argues that ‘Craft only exists in motion’; at its core it is a ‘way of doing’ rather than a series of static classifications (Adamson 2007, 4). The medieval silk trade is particularly emblematic of this, and I would argue that silk textiles survive as a physical trace of people in motion. On a macro scale this is reflected by the movement of cocoons, yarn, or cloth from their sources of production to other settlements, ports, and cities, marking out vast networks of trade, diplomatic connections, and the paths of transmitted knowledge. On a micro scale, this is much more direct; yarn can be considered a physical trace of the motion of the maker’s hands, reeling, twisting, winding, while the weft thread in a piece of cloth survives as a tangible trail of the path of the shuttle as it was propelled from one edge of the warp to the other, by the weaver's hand: fast, ephemeral movements, frozen in time.

This thesis is based on the premise that the macro and the micro are equally important. Just as the shape, appearance, and diameter of the fibre is as important as the structure, texture, and appearance of the cloth, the decisions made by an individual maker and the haptic experience of the artisan are as important as the locations of production sites and the mechanisms of exchange that influence the movement of textiles. More importantly, this thesis will demonstrate the value of considering the macro and micro in combination, as one can easily inform the other. The focus of this research of course is how the actions of the maker influence the characteristics of the product, with the aim of determining how these differences in characteristic indicate the location of production.

1.8 Thesis Structure

The remaining chapters of this thesis will cover the exploration of the research question through textual and art-historical analysis, experimental archaeology, and the analysis of both experimentally produced silk samples and the archaeological silk textiles introduced in this chapter. The results of this multi-faceted research approach will be presented and discussed, as will the potential for future research directions. **Chapter 2** will summarise the body of pre-established information regarding technical silk production, and methods of textile analysis. **Chapter 3** will explain the steps taken to research and reconstruct silk-processing devices based on medieval sources in preparation for the silk-processing experiments. **Chapter 4** will explain the design and execution of the silk processing experiments. **Chapter 5** will discuss the results of the silk processing experiments including observations made throughout. **Chapter 6** will describe the methods applied to further the development a comprehensive protocol for silk textile analysis. **Chapter 7** will present and discuss the qualitative and quantitative data generated during the analysis of the experimental silk textiles, highlighting which results are most relevant to archaeological textile analysis. **Chapter 8** will present and discuss the results of the archaeological silk textile analysis, presenting qualitative and quantitative data that has generated new information regarding silk processing techniques. Finally, **Chapter 9** will close with a discussion the research findings in relation to the research question, the implications of the experimental and analytical results, and the potential for further research in this area.

2 Researching Medieval Silk Production

Medieval silk production is a vast research subject, even when narrowed down to the manufacture of silk threads. Foundational information regarding this topic is essential to developing a rigorous research methodology on silk as a raw material in the Middle Ages. Establishing what is known about medieval equipment and methods of manufacturing silk will help identify unknown aspects that require further exploration.

There are in fact 3 key elements to understanding the production of silk thread during the Middle Ages:

1. The equipment used to produce silk yarn
2. The operational sequence of silk yarn manufacture
3. The analytical methods used to interpret medieval silk textiles

This chapter will provide an overview of current knowledge of these 3 topics.

2.1 The Equipment Used in the Production of Silk Yarn

It should not be surprising that the number of sources concerned specifically with the technology used to produce silk thread in various regions between c. 400-1500 CE is limited. That said, enough information has been gleaned from a few dedicated sources on the topic (and more numerous sources on the medieval silk trade) to construct a general overview of both the technical information available and the gaps that remain. Some contemporary sources on silk production survive in a variety of languages, particularly from medieval China and Italy. When possible, accepted English-language translations of these sources have been relied upon.

Since the 1980s, the key English-language source on medieval silk-reeling equipment from has been the work of Dieter Kuhn. Kuhn has published and edited several texts on the topic of Chinese silk production, but particularly relevant to the topic of silk processing mechanisms are his 1981 article on Song dynasty (960-1279 CE) silk technology and the 1988 book, *Chemistry and Chemical Technology, Part 9, Textile Technology: Spinning and Reeling*, a volume of Joseph Needham's series *Science and Civilization in China*. Kuhn's research on silk-reeling equipment from China has particularly focussed on the Northern and Southern Song Dynasties but has also drawn additional informative parallels to later European silk-reeling technology. Dr Feng Zhao, the Director of the China National Silk Museum has also published extensively on this subject, although has focussed in more detail on Chinese weaving technology. Other authors have addressed the topic of silk-reeling in medieval Europe, in particular Dr Luca Molà who specialises in Renaissance technology, particularly in connection with the Italian silk trade, and textile specialist Sophie Desrosiers who has published extensively on medieval silk textiles. Despite the work of these researchers, specific information on the reeling technology used in this context is limited by a relative scarcity of primary source material.

The equipment used to create silk thread can be subdivided into 2 categories: The equipment used to reel silk, and the equipment used to process raw, reeled silk into useable thread. This technology will therefore be discussed according to those 2 categories.

2.1.1 Equipment for Reeling Silk

It is generally agreed that silk-reeling was first established in China, and that the equipment used initially for silk-reeling was simple in both construction and operation, becoming more complex and automated over time. Dieter Kuhn suggests that early reels from the Shang (1600-1046 BCE) and Zhou (1046-256 BCE) dynasties were similar in form to devices depicted in much later (16th- to 19th-century) Chinese and Japanese sources (Kuhn 1988, 348–349). This equipment, consisting of a water basin over a small stove and a simple hand-operated "bobbin-shaped" reel is, according to Kuhn(1988, 350), the simplest iteration of silk-reeling equipment that could be operated efficiently. A description of equipment in use during the Shang and Han (206 BCE-220CE) dynasties by Feng Zhao (2020) expands slightly on this, describing an additional silk-reeling component: a type of frame with 2 small “wheels”, likely made from bamboo, which was positioned above the water pan. Zhao implies that thread was pulled through this frame and wound onto a separate “wheel” but does not describe exactly how. This equipment is still in use in some parts of Southeast Asia (Zhao 2020, 3/16). Both Zhao’s description of this wheel frame and his reference to contemporary Southeast Asian equipment correlate with Kuhn’s description of the “Soundless-roller Silk-reeling Frame” that was described in some 18th- and 19th-century sources as a new invention, but which Kuhn(1988, 379–384) argues based on literary evidence dated between 1037-1101 CE was used during the Song dynasties (960-1279 CE), and may be older. Kuhn does not argue for the introduction of the “Soundless-roller” or a similar equivalent as early as the Shang or Han dynasties, but he does theorise the introduction of a frame comprising 2 upright posts and a crossbar with a hook over the reeling basin. This would free the reel operator from guiding the silk onto the reel as they turned it. Kuhn(1988, 350) also argues that this alteration may have started small, allowing the operator to work alone (as appears to be the case with the simplest reeling set-up), but likely increased in scale, eventually requiring 2 people to operate it. He also argues that this transition to a two-person reeling device likely took place prior to the Song Dynasties (Kuhn 1988, 351). Zhao(2020, 7/16) does not discuss similar intermediary equipment, but instead jumps ahead to the development of the treadle-operated silk reel, which he attributes to the Tang dynasty (618-907 CE), although it continued in use into the Song dynasties. Treadle-operated silk-reeling devices are also a focus of Kuhn’s research, and he divides this type of reel into 2 styles, the Southern style and Northern style. This distinction is geographic and should not be confused with chronological distinctions between the Northern (960-1127 CE) and Southern (1127-1279 CE) Song Dynasties respectively. Kuhn makes several distinctions between Northern and Southern silk-reeling devices. The Northern device accommodated 2 cocoon groupings rather than one, allowing for double the volume of silk filament to be reeled at a time. The Northern device also had a ramping-board on the front of the frame, which guided the silk filament on to the reel. A roller frame, which will be discussed in more detail, would have sat separately on the reeling basin. The southern device reeled a single filament from one grouping of cocoons and may have had no ramping-board, or had one that was placed high above the pan. Kuhn(1981, 68) notes that the Northern style was longer-lived, eventually being adopted in the south with the implication that the southern device was not as technologically sophisticated as the northern one.

A further note is required on the component that Kuhn calls a ramping-board. By Kuhn's description the ramping-board is a rod or flat piece of wood that would sit across the front of the Northern style silk reel. One end of the ramping-board was connected to a protruding rod affixed to a pulley on the corner of the reeling frame; this pulley was in turn connected to the axle of the reel, so that it turned when the reel turned. The opposite end of the ramping-board apparently fit into a cord or ring on the opposite front corner of the frame, and being fixed in this way would move back and forth along the front of the reel (Figure 2.1). The silk being reeled was fed through 2 guides on the ramping-board that were made from bent bamboo, so that as the ramping-board moved it would lay the silk evenly across the width of the reel (Kuhn 1988, 361–362). Although Kuhn mentions the possible presence of a ramping-board associated with the southern reeling device, his description of this moveable ramping-board having 2 thread guides aligns it with the northern device. This implies that the movable component to this part was another distinguishing feature of the northern reeling device, and that the "ramping-board" associated with the southern reeling device was stationary.

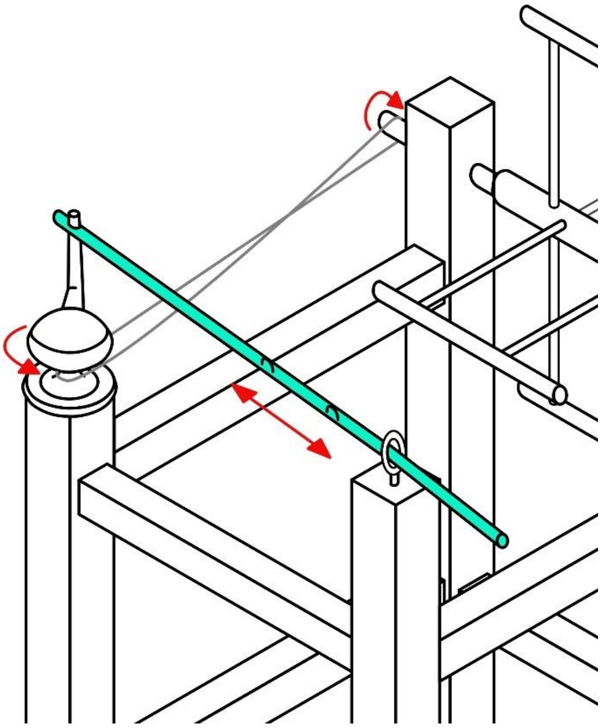


Figure 2.1: The moveable ramping-board (green) as described by Kuhn (Source: the author)

Medieval silk technology in Europe is frequently linked to Italy. From the late Middle Ages, the Italian silk industry increasingly used locally produced silk thread, where it had previously imported raw silk from other regions including China and Persia (Molà 2016, 211). Molà(2016, 214) describes the basic silk-reeling apparatus used around the 16th century as comprising a stove, a basin, and a reel, which he describes as being operated by hand, but gives no further details. It is unclear when this simple equipment was introduced to the medieval Mediterranean. Considered in relation to suggestions from Hills(1992, 66) and Kuhn(1988, 421) that when silkworm eggs were brought to Emperor Justinian in the 6th century, knowledge of a basic reel mounted on a stand must also have been introduced to the Byzantine Empire, it is possible that the equipment described by Molà is a continuation from equipment introduced to this region during the 6th century, if not earlier (see chapter 1.3.1).

With the exception of later inventions such as the Piedmont reel (which used geared connections rather than drive-bands; (Diderot and D’Alembert 1751, 4), the post-medieval silk-reeling equipment used in Europe has generally been described as more-or-less identical to the equipment developed in China during the Tang or Song dynasties. Zhao(2020, 9/16) describes the introduction of Sericulture and silk-reeling to Europe, as occurring “via the silk road from the thirteenth to eighteenth centuries” and states that the silk-reeling equipment eventually used in Italy was identical to Chinese mechanisms. Kuhn(1988, 426–428) provides a similar assessment, although also remarks upon minor ways in which European devices could be considered inferior to Chinese devices. Neither Kuhn nor Zhao entertain the possibility that some elements of the later European reeling devices could result from convergent development, which suggests multiple instances of technology transfer between east and west. A comparison of European and Chinese reeling devices will be expanded upon in chapter 3.

2.1.1.1 Crossing Silk Filaments

According to Kuhn(1988, 425), “the problem of evening and rounding [silk filaments] in the reeling process” was a concern in most areas where silk-reeling took place. This problem was often addressed by crossing the silk either around itself or an adjacent filament, a method that supposedly spread the sericin (the gummy protein surrounding silk fibres) more evenly, binding the individual filaments together more effectively (Hills 1992, 66). Specific apparatus are required to facilitate the crossing of silk thread, but there is some uncertainty regarding the chronology of different forms of this equipment. Kuhn(1988, 372) identifies the description of a “butterfly eyebrow staff” in the 12th-13th century source, the *Shi Nong Bi Yong* as the earliest reference to a roller frame that may have been used to cross threads. The frame supports an upper and lower roller, each of which turns freely on an axle. According to the original description, the silk filament is wrapped twice around the top roller and then twice around the bottom roller, before being drawn onto the silk reel. This method was apparently referred to as “Complete Winding” (as translated by Kuhn). Kuhn(1988, 374) offers an expanded interpretation of this translated description, which involves wrapping the thread several times around itself in the process of causing it to pass around each roller twice (Figure 2.2). How Kuhn derived his interpretation of this winding method based on the original description is an interesting question that merits further exploration elsewhere, as it would require further analysis of other primary sources.

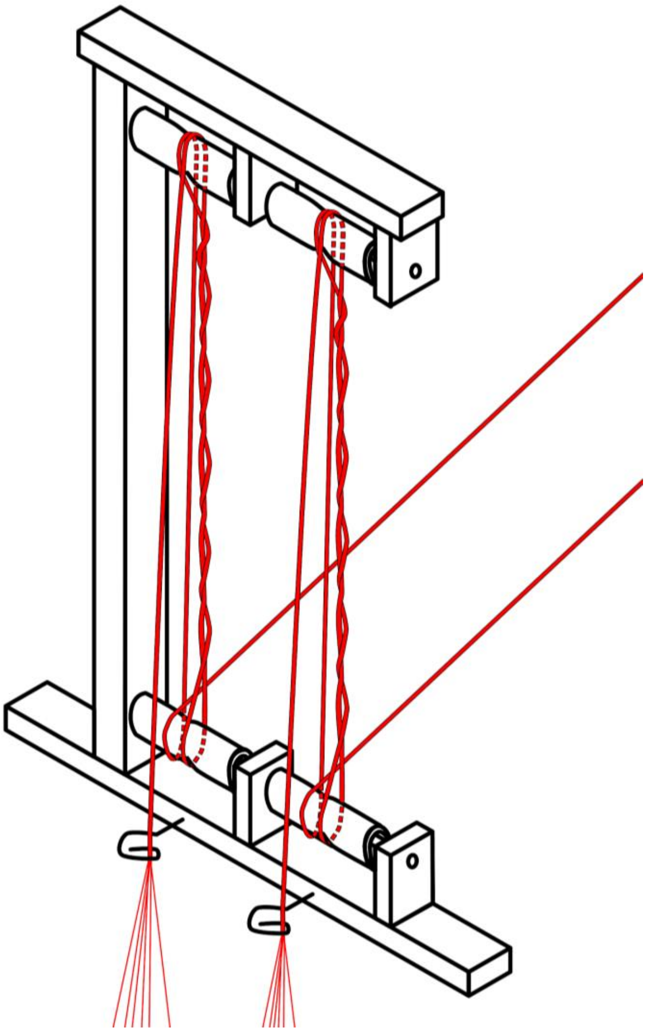


Figure 2.2: Complete Winding method after diagram from Kuhn (1988, 375) redrawn for clarity (Source: the author)

Kuhn explains 2 other methods for winding the silk around rollers described in the *Shi Nong Bi Yong*. The second he calls “double winding”, in which the filament wraps around the roller “only twice”. Kuhn states there is some ambiguity regarding whether the filament wraps only around the top roller in this case (Figure 2.3), or whether it does travel back around the bottom roller (Figure 2.4). In either case the main distinction seems to be that in double winding, the silk crosses around the roller but not itself. This method would therefore not have produced silk that was as round or even as that produced via complete winding, but it was apparently more efficient, which Kuhn(1988, 377) argues was a priority in Chinese silk production.

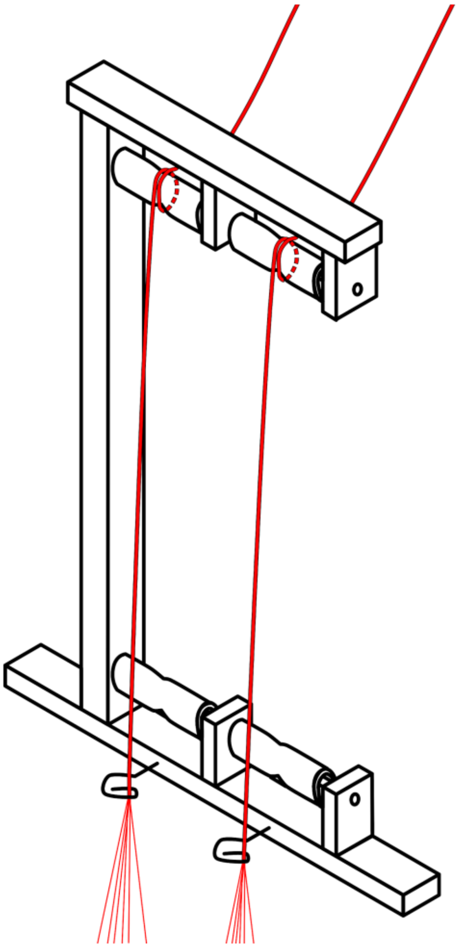


Figure 2.3: An approach to the double winding method as described by Kuhn using only the top rollers on the double roller frame (Source: the author)

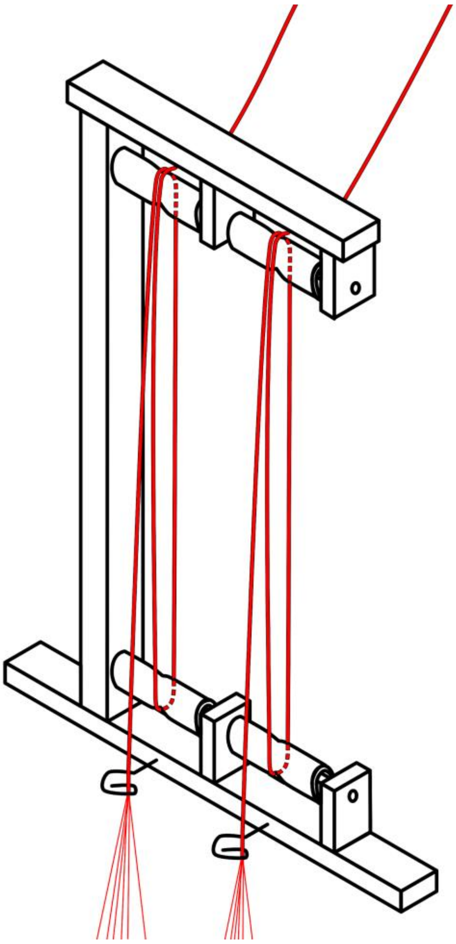


Figure 2.4: An approach to the double winding method as described by Kuhn using top and bottom rollers on the double roller frame (Source: the author)

Kuhn(1988, 377–378) calls the third method “Single Winding”; this was apparently the cheapest and most efficient method, and was performed using a frame with a single set of rollers (in all cases Kuhn describes the rollers in side-by-side sets, aligning this apparatus with northern silk-reeling devices), and does not actually involve any wrapping or winding, but instead allows the silk to be guided along the top of the roller (Figure 2.5), apparently producing thread that was of inferior quality but could be reeled very quickly.

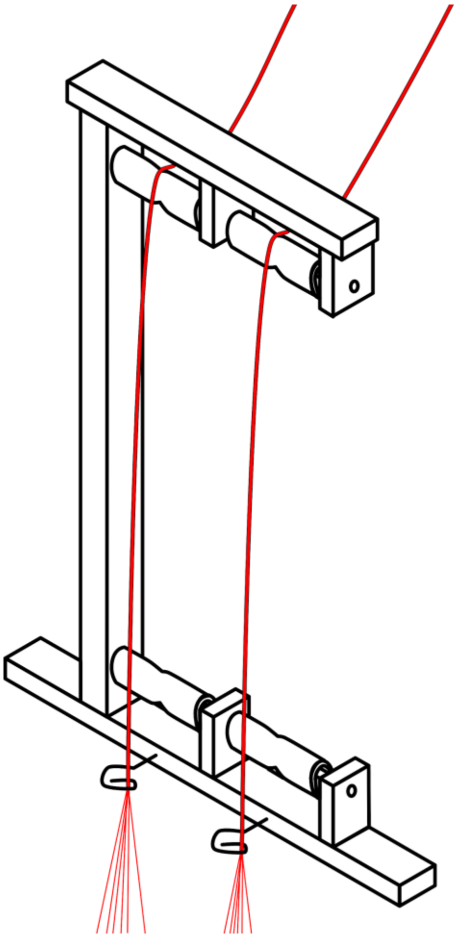


Figure 2.5: The "single winding" method executed on a double roller frame (Source: the author)

It is important to note that the "soundless-roller" as described by Kuhn and alluded to by Zhao also falls into this category of thread-crossing device, although neither Kuhn nor Zhao describe exactly how the thread may have been wrapped or crossed using that configuration.

One method of thread-crossing of European origin is relevant to this summary. It was described in the 18th century as "*commes les Piémontois*" (Pomier 1754, 221). This style of crossing threads that Pomier attributed to Piedmont, Italy was a fairly simple method of twisting 2 parallel silk filaments around each other multiple times in the space between guide eyes situated over the reeling basin, and the guide eyes affixed to the ramping-board (Figure 2.6)(Hills 1992, 67). The authors who discuss this method agree that it is Italian in origin, but do not speculate on when it was developed. The sources referred to are primarily from the 18th century, and Kuhn(1988, 425) argues that this method was labour-intensive and slow, and would therefore have reduced the productivity of Italian silk reelers. All that said, this method merits further research, both in terms of efficiency and because it is possible that such a simple innovation was developed earlier than its peak popularity during the 18th century. There seems to have been significant variation in the apparatus and methods used in crossing (or not-crossing) silk filaments, and the claims made about the impact of this equipment on the quality of silk cry out to be tested through experimentation.

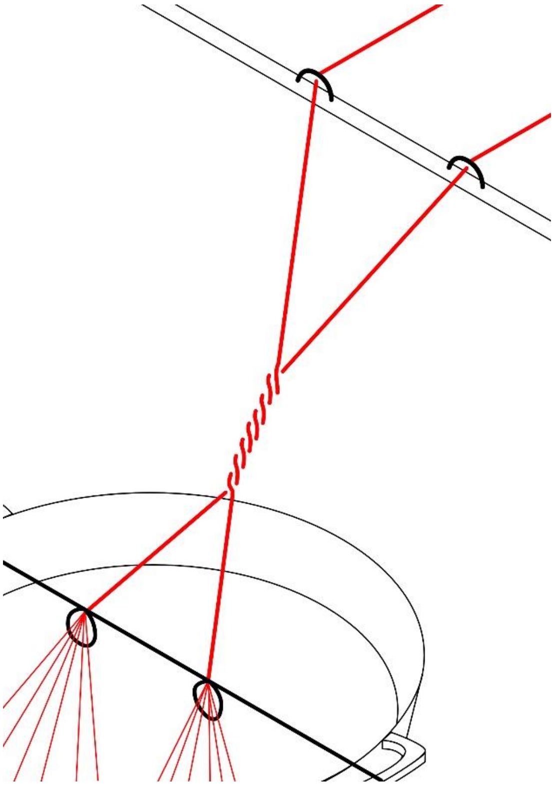


Figure 2.6: Diagram of the "Piedmont" style of thread crossing (Source: the author)

2.1.2 Equipment for making silk thread and Yarn

An array of equipment was used to process raw silk filaments into useable thread. Small spools or bobbins were essential for winding silk in several intermediary processing stages, but the best studied pieces of equipment are the devices used to twist silk filaments.

2.1.2.1 The Spindle-wheel

Harold Burnham first wrote about the use of a “throw-wheel”, describing it as “virtually the same as any spinning wheel that has a direct drive and is not equipped with a flyer”. Burham(1968) drew his information from the 17th-century *Tiangong Kaiwu*, and used the diagrams therein to describe the process of twisting silk filaments, connecting this information to Han Dynasty reliefs (Figure 2.7), which appear to depict the same equipment. Kuhn’s research on the “spindle-wheel”, as he terms it, is more exhaustive but was clearly influenced by Burnham’s article. Kuhn(1979, 17) also analysed Han dynasty reliefs, and later pictorial sources for his detailed description of the spindle-wheel and the different ways it could be used (twisting vs. winding thread, for example). He also clarifies that the varied names used for this device (including *quilling wheel* and *spinning wheel*) refer to different uses of the same tool, rather than distinguishing between different devices (Kuhn 1988, 161). Kuhn (1988, 165–168) notes a continuity between the spindle-wheel and the early spinning wheel introduced to medieval Europe around the 13th century, noting that other scholars had previously attributed the invention of this version of the spinning wheel to India, though the evidence of this style of wheel in China predates the earliest evidence for its use in India. That said this should not rule out India as a contributor in the transfer of this technology westward to Europe.

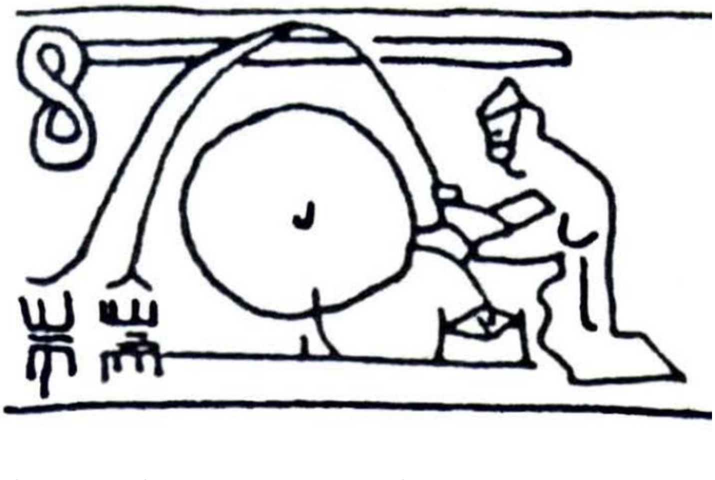


Figure 2.7: Detail of a drawing of a Han dynasty stone relief showing a spindle-wheel in use (Kuhn 1988, 161)

There is some ambiguity regarding how silk throwing was approached across the Mediterranean and Europe as silk production was introduced to these areas. According to Molà(2016, 215), in Italy silk throwing was carried out with a spinning wheel in the 13th century.

A source from 13th-century Paris, the *Livre de metiers* (c.1266-1275) distinguishes between 2 types of equipment "*filleresses de soye a grans fuiseaus*" and "*filleresses de soie a petiz fuizeaux*" (Farmer 2016, 51). This passage has been translated as 'throwsters working with large spindles' and 'throwsters working with small spindles' (Dixon 1895, 219–220). The term throwster refers to a person whose job it was to throw silk (in these examples that means combining silk filaments with twist). Farmer(2016, 51). questions whether the terms 'large spindle' and 'small spindle' simply refer to 2 different sizes of spindle, or whether they could be interpreted as making a distinction between some version of a spinning wheel in the first instance, and a drop spindle in the second. Ultimately this potential distinction suggests that both drop spindles and a form of spinning wheel were used to twist thread in medieval France.

All discussions of spindle-wheels and early spinning wheels posit that these devices enable more efficient twisting than use of a drop spindle. Efficiency is not a primary concern of this thesis, but it is relevant to medieval silk production concerns and relates to the development of another late-medieval twisting device: the silk twisting mill.

2.1.2.2 The Silk Twisting Mill

An innovation in efficient silk-thread processing appeared in Europe around the late 13th century in the form of automated silk-throwing mills (Figure 2.8). The general principle of these mills is that multiple bobbins at the base of the machine, wound with reeled silk, were rotated in unison, while the filaments were simultaneously wound onto reels from the bobbins (Figure 2.9). This transfer caused the silk filaments to be twisted as they were pulled off the rotating bobbins (Hills 1992, 71–72).

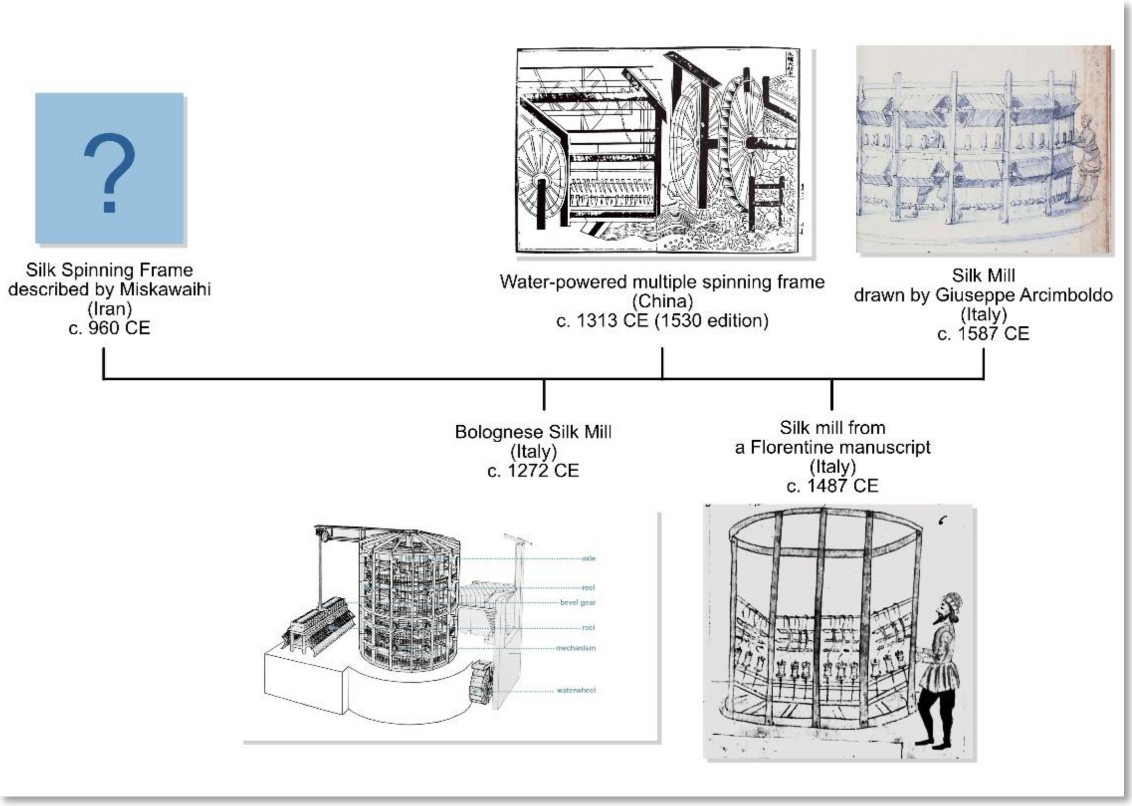


Figure 2.8: Timeline of earliest evidence for twisting mills from different regions (Source: the author)

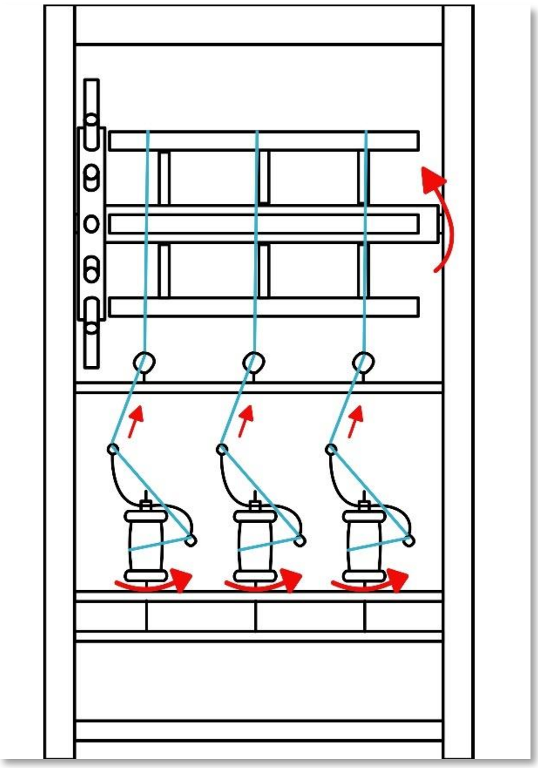


Figure 2.9: Schematic detail of the bobbins and reel in one section of a silk throwing mill (Source: the author)

The water-powered silk mill, constructed within a circular frame, is strongly associated with the late-medieval Italian silk industry, but there is some disagreement over its precise origins. According to Battistini, this silk mill, or *filatoio,* was invented around 1270 in Lucca (Battistini 1998, 21). The association of the invention of the *filatoio* with Lucca partially results from descriptions of the introduction of this type of mill to Bologna. Dates for this transfer vary widely, with some sources attributing the construction of Bolognese *filatoio* to a Lucchese named Borghesano c. 1272 (Bratchel 1995, 136), not long after the purported invention in Lucca. Molà(2016, 216) however describes this as an "historiographical myth", and states that the Lucchese innovation likely took place between the end of the 13th century and the very beginning of the 14th, pointing out that the earliest reference to this device comes from the registers of Lucchese notaries in the 1340s, suggesting that the machine was already "highly refined" by that point. This date range provided by Molà fits better with another claim that the mill was introduced to Bologna in 1341 by a Lucchese "spinner" (Bartolomei and Ippolito 2016, 34). In addition to greatly increasing the output of thrown silk, the Italian silk mills were large – a single example could measure over 2 metres in both diameter and height – and they could apparently be stacked one on top of the other, occupying several floors of a building. This meant that throwing took place in highly specialised workshops, which would have had implications for the organisation of the Italian silk industry (Molà 2016, 216).

While in a European context, throwing mills seem to have debuted in Italy, there is also evidence for the use of similar mechanisms further east. Kuhn(1988, 405) states that the earliest Chinese reference to what he calls "The multiple spindle twisting-frame for warp threads" comes from the 1313 *Nong Shu* by Zhen Wang. He argues that this twisting frame was used for silk by the Yuan period (1271-1368), but may have been developed during the Song dynasty. Kuhn(1988, 230) compares this device for twisting silk to a similar example that was used to twist bast fibres such as ramie (*Boehmeria nivea*); the 2 devices functioned in the same way. Both were rectangular in layout – in contrast to the circular design of the Italian mills – and their construction further differed in that they held the material to be twisted in cylindrical "boxes", which were rotated by a driving belt to twist the fibres. The "spinning frame" for ramie could be powered either by hand, water, or animal power (Kuhn 1988, 226). Kuhn suggests that the appearance of the silk mill in Italy is another instance of the transfer of silk-processing technology from China to Europe. That said, noting an apparent disappearance of silk-twisting frames from Yuan and Ming (1368-1644) writing and, further praising the sophistication of the Italian reeling mills, Kuhn(1988, 429–433) also suggests that after an initial technological transfer, improvements on the Chinese invention were made in Europe.

Not all scholars share Kuhn's view that the silk-throwing mill originated in China. Both Hills and Zanier point out that the Chinese throwing technology is noticeably different in form to the Italian mills. Hills(1992, 73) states firmly that the Italian mills "would appear to owe nothing in their origin to the far east". Zanier(2020, 28) shares this view, and argues that the Chinese throwing machines were less efficient than the Italian mills, producing thread of inferior quality although it is unclear by what metric this has been determined. Zanier(2020, 28) suggests that this technology may have originated in the Middle East, presumably being subsequently transferred both eastward and westward, since it apparently arose "out of the blue'' in Lucca. Zanier's suggestion may be supported by the fact that the earliest references to both Chinese silk-throwing machines and Lucchese silk mills date to the first half of the 14th century. Desrosiers (2019) has identified potential evidence for the earlier development of a silk-throwing mill in the Middle East, describing a 10th-century reference to a silk-processing device, written by Miskawaihi, a counsellor at the Buyid court in Baghdad. Desrosiers (2019, para.33) interprets this device as a throwing mill, but acknowledges that the description is imprecise, and it is therefore difficult to compare it to the Italian and Chinese mechanisms. Desrosiers does not attribute the invention of the throwing mill to a specific region, apart from arguing that it did not originate in Italy, stating that there is evidence for the use of a silk-throwing mill in both the Middle East and China predating the Italian *filatoio*. Part of this argument is a claim that the use of the multiple-spindle frame in China began in the 10th century, but it should be noted that the evidence Desrosiers cites is the same provided by Kuhn: the 1313 *Nong Shu* by Zhen Wang, and that the only mention of an earlier date by Kuhn is the suggestion that this technology could have been developed during the Song dynasty, meaning that it may have developed in China between 960 and 1279 CE, but this was speculative on Kuhn's part.

Despite his argument that the Italian silk mills do not owe their origin to Chinese throwing machines, Zanier, like Desrosiers, claims that there is documentary evidence for the development of these devices in the early Song dynasty, but provides no primary sources to support this. This is interesting, as it means that the earliest reference to an automated silk throwing device may be the letter of Miskawaihi identified by Desrosiers.

Given the diversity of interpretations of this topic, and the apparent investment in attributing the invention of the automated silk mill to one region over another, further research on these devices is merited. Fresh research approaches incorporating practical trials may shed new light on this topic, although to approach this through experimental archaeology would be an incredible undertaking, due to the scale of these mills.

2.2 Interpretations of Silk thread and Yarn Manufacture

Interpreting operational sequences of silk production is complicated by the highly varied focus of previous researchers, with few specialising specifically in the technical details of silk manufacture. Still, thanks to the work of these previous researchers, it has been possible to develop an overall picture of the many tasks involved in silk production. Dieter Kuhn, whose extensive research on the history of Chinese silk-reeling technology has been so far unparalleled, helpfully described 5 categories of task involved in silk production. These give a good general overview of the work required to produce silk cloth (Kuhn 1988, 284) They are:

1. Basic Tasks (Moriculture and Sericulture)
2. Preparatory Tasks (Silk reeling, twisting and doubling, and the spinning of waste silk)
3. Main tasks I (Degumming, dyeing, warping and dressing the loom)
4. Main tasks II (Weaving)
5. Final tasks (cloth finishing)

In comparison, Anna Muthesius (1989, 135), typically writing with more focus on the post-production uses of silk in the Byzantine Empire, divided the process into 3 major stages:

1. "The production of the raw material"
2. "The processing of the yarn into woven cloth"
3. "The marketing of the finished products"

Muthesius then further divided Stage 1 into 3 sub-stages:

1. Moriculture
2. Sericulture
3. Cocoon processing

The key stages of silk production that are relevant to this thesis are the reeling of silk, and the processing of raw silk into thread (Kuhn's "Preparatory Tasks" with minor spillover into "Main tasks I", or Stage 1, sub-stage 3 by Muthesius description). The previous section of this chapter has already demonstrated that even with a narrowed focus on the manufacture of silk thread, there is evidence for the use of a wide range of tools in this process that in turn denotes significant technical variation during manufacture. Examining these varied methods is vital to understanding the larger context of silk production (Lemonnier 2004, 3), particularly in relation to the long-distance trade of raw silk (filaments of silk that have been reeled, but not degummed) during the Middle Ages. Despite the variability of silk production, the overall process can still be broken down into general steps that maintain a reasonably consistent sequence.

Providing further opportunity for sub-division, R.L. Hills describes the production of silk thread as consisting of 2 key stages: 1. unwinding the cocoon (*reeling*), and 2. the preparation of the thread (Hills 1992, 63). The latter is often referred to as *throwing*, but this terminology varies. Following Hills' example, the following discussion of previous researchers' interpretations of the silk thread production steps will be subdivided into the overarching tasks of *reeling* and *throwing* respectively, with the addition of a third task: *degumming*. The variable subordinate steps according to currently available source material will be described in further detail under these headings. As will be seen, many authors writing on the subject of medieval silk thread-production have a tendency to focus on either reeling, or throwing, which has resulted in a somewhat unbalanced survey of medieval silk thread-processing methods.

2.2.1 Reeling

The process of reeling silk from the unhatched cocoons of the Bombyx mori caterpillar requires several preparatory steps. These initial stages are where we first encounter varied information on the reeling process. It should be noted that the authors cited do not always present a clear chronology for the methods they describe, nor do they always specify whether these methods are limited to a specific region. That said this overview has attempted to include all relevant dates and geographic regions when they have been specified.

2.2.1.1 Sorting and Storing Cocoons

It has been clearly established that silk cocoons must go through a sorting process prior to reeling. This step is only alluded to briefly by the typically thorough Kuhn (1988, 345), but cocoon selection criteria in 19th- and 20th-century China gives some insight into the qualities of cocoon that would likely not have been desirable for reeling in earlier periods. Lilian M. Li (1981, 24) states that only small and firm cocoons were used for reeling; cocoons that were loosely spun (by the silkworms), doubled, or infested with insects were sorted out to be degummed and spun separately. There is some evidence for this basic cocoon criteria spanning different regions as well as time periods; a 17th-century sericulture manual by Nicholas Geffe states that spotted or pierced cocoons were sorted out and used "to make faire fleaue, as being of the most fine substance..." while whole, unstained cocoons were used for reeling (Geffe and de Serres 1607, 82). From context, the "faire fleaue", appears to refer to the method also mentioned by Li of degumming and spinning the silk from cocoons that were not suitable for reeling.

Multiple Chinese agricultural manuals dating between the 12th and 14th centuries (Including the *Nong Sang Zhi Sho*, and Shi *Nong Bi Yong*) advocated for the quick reeling of silk from the (sorted) cocoons before the pupae inside had the opportunity to emerge as moths, thus breaking the threads of the cocoons and making them impossible to reel (Kuhn 1988, 336–337). In the absence of sufficient time to reel all the cocoons gathered in a season, these manuals give directions on preventing the moths from emerging so that the cocoons can be stored and reeled later. These methods included steaming the cocoons over salted water, heating them in the sun (which Kuhn notes can damage them), or packing them with salt into jars sealed with mud, which Kuhn describes as the most highly recommended method (Kuhn 1988, 336–343). Kuhn suggests that it was common practice to kill the pupae within the cocoons, despite recommendations of storing cocoons as a last resort. This is supported by descriptions of the method of steaming cocoons for this purpose in sericultural texts from between the Song and Qing (1644-1912) dynasties (Kuhn 1981, 56–57). Li also notes that Yuan and Ming dynasty manuals describe methods of steaming, heating in the sun, and soaking in a salt solution to prepare cocoons for storage. Li likewise notes possible variations in cocoon quality based on different storage methods, describing a 19th-century account from a maritime customs inspector who reported that silk from cocoons that had been steamed in advance of reeling was of inferior quality, with less of a sheen (Li 1981, 26).

2.2.1.2 Soaking the cocoons

Just prior to reeling the silk, the cocoons would be placed in a pan of water, typically positioned on a stove or furnace. The heated water would soften the sericin protein that keeps cocoons in their stiff shape just enough that the cocoons could be easily unravelled. Information on this step varies, particularly when it comes to water temperature. Kuhn states that the temperature for hot-water reeling in China varied between 77°-100°C. This temperature would kill the pupae inside of cocoons that had not been treated and stored, but Kuhn also explains that cocoons could also be reeled "alive" (they would not survive the process) in a "cold" water pan (Kuhn 1988, 352). Another caveat is required here, since the term "cold" pan actually refers to a basin of water that is *warm* rather than hot, but a specific temperature range is not given. (Kuhn 1988, 371–372). The "cold" water method was recommended for thin or "fine" cocoons, which Kuhn interprets as cocoons that are freshly formed, and not close to hatching (Kuhn 1981, 57). The process of reeling silk was apparently faster when hot water was used, but better quality silk when "cold" water was used (Kuhn 1988, 371). After soaking for an unspecified length of time, the cocoons would be stirred and the ends gathered with a brush or chopsticks, then jerked several times to loosen the coarse outer threads from the cocoon (Kuhn 1988, 352). Zhao and Liu note that precise temperature control was considered particularly important during the Song dynasty. They cite a passage from Qin Guan's *Can Shu* (c.1090 CE) which specifies that when the water for soaking the cocoons is heated to the correct temperature "it should be like the eyes of crabs", or 80°C according to the authors (Zhao and Liu 2020, 42). Hills states that cocoons were initially soaked in water with a temperature of 90°C, but states that the cocoons would soften too much if held at this temperature for the duration of reeling. To prevent this, the cocoons would be moved to another basin of 50°-60°C water once they had been sufficiently softened and the ends gathered (Hills 1992, 65). When Kuhn presents a general description of silk-reeling (Kuhn 1988, 352–353), he doesn’t mention the transfer of the cocoons to a new water pan once the ends are gathered, implying that the cocoons were reeled from the same basin in which they were originally soaked. However, Kuhn does provide a translated section of the *Shi Nong Bi Yong,* which describes the difference between reeling cocoons directly from the pan in which they are soaked, and pre-preparing cocoons in an auxiliary pan, as Kuhn describes it. The main difference is apparently that cocoons soaked and reeled directly in the same pan are more likely to result in lumps and knots when joining new fibres, while separately prepared cocoons would result in smoother joins, and fewer to no lumps and knots. This is a helpful clarification, and also demonstrates that both methods were known to have been used during the Song dynasty (Kuhn 1988, 375). Despite the detail given so far, neither author describes the length of time for which the cocoons were soaked before the ends could be gathered up, suggesting that this was not specified in the primary sources. It is possible that this length of time was highly variable, which could also indicate that an understanding of when cocoons were ready to be reeled constituted a form of tacit knowledge that the authors of the cited silk manuals were not privy to, or else was considered “common sense”, and not necessary to include. The only reference I have found for this is once again connected to the 19th and 20th centuries, and specifies a soaking time of only 5 minutes, although the water temperature in this case is not given (Li 1981, 29).

2.2.1.3 Reeling the Raw silk Filament

Once the ends of the cocoons had been gathered they were passed through the reel's guiding eye (or eyes) (Kuhn 1988, 352). Strangely, perhaps because this is assumed to be obvious, Kuhn's overall description does not specify that the silk must be attached to the reel itself, so that as it rotates, the silk is drawn up and wound onto the reel. Despite this, it is clear from the context of Kuhn's description, that this was how the reeling devices were set up.

Kuhn states that during reeling, the worker tending the cocoons would rotate the water pan, causing the cocoons to rotate, adding a slight twist to the filament, and apparently resulting in a more even and rounded strand of silk (Kuhn 1988, 53), The use of roller frames and thread-crossing methods to further improve the quality of the silk have already been described in the section on reeling mechanisms. Further notes on water temperature are also given; according to the *Nong Sang Zhi Shuo*, the water was required to be constantly hot, and it was this heat that caused the cocoons to rotate (Kuhn 1988, 370). This does raise the question of the temperature necessary to initiate the effect. According to Kuhn, the *Can Shu* states that the water must be boiling/bubbling when reeling begins (Kuhn 1988, 358), but there is a significant temperature difference between simmering water that is gently bubbling, and water that has reached a rolling boil. Furthermore, if Zhao and Liu were citing the same *Can Shu* passage that Kuhn has, we may have a clear indication that the water temperature was at a simmer rather than a boil. Whether this is enough to rotate the cocoons would need to be tested. Furthermore it is worth noting that in an earlier publication Kuhn(1981, 67) specified that the rotation of the cocoons in the pan, or the rotation of the pan itself was an innovation of the Song dynasty, indicating that silk was not always reeled in this manner.

Descriptions of silk-reeling in a medieval European context are rare, and assertions that silk-reeling took place in at least the more temperate regions of medieval Europe are typically based on evidence for the introduction of moriculture and sericulture in these regions during the Middle Ages, but are rarely accompanied by technical descriptions.

Silk thread-production in Verona is suggested by early 15th-century tax assessments listing the profession of "silk spinner" (Molà 2000, 237). Spinning is of course a completely different activity to reeling, but a century later, "peculiar reeling techniques" are described as being adopted in the city, which contrast sharply with the previous descriptions of carefully controlled reeling. Apparently, the practice in Verona skipped cocoon sorting altogether, lumping good with bad (doubled cocoons specifically, which do not reel cleanly) in the water basin. This mixture in quality made it necessary to heat the cocoons to a higher temperature (not specified), which apparently resulted in more wasted silk and a less glossy thread. Veronese reelers also apparently reeled from a higher number of cocoons at a time, Their silk gained a reputation of being thick and round, which strangely did not hurt its reputation (Molà 2000, 245).

Overall, while it seems to be taken for granted that silk-reeling took place in parts of Europe from as early as the 6th century CE (depending on one's definition of both Europe and the Mediterranean), detailed descriptions of the process are rare, particularly prior to the 16th century. This scarcity is what has led so many researchers to extrapolate both forwards and backwards in chronology, in an effort to fill information gaps. This extrapolation is the key reason that many pre- and post-medieval sources will be considered relevant to medieval silk production in Chapter 3.

2.2.1.4 On the number of cocoons reeled

The number of cocoons reeled at a given time will naturally affect the thickness and strength of a silk filament, and the resulting thread. The ideal number of cocoons varies by historical record (Table 2.1). As a general guide, Kuhn(1981, 67) explains that the number of cocoons reeled in China varied from 3 (producing the finest thread) through 6-7 (considered average) to 18 or more (considered heavy). The *Shi Nong Bi Yong* (12th-13th century) states that high quality silk should not exceed 4 cocoons, and describes the preparation of 15 cocoons in advance of reeling (Kuhn 1988, 360–364). Meanwhile, an analysis of a very early silk gauze fragment dated to the Eastern Zhou dynasty (770-256 BCE), estimates it was woven with silk reeled from 10 cocoons at a time (Hao 2012, 86–87). A broader range of cocoon numbers is described for renaissance Italy, with a range of 8-20 cocoons given based on the 1572 publication *Specchio di scientia universale* by Leonardo Fioravanti (Molà 2016, 213–214). The largest number of cocoons reeled at a time is given by Zanier(2020, 26), who specifies that European cloth was generally heavier than the finer Chinese silks, suggesting that 20, 60, 80 or more cocoons were reeled at a time in medieval Europe.

Number of cocoons	Region	Time period	Source	Primary source
"No more than 3"	Northern China	11th century	Kuhn 1981, 70	*Ts'an-shu*
6-8	Manchuria	c.1920 CE	Russel 2017, 34	Undetermined
8-20	Italy	1400-1600 CE	Molà 2016, 213-214	*Specchio di scientia universale* by Leonardo Fioravanti (pub. 1572)
3 (fine)	China	Unspecified	Kuhn 1981, 67; 1988, 352	None cited
6-7 (normal)	China	Unspecified	Kuhn 1981, 67; 1988, 352	None cited
18+ (heavy)	China	Unspecified	Kuhn 1981, 67; 1988, 352	None cited
3-4 (Fine)	China	12-13th century (Song)	Kuhn 1988, 364	*Shi nong bi yong*
10-11	Possibly China	20th century	Rayner 1903, 13	None given
15 (Average)	China	12th-13th century	Kuhn 1988, 360	*Shi nong bi yong*
10	China	Zhou (1050-221 BCE)	Hao 2012, 86-7	Estimate based on analysis of surviving silk gauze handkerchief found at Changsha, Hunan
20	China	Ming (c. 1637)	Kuhn 1988, 377	*Tian gong kai wu*
15-20	China	14h century	Kuhn 1988, 377	*Nong Shu*
4-6, or 12-15	France	1754	Pomier 1754	N/A
3-10	Unspecified	20th century	Paddock Hess 1954, 70	N/A
40, 60, 80, or more	Europe	Middle Ages	Zanier 2020, 26	None cited
5, 6, or 7	Unspecified	Unspecified	Hills 1992, 65	None cited
6	England	1607	Geffe 1607, 92	Geffe 1607, 92

Table 2.1:Common quantities of cocoons reeled at one time in different regions and time periods from a variety of sources

2.2.2 From Filament to Thread: Silk throwing

Silk throwing is a term typically applied to the transformation of silk filaments into a usable thread. As will become clear, there are several conflicting claims regarding the degree of twist added to silk threads and the way in which this was approached. The steps of transforming filaments into thread are separated into a preliminary winding stage, followed by what most authors define as the act of throwing for ease of comparison.

2.2.2.1 Winding onto spools

On the topic of silk throwing in China, it is important to mention Harold Burnham's foundational work on the throw-wheel/spindle-wheel, with the minor caveat that his description of the process is based on sources from a broad date range, primarily drawing from Han dynasty (202-220 CE) stone reliefs and the 17th-century *Tiangong Kaiwu.* Burnham describes how a skein of raw silk, having been removed from the reel, was first placed on a rigid swift, and the end of the silk was passed over a hook located c. 2.5 metres above the ground. The silk was then guided by the left hand onto a cage spool mounted on a handle that was held in the right hand and twisted clockwise, which Burham (1968, 49–50) states is the most natural way for an object to be rotated between thumb and fingers (Figure 2.10).

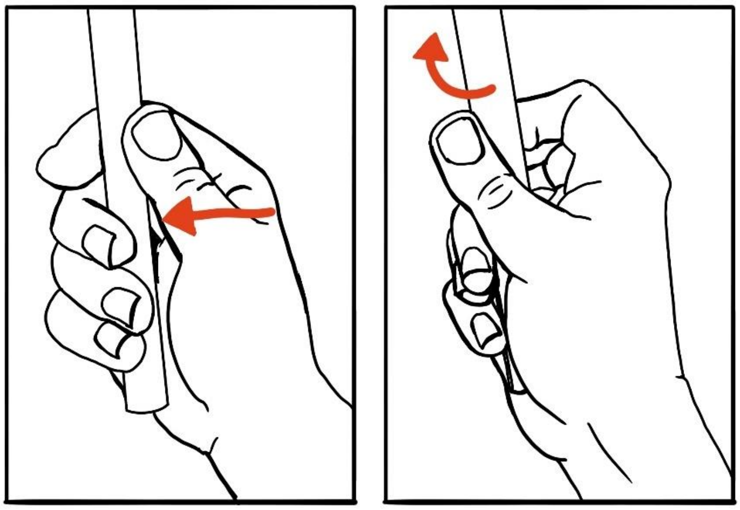


Figure 2.10: Illustration of a throwing rod being rotated between thumb and forefinger as described by Burnham (Source: the author)

Kuhn's description of this process is similar to Burnham's, although Kuhn also consulted an earlier source, the *Nong Shu*, which suggests continuity in these methods between the 14th and 17th centuries at least. Kuhn notes that in early Han reliefs depicting spooling it is hard to tell whether a frame is being used to stretch the skein of silk, or whether the reel itself has just been removed from the reeling frame and turned on its end (Kuhn 1988, 169), which suggests that the step of transferring the silk from the reel to an intermediary frame could have been introduced after the Han dynasty, if not as late at the 14th century. Kuhn also states that the clockwise rotation of the cage spool, which Kuhn calls a "throwing rod" would introduce a slight twist to the silk filament. Another final important detail about Kuhn's description here, is that these specific steps, involving the transfer of silk fibre to the cage spool are what Kuhn defines as "throwing" (Kuhn 1988, 169–170), which distinguishes Kuhn's use of the term from the more generalised use of the term as a descriptor of the overall process of converting silk filament to silk thread.

Kuhn also describes another method of winding silk onto a spool in preparation for further processing, which is also described in the *Nong Shu*, and apparently was specifically carried out in northern China during the Song Dynasty. This method – which he calls "Drag-spooling"— is carried out on a frame that holds the spool horizontally. The spool is set in motion by pulling a string that is wrapped around its axle. This method would wind the silk efficiently, without any added twist (Kuhn 1988, 174–175), but Kuhn does not explain how the spool would be kept spinning for the duration.

2.2.2.2 Twisting/throwing

Following the lead of previous researchers, this section focusses on twisting silk to produce yarn. It is common practice to notate direction of twist as either Z (spun clockwise) or S (spun counter-clockwise) (Walton and Eastwood 1988, 5). The system for describing various types of twisted yarn will be discussed in greater depth in section 2.3.5.1.

Once initial spooling had occurred, Burnham states that the cage spools would be arranged, 3 at a time, and sprinkled with water. The 3 threads were twisted together in a clockwise direction using a throw-wheel. An important detail of Burnham's description is that the silk filaments were apparently given a subtle degree twist as they were pulled from the ends of the cage spools in a counterclockwise direction. This means that the simultaneous individual twisting of the 3 filaments as they came off the spools and were twisted together by the throw-wheel in a clockwise direction would create a lightly twisted plied thread in one fluid step. This method is significantly more efficient than the usual method of plying spun yarns, wherein they are spun in one direction in one step, and then twisted (plied) together in the opposite direction in the next step. It should be noted that this is not something that Burnham observed, but is a theory drawn from his own extensive knowledge of textile production applied to a more general description of the process from the *Tiangong Kaiwu*, which presents this as a method for producing weft thread. Burnham notes that the level of twist resulting from this method was so slight that it may not be detectable in the finished weft. He further states that although silk threads from the "Far East" generally received a lower degree of twist than European silk, warp threads would require a higher level of twist than weft for strength. Burnham also clarifies that in the sources he consulted, the warp thread was twisted from 2 filaments rather than 3 (Burnham 1968, 50–52). These combined factors demonstrate that a slightly different working method was used in preparing thread to be used in the warp.

This other potential working method may be illuminated by Kuhn, who provides a more detailed description of how the spindle-wheel may be used to add twist to silk filaments and wind them onto a small bobbin fitted onto the spindle, simply by changing the angle and position at which the filaments were positioned in relation to the spindle (Figure 2.11). First the wheel operator holds the silk filament(s) in their hand at a roughly 45° angle to the spindle, and gradually draws their hand backwards along the filament(s), away from the spindle, allowing twist to build up on the strand. Kuhn notes that the angle at which the silk is held can also vary: holding the strand at a lower angle to the axis of the spindle (closer to parallel), results in a loose twist, while an angle closer (but not equal) to 90°, results in a tighter twist. When the throwster is satisfied with the amount of twist added, they can wind the silk onto the bobbin by holding the thread at a 90° angle to the spindle (Kuhn 1988, 162).

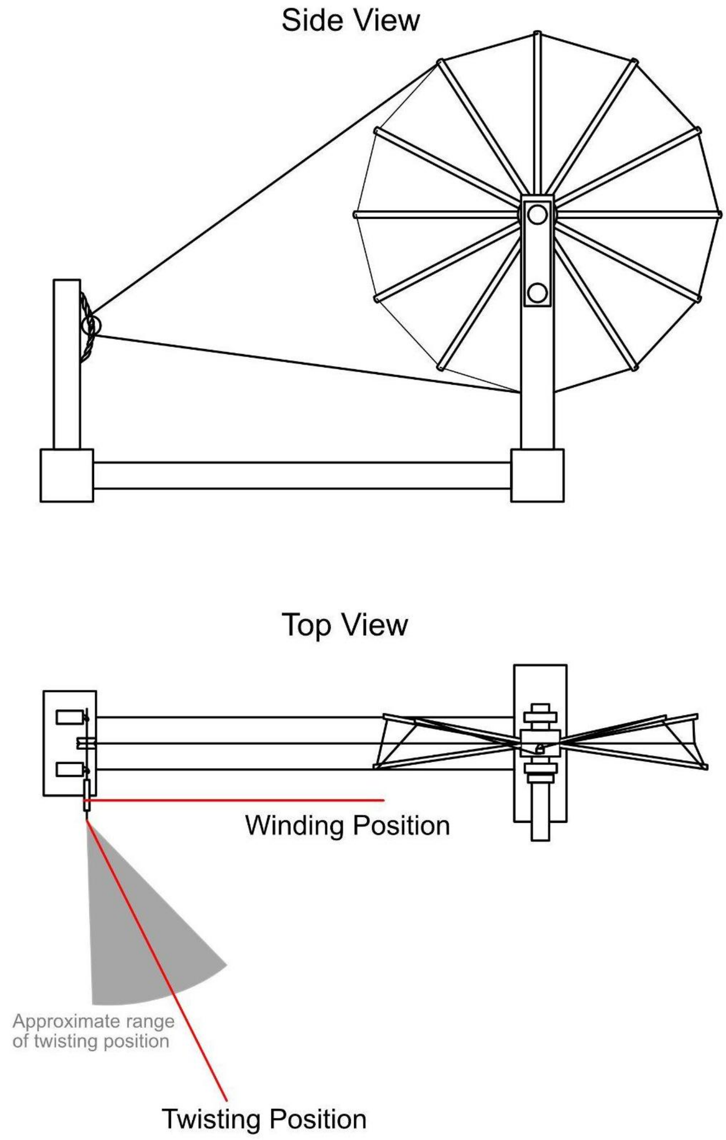


Figure 2.11: Diagram of spindle-wheel structure showing positions for twisting and winding yarn (Source: the author)

The method described by Kuhn is notable, because it seems to offer the throwster the highest level of control regarding the degree to which the silk is twisted. Additionally, while the default direction for turning the spindle-wheel is clockwise, Kuhn(1988, 163) describes how the wheel can be made to turn counterclockwise while still turning the crank in a clockwise direction, simply by adding a cross to the wheel's drive band between the wheel and the spindle (Figure 2.12).

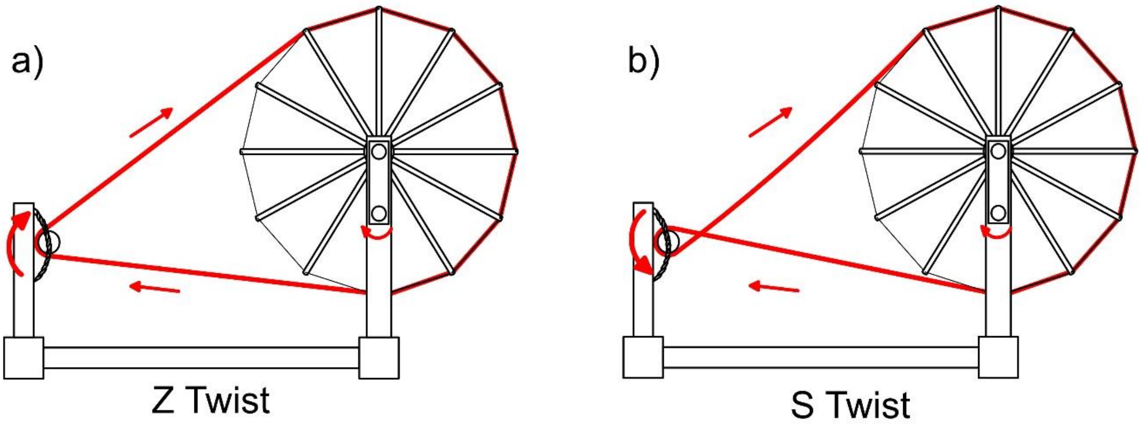
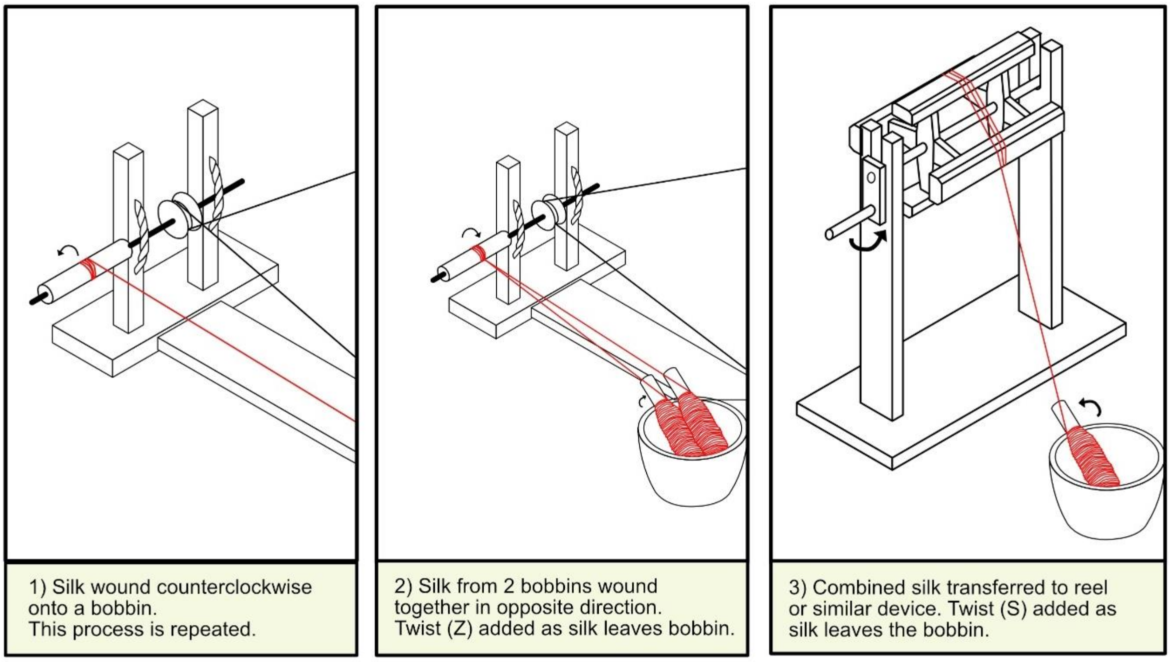


Figure 2.12: Spindle-wheel diagram showing drive band orientation for producing Z twist (a), and S twist (b) (Source: the author)

Like Burnham, Kuhn argues that thread for a warp must be twisted tightly or else it will break under tension and "fall into its individual filaments" during weaving. Kuhn outlines that after spooling (Keeping in mind that he suggests that twist is added to the silk while it is wound onto the cage-spool) 2 single-twisted threads were twisted together in the opposite direction, then doubled and thrown (Kuhn 1988, 405). This method would result in a final product composed of 4 strands twisted together with a final Z twist, which could be notated as Z2S2Z. Unfortunately, this description still lacks some clarity since Kuhn says the final step of this process is throwing, which, if following his own definition, would add little twist to the final thread. Another possibility is that Kuhn is using the more conventional use of the word *throwing* to suggest that the thread was twisted one final time on the spindle-wheel, and this confusion demonstrates a key flaw in Kuhn's decision to use this term for a more specific application than other authors.

Sophie Desrosiers describes yet another possible approach to the use of the spindle-wheel (Figure 2.13), drawing on the same principle Burnham does, of twist being added to filaments as they are pulled from the end of a bobbin. Desrosiers frames this passive method of twisting as an explanation for a trend she has observed of warp threads in polychromatic figured silk textiles from the Tang dynasty (690-705 CE) that have a low level to no visible twist. In Desrosiers' description, the silk from 2 bobbins are wound together using a spindle-wheel (Desrosiers 2019, para.21). Desrosiers bases her theory on observations she made during a visit to a silk workshop in Khotan in 2002. Desrosiers' description of this method, unlike Burnham's interpretation, does not involve the combination of S and Z twisting in one step, and instead describes a technique that relies solely on the slight twist (Z in her description) added when the silk filaments wind off from the bobbin, meaning the step of winding threads together must be repeated in order to twist the combined threads in the opposite direction (S), no twist being added by the wheel itself. One crucial detail to this method pointed out by Desrosiers is that the smaller the diameter of the bobbin used, the more twists are added to the filaments as they are pulled from the end. (Desrosiers 2019, para.22). This is relevant since the cylindrical bobbins used in Khotan are very small in diameter when compared to the cage-spools in the Han dynasty depiction referenced by all 3 authors, meaning the Khotan method could produce a slightly higher level of twist than would be possible with the equipment of the Han dynasty. A further important distinction is that the method relayed by Desrosiers requires twice the work of Burnham's and produces a thread composed of 2 elements instead of 3, with an overall S twist rather than Z.


1) Silk wound counterclockwise onto a bobbin. This process is repeated.

2) Silk from 2 bobbins wound together in opposite direction. Twist (Z) added as silk leaves bobbin.

3) Combined silk transferred to reel or similar device. Twist (S) added as silk leaves the bobbin.

Figure 2.13: Steps of the low-twist throwing method described by Desrosiers (Source: the author)

Desrosiers does not reference the method described by Burnham, but has argued that Kuhn – unaware of how the motion of the silk leaving the bobbins could add twist – has misinterpreted the activities represented in the Han dynasty depictions of spindle-wheels. Desrosiers declares them instead to be “spooling-wheels”, which do not add twist (Desrosiers 2019, n.44). It is unclear why this distinction is made, as the devices appear to be of a design that could both spool and twist. To clarify, the wheel which Desrosiers photographed in use in Khotan (Desrosiers 2019, fig.11) appears more or less identical in basic form and function to the “spindle-wheels” described by Kuhn, and the difference appears to be entirely based in how it is being used. Furthermore, Kuhn’s description of the use of a spindle-wheel to twist thread is demonstrated by craft practitioners using similar wheels (See, for example Karuno 2013). Ultimately, the method described by Desrosiers has clearly been used successfully in the workshop in question and this is a valuable example of one of many possible working methods for adding a low level of twist to silk. That said, it would be a mistake to consider it the only possible method that may have been used with the early spindle-wheel.

Another novel description of how a spindle-wheel may have been used to add twist to silk is contributed by Hills. In contrast to the method described by other authors, Hills suggests that twist may have been added to silk thread by using the spindle-wheel "in reverse", meaning that the thread would be wound with the spindle-wheel without adding much or any twist, and from there wound onto a reel, while the spindle-wheel was simultaneously turned, thereby twisting the silk thread in the process (Hills 1992, 69). Hills draws a convincing parallel between this proposed method of adding twist, and the way in which late-medieval water-powered silk mills functioned, by twisting bobbins of silk while the threads were combined and wound onto reels (Ibid). While it is easy to follow the argument that this automated mechanism was derived or inspired by this use of the spindle-wheel, Hill's theory does not appear to be supported by written or ethnographic evidence.

Silk throwing in the Byzantine empire is briefly mentioned by Muthesius who, like Kuhn, states that a high level of twist is required for warp threads, specifying 2000-3000 twists per metre, which seems to far exceed the degree of twist described by other authors. Muthesius claims that this level of twist could not be achieved with a drop spindle and because of this argues for the early adoption of the spindle-wheel in Byzantium (Muthesius 1997, 16), but it may be more accurate to say that it would require considerably more time to achieve this level of twist with a spindle, as the key feature of the spindle-wheel is its potential to speed up the twisting process.

Regarding silk thread-making in France, a general operational sequence is put forward by Sharon Farmer. Farmer's research is focussed on the silk industry of medieval Paris, with particular interest in gender and how immigrants to the city influenced Parisian silk production (Farmer 2014, 2016). As sericulture and silk-reeling practices were not firmly established in France during the Middle Ages, silk thread was either imported to France as a finished product, or as skeins of raw silk that required further processing by the (primarily female) silk workers of medieval Paris. Farmer references several primary sources related to the processing of silk, particularly the 13th-century *Livre de metiers*, but Farmer's core description of Parisian silk throwing is based on a much later source. The steps described by Farmer (Farmer 2014, 386–388, 2016, 49–56) are as follows:

1. Inspection/evaluation and weighing of raw silk by Parisian mercers, this stage may have included decisions on which combinations of fibres would form different types of silk thread;
2. Transportation of silk to the throwsters;
3. Opening and untangling the skeins of raw silk;
4. Division of skeins into "workable sections". During this stage any sections of filament that were of poor quality (Farmer interprets this as any silk that was reeled from the outside of the cocoon, or the very interior of the cocoon) would be set aside to reduce the risk of breakage during throwing;
5. Winding the silk filaments onto bobbins. The winders would at the same time look for knots or breaks and introduce new, stronger filaments into weakened sections of the silk filament;
6. Twisting 2 raw filaments together;
7. "Cooking". This was the process of degumming the silk thread before it could be dyed. Apparently, degumming was often a step carried out by the dyer;
8. Dyeing the silk;
9. Processed silk would be returned to mercers, waste silk would have been used as stuffing, or have been degummed, combed and spun.

Farmer's description of Parisian silk processing helpfully highlights the role of mercers and the overall division of labour in late-medieval silk industries. Oddly, Farmer's primary source for many of these steps is the 1903 publication *Silk throwing and waste silk spinning* by Hollins Rayner. This book describes the methods by which imported silk was thrown in English factories using steam-powered machinery. This context is important, since the methods that may have been necessary to prepare silk to be thrown by steam-powered machine may have differed from those used ahead of the slower-paced twisting that would have taken place using a spindle or spinning wheel.

Most other descriptions of silk throwing in medieval Europe focus on the use of the silk mill or *filatoi* in Italy, which has already been discussed in detail. Regarding more basic methods, while the potential use of a hand-spindle to twist silk in pre-Han China and early-medieval Europe has already been alluded to, no descriptions of the working method for this are offered. In the case of Chinese silk throwing this is likely a result of the early innovation of spindle-wheel, which after the Han dynasty renders the use of a spindle to process silk threads irrelevant in this region. Beyond previously mentioned references to the use of spindles in medieval European silk processing, the lack of detailed description may be the result of assumptions that the use of a spindle is too simple to require explanation. Whether this is the case can be tested through experimentation.

In a similar vein, despite evidence of silk cloth woven from untwisted threads, little attention is paid to the process of combining filaments without twist. It is unclear if this is connected to assumptions about the constant presence of some degree of twist in silk threads, or because the premise of winding threads together without twist is a less stimulating topic of scrutiny, but this does leave unanswered some questions about the processing of silk threads without twist. For example, did silk without twist go through a different doubling process, or did it jump to the next stage of production after it had been spooled? If the doubling process was not carried out for threads without twist, this suggests that variability in the thickness of a thread without twist would depend entirely on the number of cocoons from which the strand of silk was reeled. This is an important detail, as it has implications regarding the importance of the number of cocoons used in the initial reeling process in determining the thickness of the finished thread.

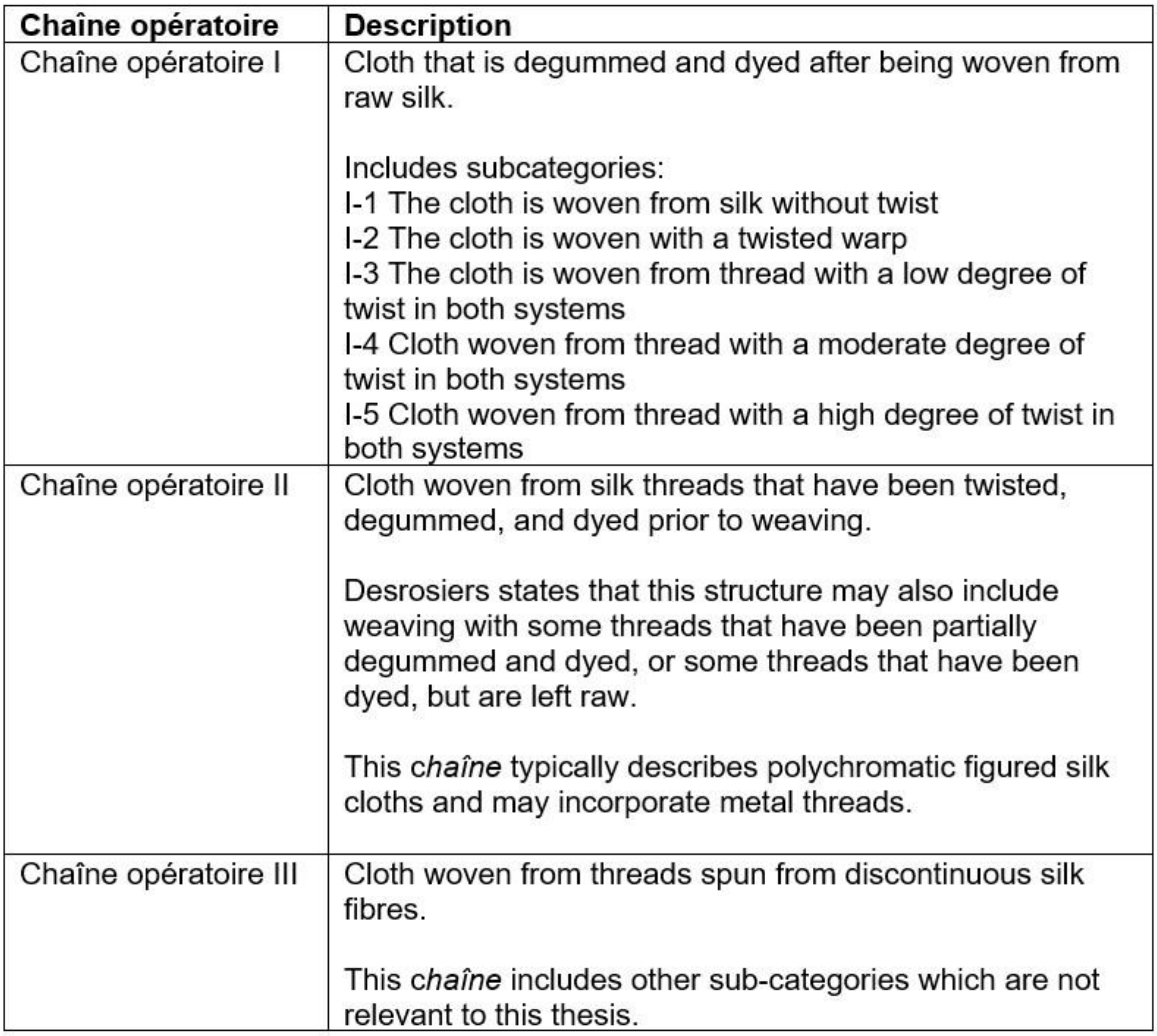
2.2.3 Degumming

Degumming is the chemical process of removing the sericin protein from silk thread in order to reveal the soft, shiny fibre underneath. Two considerations are relevant to the topic of degumming, the first being the degumming method itself, and the second being the point at which degumming took place in the silk production chaîne opératoire, if it occurred at all.

The process of silk degumming is multi-faceted; the term can describe the removal of sericin from reeled silk, as well as the removal of sericin from waste silk and cocoons intended for spinning. In fact, the only detailed descriptions of the degumming process provided by Kuhn involve waste cocoons rather than reeled silk, and appear to come from sources ranging between the 14th and 18th centuries (Kuhn 1988, 83). The varied techniques described have some common features that may also have applied to degumming reeled silk. All methods involve warm to hot water and an alkaline additive. One "boiling technique" requires the cocoons to be soaked in warm water for a day before being rinsed in clear water, and then boiled multiple times in water enriched with an unspecified amount of sodium carbonate or natron. After this the cocoons were steamed for an unspecified length of time, although with a warning that steaming for too long would rot the silk. A far more straightforward method involved boiling cocoons in water with sodium carbonate for 2 hours, rinsing in clear water, and then drying in the sun (Kuhn 1988, 83–84), while another method involved boiling cocoons in water with rice stalk ash while constantly agitating the cocoons with a hook. From context it seems that this method may have resulted in more thorough degumming (Kuhn 1988, 85), which raises the important question of how different approaches to degumming may have affected the quality – particularly the sheen and rigidity—of reeled silk, and how these methods may have been differently applied to achieve specific results.

There is evidence for the importance of degumming as a practice further west; Muthesius discusses one of several non-imperial guilds involved in silk production established in the Byzantine empire by the 10th century: the *katartarioi*. Muthesius interprets this guild as carrying out silk-degumming (Muthesius 1989, 144–146). It has been suggested that this was linked to an established silk-reeling practice, but the role of degummer would be equally crucial to the processing of imported raw silk.

Sophie Desrosiers has proposed theoretical silk-processing *chaînes opératoires* with a focus primarily on the activity of degumming in relation to weaving (Desrosiers 2019), though it may be fair to say that the *chaînes* proposed by Desrosiers (Table 2.2) are as much about understanding thread twist as degumming.



Chaîne opératoire	Description
Chaîne opératoire I	Cloth that is degummed and dyed after being woven from raw silk. Includes subcategories: I-1 The cloth is woven from silk without twist I-2 The cloth is woven with a twisted warp I-3 The cloth is woven from thread with a low degree of twist in both systems I-4 Cloth woven from thread with a moderate degree of twist in both systems I-5 Cloth woven from thread with a high degree of twist in both systems
Chaîne opératoire II	Cloth woven from silk threads that have been twisted, degummed, and dyed prior to weaving. Desrosiers states that this structure may also include weaving with some threads that have been partially degummed and dyed, or some threads that have been dyed, but are left raw. This *chaîne* typically describes polychromatic figured silk cloths and may incorporate metal threads.
Chaîne opératoire III	Cloth woven from threads spun from discontinuous silk fibres. This *chaîne* includes other sub-categories which are not relevant to this thesis.

Table 2.2: Silk textile production chaînes opératoires proposed by Sophie Desrosiers (2019)

The proposed sequences highlight the many ways in which certain stages of silk production could be differently ordered to accommodate, or emphasise the characteristics of raw, or degummed silk.

Desrosiers bases chaînes I and II on the following premises:

1. During the process of reeling silk, the sericin is the only means of keeping all of the disparate silk filaments together and functioning as a single strand (Desrosiers 2019, para.6)
2. The sericin must be removed from the silk in order to allow for better dyeing, and to produce a shiny and smooth cloth, but;
3. degumming cannot occur unless the silk yarn has been woven into cloth or twisted (the implication being that the silk yarn or thread will otherwise fall apart when it is used) (Desrosiers 2019, para.7)

Premise 3 in particular merits further exploration and will be discussed in relation to the experiment results in chapter 9.3.4.

2.3 Approaches to silk textile analysis

The analysis of silk textiles has been approached in several different ways. Two key questions are typically the driving force behind silk textile analysis: 1) How was the textile produced? and 2) Where was the textile produced? Over the years, numerous textile specialists have contributed to the development of methods and criteria for describing and cataloguing historical and archaeological silk textiles. Silk textile analysis has been developed within the context of broader archaeological textile analysis, which was pioneered by researchers such as Grace M. Crowfoot(1937), Gale Owen-Crocker(2004), and Lise Bender Jørgensen(1992) along with many of the authors cited throughout this thesis. Common approaches to silk textile analysis include art-historical, structural, and chemical analysis.

2.3.1 Art historical analysis

Applying an art historical approach is a common and long-established practice in the analysis of medieval patterned silks. Specific motifs are often used to determine the production date of a textile. For example, Anna Muthesius describes shifts in common motifs found in Byzantine silks over time, noting a prevalence for mythological themes and hunter and charioteer imagery in the 8th-9th centuries CE, a result of Byzantine Iconoclasm. This was followed by popularity of large-scale bird and animal motifs after c. 850 CE and monochrome silk patterned with foliate and geometric designs from the 10th to 11th centuries. These trends were initially set by the Imperial weaving workshops, and Muthesius also notes that specific motifs bore imperial significance; the eagle and the griffin, for example, operated as symbols of the Byzantine Court between the 10th and 12th centuries (Muthesius 2008, 7–9).

Diagnostic patterns may also be layered, and in these cases a partial object biography may be constructed, highlighting the exchange of silk during the Middle Ages. One example of this is a late-medieval chasuble in the collection of the Victoria and Albert Museum, which was made from silk with a woven-in pattern that had also been embroidered with religious iconography. Donald King identified the silk embroidery as being English work, and based on a stylistic assessment assigned a date range of 1400-1430, further narrowed to production in Italy between 1400 and 1415 based on the woven-in animal motifs (King 1968, 35), assuming of course that the embroidery was carried out not long after the cloth was woven.

Another approach involves the comparison of silk textile patterns depicted in paintings with surviving figured silk fragments, connecting physical artefacts with historical figures, time periods and regions, which builds a useful picture of the medieval silk trade, particularly when compared with historical wardrobe accounts. This type of work has been skilfully carried out by Lisa Monnas(2008) in her research on silk fabrics in Italian and Northern European paintings.

It is important to acknowledge that the examples provided of art historical analysis are focussed on patterned silk textiles. This emphasises the perhaps obvious point that art-historical analysis of textile appearance is less helpful in determining the provenance or chronology of plain-weave textiles. Other methods, such as structural analysis, are often the preferred approach when analysing tabby silk textiles.

2.3.2 Analysis of Cloth Structure

Cloth structure has been demonstrated to be particularly important in understanding both the place of origin and the techniques used to produce silk textiles. For the purposes of this section, structural analysis includes woven structure, as well as the structure and physical characteristics of thread and yarn. In the field of textile research, a quantitative approach to recording archaeological textiles is one of the most common. Generally, the key measurements taken from a woven archaeological textile are thread counts (The number of warp and weft threads per centimetre of cloth), and yarn diameter. These measurements may also be accompanied by fibre diameter, as was the case with the original catalogue of Coppergate textiles (Walton 1989). Occasionally the angle of twist of the yarn is also recorded, although this last measurement is more frequently recorded with a qualitative descriptor (High twist, low twist, etc.).

2.3.2.1 Figured Silk Structures

In the study of medieval silk textiles, particular attention has been paid to loom-controlled figured weaves: silk cloth with woven-in patterns. This category of cloth requires specialised looms and weaving methods, and encompasses several different woven structures including compound twill, damask, samite, and taqueté. In the case of figured silks, both surface design and structure can be seen to intersect, as the structure of the cloth determines the visual pattern of the textile. Nonetheless, Krishna Riboud cautioned against conflating the 2, arguing that it is essential to distinguish between a textile structure and its visual design, particularly because certain features such as weaving errors can be diagnostic of the type of loom used to produce the textile being studied (Riboud 1972, 13).

Even subtle variations in these structures may be useful in determining the origin of a textile fragment; Desrosiers, for example, argues that early-medieval figured silks were technically homogenous according to region. Therefore technical characteristics such as the order of weft thread passes can support the geographic and chronological attribution of a given textile (Desrosiers 2004, 184).

J.F. Flannagan set an important precedent for this sort of structural analysis, his early work on figured silk weaves covering variations such as the use of a scale harness in early Islamic textiles (no date specified) to size-up pattern repeats, resulting in more blocky geometric patterns in contrast with the finer repeats of the “Alexandrian school” (Flanagan 1936, 145–146).

A distinctly important comparison relates to a significant transition in the prevalent woven structures found in Chinese silks. In China, patterned silks were initially warp-faced compound tabby (Figure 2.14), expanding to include warp-faced compound twills prior to the early Tang dynasty (618 CE).

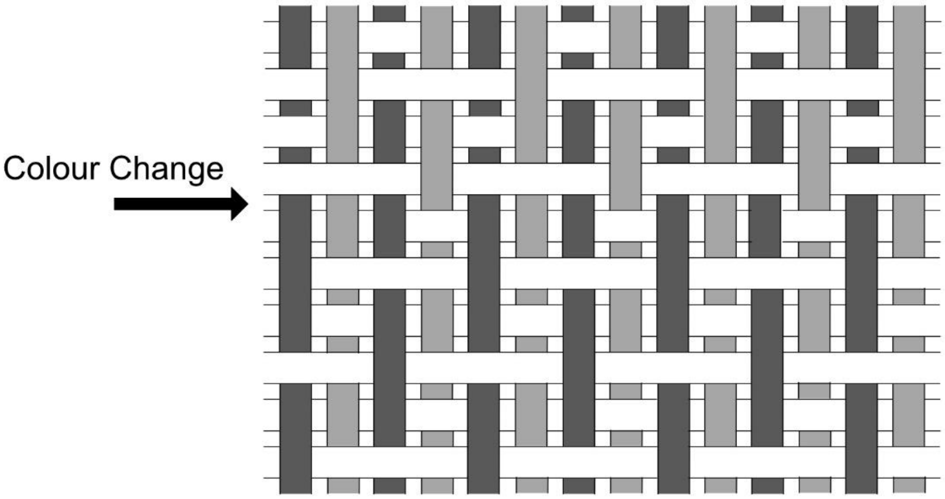


Figure 2.14: Expanded view of a warp-faced compound tabby structure. In the actual cloth only the dominant warp threads would be visible.

This early structure is significant because outside of China, figured weaving was known to be weft-faced (Kuhn 2012, 27), and a number of identifications can be made from this fact that could not be made from pattern alone. For example, evidence of external cultural influences on China can be seen in examples of Tang dynasty silks that are woven with Sasanian and Coptic designs but can be confirmed to have been produced in China because their structure is warp-faced (Kuhn 2012, 33). By the Song dynasty, weft-faced compound weaves (Figure 2.15) had apparently supplanted warp-faced compound weaves (Kuhn 2012, 50), which establishes some clear chronological guidelines regarding the structure of Chinese silk textiles.

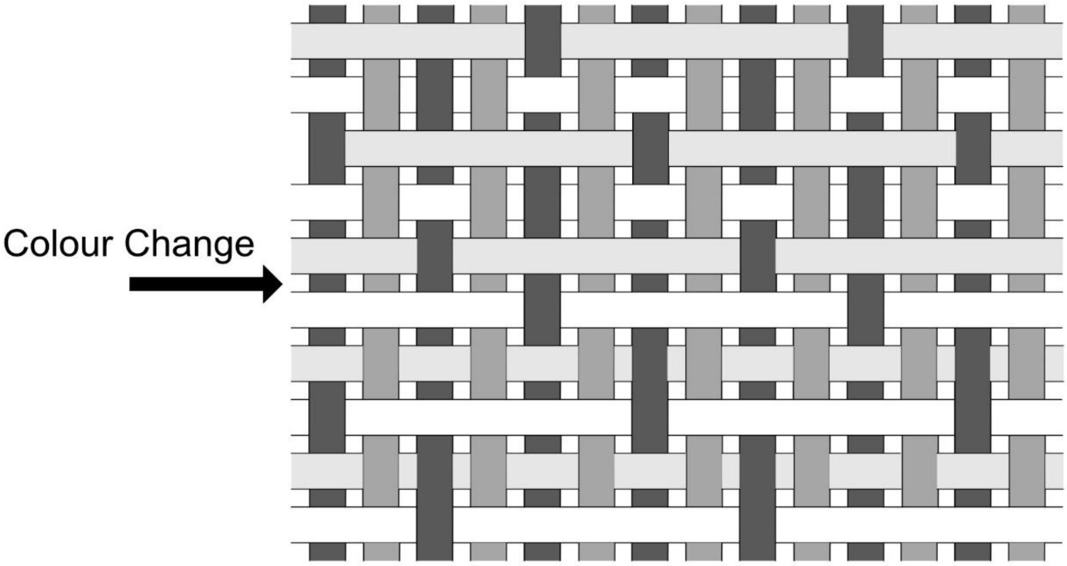


Figure 2.15:Expanded view of a weft-faced compound twill structure. In the actual cloth only the dominant weft threads would be visible.

2.3.2.2 Tabby Silks

Tabby (Figure 2.17), sometimes referred to as “plain weave”, is the most basic cloth structure, wherein the warp and weft interlace in an alternating over-under pattern, typically with only one thread passing over the other. This cloth structure is found in just about every weaving culture regardless of time period, and can be extremely difficult to attribute to a particular region or workshop in the absence of other unique markers. It should be unsurprising, then, that structural analysis of tabby silk typically does not dig much deeper than identification of structure.

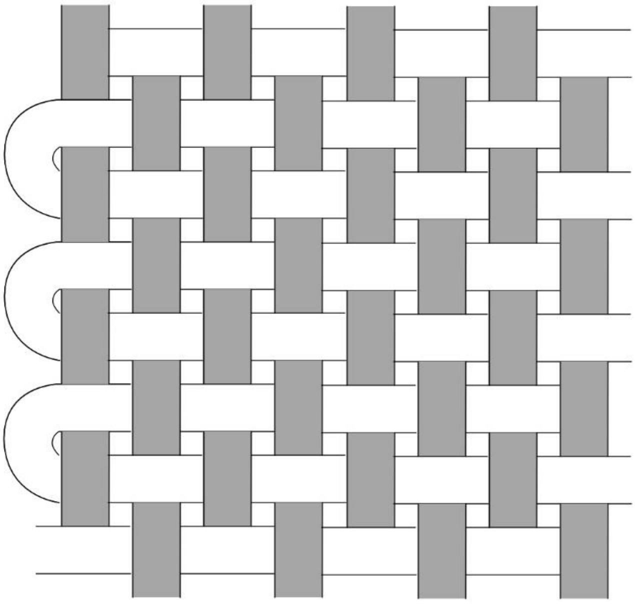


Figure 2.16: Diagram of a basic tabby cloth structure with selvedge visible at left edge.

More recently this issue has been discussed in relation to the silk tabby cloth and ribbon fragments that were excavated at 16-22 Coppergate in York but cannot be attributed to specific regional workshops (Walton Rogers 2020, 110). Desrosiers, writing in 2019 on varying silk production *Chaînes Opèratoires* has also pointed out that plain silk textiles rarely garner as much attention from researchers as their more complex counterparts, and emphasises the importance of a technical understanding of silk production in examining tabby silks (Desrosiers 2019, para.1). Despite the lack of attention, the potential importance (and complexity) of studying tabby silks is not a new topic; in 1977 Krishna Riboud pointed out that more than half of surviving early Chinese textiles were plain silk tabbies, though it is unclear if this ratio is the same more than 40 years later. Riboud also noted that "for such a simple weave, the problems remain slippery." (Riboud 1977, 253). The answer to better understanding silk tabbies may lie in analysis of the silk yarns from which they are woven. This has been pointed out by Walton Rogers, who suggests that the variation in combinations of yarn with different twists found in tabby weave silks "may eventually prove to be diagnostic" (Walton Rogers 2020a, 110) while Desrosiers has also argued along similar lines, albeit with a slightly different focus, in writing on the importance of understanding the production methods involved in transforming raw silk into cloth (Desrosiers 2019, para.2).

2.3.3 Describing Textile characteristics

A key body of research that emphasises the importance of qualitative textile descriptors was carried out by weaver and textile researcher Lena Hammarlund, and further explored in collaboration with other textile researchers (Hammarlund et al. 2008). Hammarlund identified key visual and tactile textile characteristics such as cloth density and thickness, which are not adequately expressed through the quantitative measures of thread counts and yarn diameters (Hammarlund et al. 2008, 70). Hammarlund’s motivation for developing a framework was based on a desire to express clear visual differences between textiles that might otherwise be grouped together due to their similar technical attributes; the textiles in question being more than 100 wool tabby fragments from the Roman quarry site, Mons Claudianus in Egypt (Hammarlund 2005a, 88–89). In the process of determining visual categories for the textiles in question, Hammarlund established “the pentagon” as a way of visualising what she considers to be the foundational “handicraft factors” that impact the appearance of a woven textile (Hammarlund 2005a, 106). While defining these factors, Hammarlund discusses the way in which they are interconnected and employs several useful descriptive terms when characterising features such as the surface texture of the cloth. Particularly evocative are phrases such as “movable”, which describes the behaviour of yarn within a woven structure, ie. does the yarn remain locked in a 90° grid, or does it meander and shift within the cloth?

2.3.4 Quantifying Textile Density

Thread counts –communicating the number of warp and weft threads per cm of cloth – are a common quantitative measure used to describe archaeological textiles, along with yarn diameter (Walton and Eastwood

1988, 4–5; Hammarlund and Pedersen 2010, 1).These 2 measurements are typically used to infer the density of a cloth fragment, although several authors have noted that these measurements alone do not fully communicate the density of a textile, and it has been argued that they are not useful to readers who wish to visualise textile characteristics (Hammarlund et al. 2008, 2; Harris 2019, 2–3)

Cover factor provides a quantitative measure that can more directly be related to the density of a woven textile. Specifically, cover factor reflects the percentage of an area of cloth that is covered by threads in each system. Cover factor can be calculated by system using the formulas:

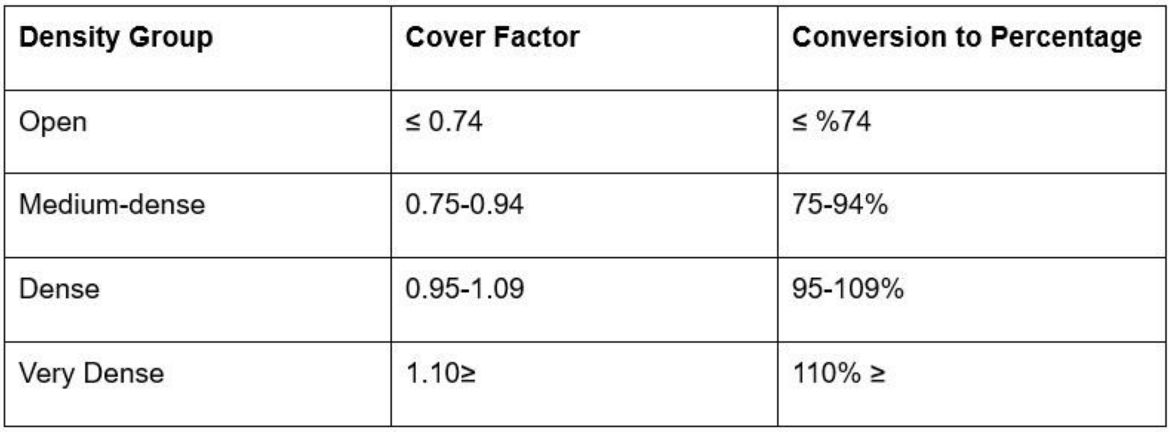
WA= Thread count/cm x yarn diameter (cm) in warp system

WE = Thread count/cm x yarn diameter (cm) in weft system

to represent the percentage of cloth covered by the warp or weft (Hammarlund 2005a, 115). Warp and weft cover factors can be taken as a quantitative reflection of the balance of the cloth (whether the warp or weft is the dominant system). These cover factors can also be combined using the formula to calculate the overall cover factor:

Cover Factor = WA + WE - (WA x WE)

This is more reflective of how densely woven a textile is. The theoretical maximum cover factor is 1.0 (100%), which would represent a textile with no gaps between the threads in either system, but as Hammarlund has pointed out, the theoretical maximum doesn't account for the ability of yarn to compress, meaning that actual cover factor measurements can exceed 1.0 (Hammarlund 2005a, 115–116). Four categories of cloth density based on calculated cover factor were established by Lena Hammarlund based on a group of wool tabby textiles from Mons Claudianus (Table 2.3).



Density Group	Cover Factor	Conversion to Percentage
Open	≤ 0.74	≤ %74
Medium-dense	0.75-0.94	75-94%
Dense	0.95-1.09	95-109%
Very Dense	1.10≥	110% ≥

Table 2.3: Cloth density groups and corresponding cover factor ranges adapted from Hammarlund (2005)

This work by Hammarlund has provided a useful framework for assessing textile density beyond thread counts. As Hammarlund has noted, these categories had not been tested on textiles made from fibres other than wool (Hammarlund 2005a, 117). It will therefore be useful to apply this framework to silk analysis to determine whether the categories of density described are as applicable to silk as they are to wool.

2.3.5 Yarn characteristics

Approaches to identifying production locations through the analysis of surface design and woven structure have been discussed. There are still clear gaps in information regarding textiles that lack diagnostic patterns or structures, such as the previously mentioned plain silk tabbies. It should be no surprise then, that the analysis of silk threads also plays an important role in the study of silk textiles. Recording the characteristics of threads in archaeological textiles –particularly diameter, twist direction and degree of twist –is well established best practice.

2.3.5.1 Twist Direction

When analysing yarns spun from discontinuous fibres, the direction of twist is recorded as either Z (spun clockwise) or S (spun counter-clockwise) (Walton and Eastwood 1988, 5). This distinction provides a visual guide to determining twist, as the angle of the connecting bar in each letter corresponds with the angle of the fibres in the yarn being analysed (Figure 2.17). Reeled and twisted silk yarn is described with the same S or Z notation as spun yarn, while silk yarn with no observable twist is described with the letter I, a convention that is used in the textile catalogue for 16-22 Coppergate (Walton 1989). Another method of describing silk yarns without observable twist is used in the textile industry in Lyon and by the Centre International d'Etude des Textiles Anciens (CIETA), which uses the acronym STA, an acronym for *Sans Torsion Appreciable* (without appreciable twist) (Desrosiers 2015, 9). This cataloguing terminology is used in *Soieries et autres textiles de l'antiquité au XVIe siècle* (Desrosiers 2004).

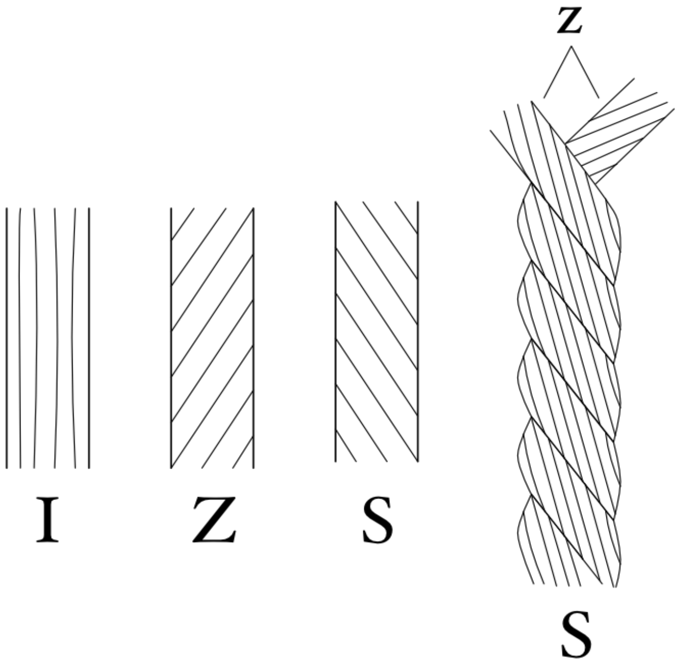


Figure 2.17: Diagram of different directions of twist in yarn with Z2S-plied yarn on the far right (Source: the author)

Yarn may be single spun or plied to combine 2 or more threads into a thicker yarn. A plied yarn is described as being composed of 2 or more spun or twisted elements, which usually have been twisted in the opposite direction of the overall yarn twist (Monnas et al. 2021, 52). According to Walton and Eastwood (1988, 5) a standard way of describing plied yarns in the UK notes the twist direction of the smallest element, followed by the number of elements in the yarn and the direction in which those elements are twisted. For example, a common structure for plied yarns as described in Walton and Eastwood is Z2S (Figure 2.17); 2 Z spun yarns that have been twisted together in the S direction (Walton and Eastwood 1988, 5). Descriptions of twisted silk yarns follow this same convention, based on the number of reeled filaments that have been observed to be twisted together.

2.3.5.2 Degree of twist

Degree of twist is often conveyed with descriptive words such as tight/hard, medium, or loose/soft, (Walton and Eastwood 1988, 5). Alternatively, the degree of twist can be quantified by measuring the angle of the twisting fibres. This angle measured in relation to the main axis of the yarn (Figure 2.17). The most direct approach involves manually comparing the fibre angles using a reference printed on card (Kania 2021, 211), but a protractor could presumably also be used. Angle measurements can also be taken digitally using software with varying degrees of complexity (Ozkaya, Acar and Jackson 2010, 91). The resulting measurement provides a number that quantifies how tightly twisted the yarn is, with the understanding that 90° represents an improbably high degree of twist. Degrees of twist corresponding to specific angle measurements were defined by Emery as follows: angles up to 10° correspond to low twist; between 10° and 25° medium twist; and 25°-45° for high degrees of twist (Emery 1980, 12). These categories of twist are also used by Malcolm-Davies et al. (2018, 16) who additionally emphasise the importance of calculating yarn twist as an average of at least 10 measurements taken from multiple sections of the yarn in question.

Most approaches to quantifying twist prioritise a 0°-45° range, and specify twist direction separately. In a slightly different approach, Ozkaya et al. (2010 Pg. 93) utilise a method that numerically indicates direction of twist by establishing that S-twisted yarn would be reflected by angles of between 10° and 80°, while Z-twisted yarn would be reflected by angles between 100° and 170°. In both cases degree measurements closer to 90° reflect higher levels of twist; this is best understood visually (Figure 2.18). This method requires a very specific orientation of the (literal or theoretical) protractor, but results in measurements that clearly communicate direction of twist without the need for additional notation. An important discrepancy between Ozkaya et al.'s method and that described by Malcolm-Davies et al. relates to twist quantification, as Ozkaya et al. utilise a twist range that starts at 10°/170°, while Emery's original classification uses 10° as a base measurement for medium levels of twist. This is an important consideration that highlights the need for more firmly established guidelines for twist characterisation in the field of textile analysis. It is also worth noting that the authors cited were not focussed on silk yarn specifically, so it is unclear whether the standards that have been established for spun yarn will apply neatly to silk yarn analysis.

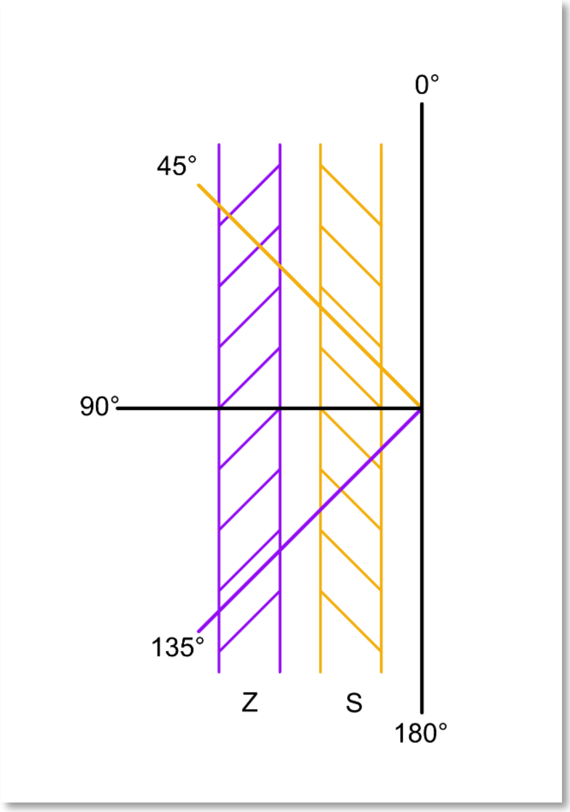


Figure 2.18: Illustration demonstrating the relationship between degree of twist and proximity to a 90° angle for both Z and S twist (Source: the author)

Another method for determining degree of twist developed by Cork et al. (1996) will be discussed in greater detail in relation to the use of computer imaging.

2.3.5.3 Provenancing Textiles using Yarn Characteristics

Some regional differences in silk-reeling methods and technology have already been discussed in detail, and from an analytical perspective there has been previous suggestion that the physical characteristics of silk yarn and thread can be attributed to specific regions. Walton Rogers' observation of different combinations of S and Z-twisted, and I "twisted" silk yarns in the textile finds from 16-22 Coppergate, and the possibility of these characteristics being diagnostic have already been mentioned, while similar variation is observable in silk finds from Viking-age Dublin (Pritchard 1988). Crowfoot et al. also state that variations in treatment, twist, and dyeing can help differentiate between silk produced in different Asian and Mediterranean workshops, while noting there can still be difficulties in attributing provenance (Crowfoot, Pritchard and Staniland 2006, 85). A case study in the same volume dates a silk compound-twill textile found in London (No 140) to having been produced in the 12th or early 13th century, probably in a workshop in Spain. This assessment is based partially on an analysis of the woven motif, the weaving method, and the presence of silver thread in the weave but, importantly, is also based on the silk warp threads having no appreciable twist, a feature that the authors note is not common in silk textiles woven in the west, and therefore rules out the possibility of it being a Byzantine product (Crowfoot, Pritchard and Staniland 2006, 103). This example demonstrates the way in which the analysis of surface design, woven structure, and thread characteristics are effectively combined to better interpret the origins of silk textile fragments, as well as highlighting the importance of metal threads as another potentially diagnostic material known to be incorporated into silk textiles.

Regarding the degree of twist as a distinguishing feature in silk threads, Sophie Desrosiers has noted among the textiles she has studied a general trend toward a low level of twist (or no twist) in the warp threads found in Chinese textiles from the Tang dynasty (618-907 CE). She set this in contrast with central Asian textiles from the 3rd century CE, which contained tightly-twisted warp threads (Desrosiers 2019, para.25), and polychrome figured European silks that also had hard-twisted warp threads. (Desrosiers 2019, para.21).

Harold Burnham also stated that Chinese silk yarn generally tends to have less twist than European yarn and, furthermore that "in the Far East, silk was often not completely degummed before weaving." (Burnham 1968, 51–52). Burnham asserted that the "basic warp" in China was composed of Z-twisted yarn made from 2 strands, while S-twisted silk is more commonly found in European silk yarn. Burnham based this on his own study of Chinese silks in the Royal Ontario Museum in Toronto, Canada but did clarify that the observed trend of S-twisted yarns in European silk is not completely consistent (Burnham 1968, 52).

In contrast to comments regarding a typically higher level of twist in Byzantine and European silk from Desrosiers and Crowfoot et al., Julia Galliker, in her analysis of silk textiles dated between the 7th and 12th centuries, reported that the majority of textiles attributed to the Near-East and Mediterranean had warp threads with a *low* level of twist. According to Galliker, 83% of the textiles had threads with a 10-15° surface helix angle, and she attributed outliers to these measurements as being a result of uneven distribution of twist in specific sections of the threads (Galliker 2015, 257). This is a noteworthy contradiction which may be the result of differing sample sizes and experience levels on the part of the researchers, or inconsistencies in measurement taking methods. Furthermore, the purported homogeneity in level of twist reported by Galliker is surprising, and it may be worth asking whether some variations have been unintentionally smoothed over, as it were, by the author's method of averaging the helix angle measurements taken.

Other distinguishing thread characteristics were also observed by Galliker in the samples she recorded. Galliker stated that silk yarns in textiles attributed to Central and Eastern Asia were made up of fibres that were glossier, as well as smoother and more regular in appearance than the other textiles in her data set. Galliker also noted that many of the silks she studied that had been attributed to Mediterranean and Near Eastern Workshops exhibited visible knots and slubs, and described 2 specific textiles in this category (TMA 711 9 and BMFA 33 519) as being notably "hairy" in appearance, suggesting this could be a result of the threads being reeled from cocoons with shorter overall fibre lengths (Galliker 2015, 255).

Given some of the contradictions mentioned above, it seems clear that it will continue to be difficult to determine the provenance of silk threads based solely on factors like twist, without a more extensive and unified study of the source material. The possibility of these features being more clearly diagnostic in future is promising, and the examination of these thread characteristics in relation to specific processing methods will contribute to the development of new analytical frameworks regarding silk thread structure and appearance.

2.3.6 Fibre Microscopy

Fibre microscopy plays an important role in the identification and analysis of silk fibres. The use of light microscopy in particular to identify silk fibres (and at lower levels of magnification to determine the structure of silk threads) in early-medieval textiles has been demonstrated in the work of Penelope Walton Rogers (Walton Rogers 2007). Fibre microscopy has also been effectively used to reclassify early textiles whose fibres had been previously misidentified. This was the case with nine 3rd-4th century spun silk textiles from Karadong in the Taklamakan Desert, which had been previously assumed to be wool (Desrosiers and Debaine-Francfort 2016, 69).

In addition to fibre identification, fibre microscopy is also typically used to gather fibre diameter measurements. The microscopic analysis of fibres can be approached through viewing the fibres in 2 ways: The first is a whole-mount preparation (Walton Rogers pers. com 2021) wherein the fibres are laid in a mounting medium across a glass slide and covered with a glass coverslip. This produces a transverse view of the fibres when examined with a microscope. The second approach involves preparing the fibres to be viewed in cross-section by slicing a section at a right-angle to the axis of the fibres (after they have been embedded in a medium) (Herzfeld 1920, 13).

2.3.6.1 Diameter and Cross-sectional Area of Bombyx mori Fibres

Sources on the technical properties of silk fibres discuss the variability in fibre diameter, usually noting that silk fibre diameters are at their largest at the exterior of the cocoon, narrowing the further the fibre is situated toward the interior of the cocoon (Chung et al. 2015, 946). Two studies on the mechanical properties and morphology of *Bombyx mori* silk fibre have compared fibre diameters from samples gathered from the exterior (anterior), middle, and interior (posterior) of the silk cocoon. One study (Chen et al. 2019, 5) confirmed this relationship, while the other (Zhao, Feng and Shi 2007, 677–678) confirmed that the interior (posterior) silk displayed the narrowest diameters; it stated that the middle sections of fibres displayed the largest diameters, which indicated the potential for varied results even in controlled contexts. This provides important data regarding natural variation in silk fibre diameter. That said, the studies in question analysed silk reeled using ahistorical methods, in most cases unravelling a single cocoon at a time. This is important as it does not take reeling processes into consideration as a potential influencing factor in silk diameter, nor can these studies provide data on fibre diameters from more than 3 cocoons reeled simultaneously.

Some authors also describe exterior cocoon fibres as more variable in diameter than those positioned further inside the cocoon. Furthermore, variations in quality of silk from the archaeological record are often attributed to differences in cocoon quality emerging from regional differences in sericultural practices. This occurs frequently in relation to silk attributed to central Asia (Desrosiers and Debaine-Francfort 2016; Zhao 2021, 100-101)

Junro Nunome's research on historical silk fibres recorded variations in the morphology, diameter and overall quality of said fibres, which he determined to be indicative of region of origin, chronology, and production methods. The diameter measurements used in Nunome's study were taken from the cross sections of fibres extracted from Chinese, Japanese, and European silk textiles spanning multiple centuries. These measurements were also used to calculate the circularity coefficient of the silk cross-sections, or the extent to which a triangular fibre cross-section fits within a circle of the same diameter as the fibre (Nunome 1988; 1989). Nunome's work emphasises the value of applying microscopy to the study of silk fibres, having produced a statistical analysis of nearly 500 fibre specimens (which included wild silk moth species as well as Bombyx mori) by 1977 (Riboud 1977, 253), with an increased sample size of over 900 specimens by 1989 (Nunome 1989, 33).

The results of Nunome's research are significant and could play a vital role in uncovering information on silk processing methods if applied to a suitable reference collection. Kuhn certainly took note of Nunome's work, describing it as "...the most profound research into the history of silk in East Asia." (Kuhn 1988, 273). Kuhn also points out that the statistics on Chinese silk fibres from Nunome's study indicate that the quality of silk fibres in China reached a peak around 1100 CE, before declining during the Yuan dynasty (1271-1368). From that point the quality appeared not to have improved again until c. 1500. These figures served as a springboard for Kuhn's discussion of substantial improvements made to silk-reeling technology and sericultural practices in China during the Song dynasty (960-1279) (Kuhn 1988, 386,87). While Nunome's work is regarded as significant foundational research, one critique levelled is that he focused on the quality of the silk fibres, but paid little attention to silk-processing methods, in particular throwing technology and yarn twist (Desrosiers 2019).

Considering the apparently groundbreaking nature of Nunome's research, the results of his study and measurement methodology seem to be rarely applied to silk textile analysis by other researchers outside of Japan, nor does his study appear to have been revisited or expanded upon more recently. This may be because Nunome published exclusively in Japanese, meaning that there is a significant language barrier in approaching his work.

2.3.6.2 Quantifying Numbers of Cocoons

Multiple authors have identified the number of cocoons used in a surviving textile, but how the numbers were determined is not always explicitly stated, and phrasing can be ambiguous. For example the silk "taffeta" from Birka grave 824, was identified as raw silk via microscopic analysis, and it was stated that the silk yarn comprised nearly 150 cocoons (Geijer 1938, 61), but it was not specified how this count was achieved. Other case studies have taken the straightforward approach of counting the fibres present in a cross-section of silk yarn (Saunier et al. 2022), but this method does not specify whether the potential deterioration of fibres has been taken into consideration.

2.3.6.3 Sericin morphology/Degumming

Experimental research regarding degumming methods is usually carried out in the context of contemporary material science research, and has particularly focused on the effect of degumming on the mechanical properties of silk fibres. Such studies have demonstrated that particular degumming methods have some effect on the molecular structure of silk, resulting in weakened tensile strength (Jiang et al. 2006).

Research on the detection of sericin in historical textiles often applies chemical analysis such as FTIR spectroscopy (Zhang and Wyeth 2010), which has produced useful guidelines for the chemical identification of sericin. Other research concerned with the chemical identification of raw silk found that the sericin in artificially aged samples deteriorated, 'leeching' from the silk fibres when exposed to high-humidity thermal ageing (Geminiani et al. 2023, 10–11). As a result of this, Zhang et al (2011, 411) have argued that sericin is unlikely to be preserved in raw silk samples outside of arid conditions. Interestingly, although surviving sericin can be detected visually via microscopy, and is noted in passing in several studies (Geijer 1938, 59; Saunier et al. 2022, 7; Desrosiers and Debaine-Francfort 2016, 69), there are no clear published guidelines for its visual identification and evaluation in the context of archaeological and historical silk textiles.

2.3.6.4 *Fibre Damage and Deterioration*

Several studies have been conducted on the causes of textile fibre deterioration, particularly in the interest of supporting textile conservation. One comprehensive study characterised the visual and mechanical effects of different types of textile fibre damage (Hearle, Lomas and Cooke 1998). The resulting *Atlas of Fibre Damage and Deterioration* is notable as it analysed both archaeological textiles and modern materials, and still serves as an important and useful reference for types of archaeological fibre damage. Other studies based on artificial ageing processes have provided useful information regarding the mechanisms of silk deterioration. That said, most of these studies make use of chemical and mechanical tests, meaning that the body of reference materials for the visual impact of different mechanisms of deterioration affecting historical silk fibres has not significantly expanded since 1998.

2.3.7 Chemical Analysis

A variety of chemical analysis approaches have been applied to historical and archaeological silk textiles. Two predominant aims appear to drive this research, one being the desire to determine the provenance of silk textiles, the other being to inform silk textile conservation practice.

Studies of silk protein have provided some valuable insights into historical silk production at a species level, such as the identification of the wild silk species Antheraea mylitta in silk textiles from Palmyra, through mass-spectrometry-based proteomics (Lee et al. 2022). Detection of silk residue left in soil imprints from Han dynasty tombs has been made possible through a combination of immunological technology and proteomics. This work has important implications for the identification of textile fibres when only an imprint remains (Zheng et al. 2021). Proteomic analysis has also supported the study of historical silk deterioration under different conditions (Yukseloglu and Canoglu 2016; Solazzo et al. 2012), which provides useful information in the field of textile conservation.

Preliminary studies exploring the potential for the use of stable isotope analysis to determine silk fibre provenance, have been conducted on contemporary silk, soil and mulberry samples (Liu et al 2022) and archaeological silk textiles (Knaller and Ströbele 2014). These studies have indicated that stable isotope analysis has strong potential for determining the provenance of archaeological silk fibres, but this research is still in its infancy.

These studies illustrate the exciting potential of chemical analysis of silk fibres, for the identification of silk fibres and to aid in the determination of their provenance. That said, these methods cannot be used to infer processing methods, nor are they likely to be able to identify whether the silk in question has been transported between production stages, which highlights the need for a multi-methodological approach to silk textile analysis.

2.3.8 Computer-aided Textile Analysis

Computer-aided image analysis has been applied to archaeological textiles in a few ways, with varied success. While some researchers have made use of Computer Vision to identify and analyse woven structures or surface textures, the most relevant research to the analysis of silk thread is concerned with the measurement of yarn characteristics.

Early work on the use of image-processing software to accurately measure the angle of twist in yarns from archaeological textiles was carried out by Cork et al.(1996). This study used image-processing software to identify and measure the direction and angle of twist in the yarns of woven textiles from the 1st-century Roman fort at Vindolanda. The method still required some input from a human operator, who would manually highlight the threads to be analysed. The program then performed a series of operations to simplify the image and extract fibre lines, and measured the angles of these lines (Cork, Cooke and Wild 1996, 338–339). The authors describe how the application of the helix measurement provides a built-in indicator of the direction of twist, since angles to the left of the yarn axis were expressed in negative numbers, while angles to the right were expressed in positive numbers, meaning that a positively expressed angle indicated Z-twisted yarn, while a negatively expressed angle indicated S-twisted yarn. One complication the authors noted is that, particularly in tightly twisted yarns, certain fibres expressed opposite signed helix angles to the majority of the other fibres. This would easily be ignored by a specialist taking the measurements manually, but were measured by the computer, and therefore a mean could not be accurately calculated for the measurements taken, and the authors note that it is necessary to express the values in alternative ways (Cork, Cooke and Wild 1996, 340).

Another approach to using computer vision software to measure helix angle developed as part of Julia Galliker's (2015) PhD thesis. This work shows some continuity in relation to Cork et al. The software was primarily developed to analyse binding points (where warp threads crossed over weft threads) in figured silks. The program was "trained" to detect these binding points, an impressive task in itself, given the degree of programming necessary to allow for the consistent identification of a feature that can vary in shape, size and colour (Patel et al. 2013, 530). To measure helix angle, the identified points were manually selected and converted into binary images, in an approach similar to that of Cork et al. A series of layered algorithms were required to detect and measure the fibre angles, and further filtering was necessary in order to determine the angle of twist. The authors did notice a problem of "noise" in the image detection, meaning that the software appeared to generate measurable lines on the image for more than just the fibres. Once the measurements were generated from different binding points, the authors selected clusters of measurements with minimum deviation in the maximum number of lines generated, in order to determine the measured angles as accurately as possible (Patel et al. 2013, 533). The authors do not mention whether they noticed Cork et al.'s problem of rogue fibres aligned in the opposite direction to the angle of twist, so it is unclear whether this would have affected the calculated angles.

Other studies have applied Computer vision and machine learning to the identification of weaving flaws and analysis of cloth texture for commercial applications (Islam, Akhter and Mursalin 2008; Rasheed et al. 2020; Wang, Georganas and Petriu 2011). These studies have produced mixed results, and it has been argued that further research collaboration is needed before these approaches are industry-ready (Rasheed et al. 2020, 21)

Overall, the application of computer vision software, machine learning algorithms and virtual imaging to the analysis of archaeological textiles is intriguing, but it seems that further research is necessary in all areas for these methods to be reliably applied to historical and archaeological textiles.

2.4 Conclusion

Thanks to the rigorous research of many dedicated scholars, there is an impressive breadth of information on the topic of medieval silk. Despite the importance of this foundational knowledge, many gaps in information have become clear through the process of summarising this previous research. I have endeavoured to highlight key questions throughout this chapter.

We still do not understand the construction details of many silk-reeling devices, or exactly when and how the silk-reeling mechanisms clearly established by the Song dynasty in China made their way to Europe. Furthermore, outside of the overview provided by Kuhn and Zhao, it is worth asking how much variation there was in the types of silk-reeling equipment used across China and the rest of Asia over several centuries. Some of these questions can be addressed by revisiting primary sources, particularly in comparing imagery from different documents, something that will be approached in chapter 3.2.

In comparing the stages of medieval silk production as addressed by various authors, a general pattern has emerged, which illuminates the many ways in which the silk-production *chaîne opératoire* may vary: not just in terms of equipment but also technical decisions. This variability of choices made during the process of silk production is referenced by Schäfer et al (2020, 7) who also stress that the processes should not be considered "technically inevitable". This relates to Lemonnier's (2004, 3) argument that technical choice is never purely material based, rather a technique can be considered the physical rendering of mental processes shaped by social constraints and phenomena often acquired through tradition. It should be clear that, while the question of how changing technology affected the quality of silk thread is an important consideration, many of the processing decisions related to silk production (including water temperature, and thread thickness) exist independently from silk-reeling technology itself. These variables are important factors that may be culturally informed as much as they are technical considerations. These different processing decisions may result from invention via the rejection of previous routine procedures, or may be the result of borrowing, that is adapting pre-existing procedures (Lemonnier 2004, 21–22). In either case, the way in which silk-reeling protocols vary can be tied to the social structures that shape these processes, and the borrowing or inventing of techniques is relevant to understanding the mechanisms via which the skills required to produce silk were disseminated and developed over long distances during the Middle Ages.

In contrasting differing interpretations of this chaîne opératoire, several different techniques that merit practical testing have been revealed, and some key methodological gaps have been identified, including the precise effects of certain technical choices, and most importantly, to what extent silk-reeling and throwing methods from China and other regions were applied to European and Mediterranean silk production during the Middle Ages. This question is important because detailed descriptions of silk thread production tend to favour Chinese sources, in no small part because of the research carried out by Kuhn, who is frequently cited by other authors.

It would also be a mistake not to mention one of the most glaring gaps in information regarding the production of silk thread: the tools and methods that were in use in other major silk production regions including Persia, and many regions under Islamic rule throughout the Middle Ages. The lack of source material on this topic may be the product of neglect, in favour of other topics such as weaving. It equally may be more connected to a lack of the necessary language skills required to track down resources that may provide more relevant information. A final question worth consideration is whether the lack of information on medieval European and Middle-Eastern silk-reeling processes arises from authorial disinterest, from trade secrecy on the part of reelers and throwsters, or as the result of contemporary research biases.

Regarding analytical methods, some of the approaches covered will not be relevant to the analysis of silk thread, but give important context to the development of textile analysis as an area of research. The work done so far in fibre microscopy has laid crucial groundwork for further fibre analysis. While there is clearly a precedent for the study of silk fibre morphology, this has yet to be applied with a practical study of silk-reeling methods. Meanwhile, certain pitfalls have been highlighted, which emphasise the importance of building up a foundation of knowledge and technical skill to generate accurate results. This applies particularly to microscopy but is certainly applicable to all areas of analysis.

Key gaps in information identified in this chapter have informed the design of the silk processing experiments (Chapter 4). The reeling experiments have particularly taken the questions of optimal reeling temperature, the effect of different crossing methods on silk quality (and relative efficiency of these methods), and the influence of different numbers of cocoons into consideration. The throwing experiments have addressed the efficacy of the different theorised approaches discussed. Use of a drop spindle for twisting silk was tested, and a method for combining silk without twist was trialled. The degumming experiments aimed to address the gap in information regarding quantity of alkaline additive, and the influence of simmering time on extent of sericin removal.

The construction of specialised equipment to be used during the experiments was crucial to this research. Preparatory work prior to construction was particularly concerned with the described gaps in information regarding the construction of medieval European silk reels.

This along with the construction methods employed will be discussed in Chapter 3.

3 Interpretation and Construction of Silk Processing Equipment

The experimental program designed to compare silk-reeling and processing techniques will be discussed in-depth in Chapters 4 & 5. These experiments relied on specialised equipment that could replicate the behaviour of the mechanisms described in Chapter 2.1. Therefore, before the silk-reeling experiments could be conducted, it was necessary to build custom equipment. A crucial stage of research prior to the equipment construction was a detailed survey of the surviving depictions and descriptions of medieval and early-modern silk production equipment. The style and structure of the silk-reeling equipment constructed was based on extensive textual (Chapter 2.1) and pictorial research. This chapter will begin with a summary of the most common parts of silk-reeling mechanisms, followed by an explanation of the stages of research leading up to and including the construction of the equipment. In the pre-planning stage this involved the compilation of a catalogue of historical depictions and archaeological examples of silk-reeling equipment, followed by an analysis of their construction and chronology. The planning stage involved trials to test the function of different styles of mechanism, and a synthesis of the measurements of reeling equipment from historical sources leading up to the drafting of final construction plans. The final stage of equipment construction and testing, including attempts to construct an appropriate heat source will be discussed, leading into Chapter 4, which will cover the silk-processing experiments.

3.1 Common parts of silk-reeling mechanisms

The following provides a summary of the most common parts of historical silk-reeling equipment. Figure 3.1 illustrates 3 different reeling configurations, annotated with explanations of the function of each part.

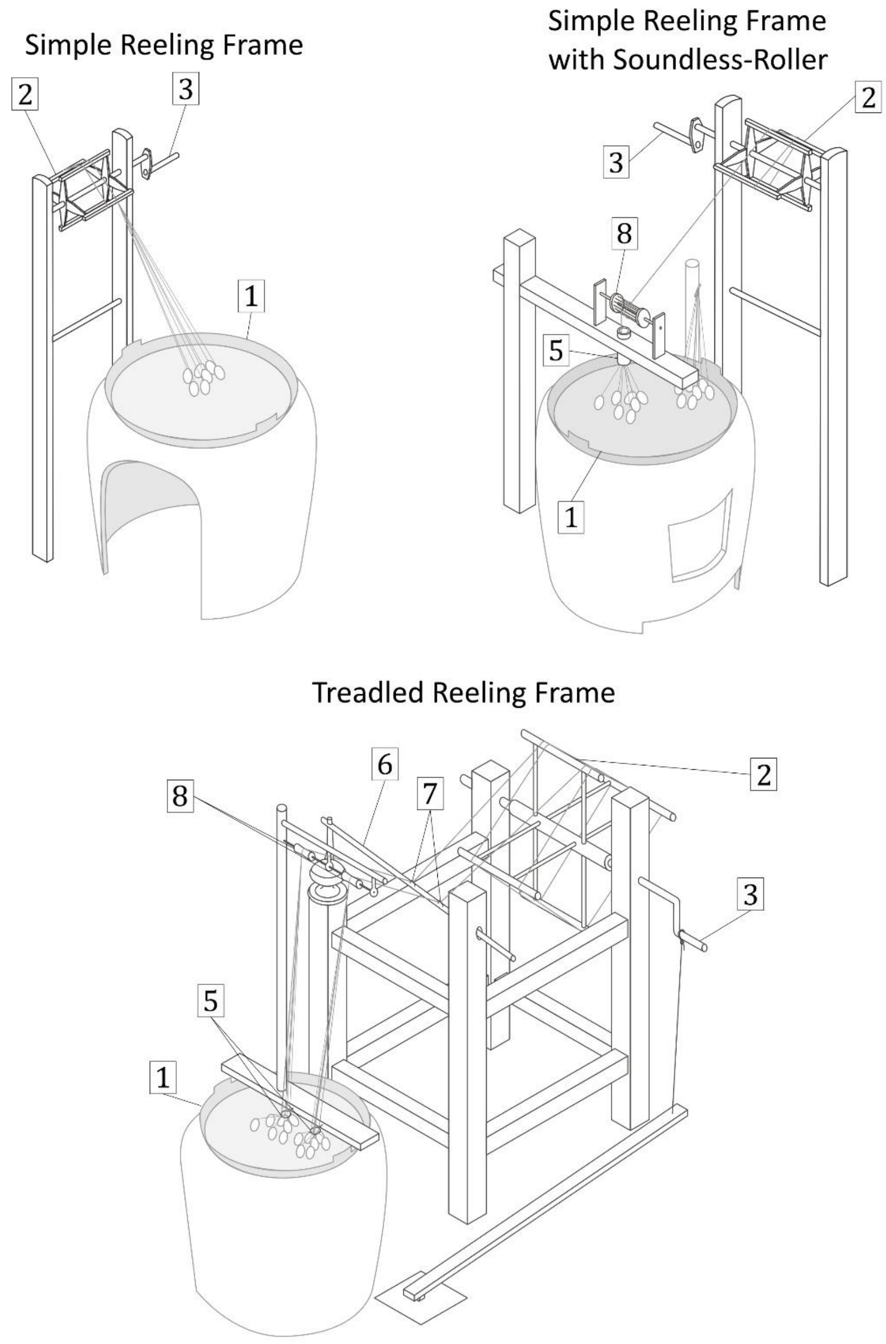


Figure 3.1: Three Different styles of silk-reeling apparatus with parts numbered (Source: the author)

1. **The water pan:** These pans were made from a variety of materials including clay, iron, copper and in some cases, lead (Geffe); they were typically combined with a stove or furnace as a heat source. The water pan is an essential part of the silk-reeling process, as cocoons must be soaked in warm to boiling water to soften the sericin protein that binds the silk fibres into their cocoon structure so they can easily be unravelled while still holding their shape.

2. **The reel:** This term refers specifically to the rotating spool onto which the unravelled silk strand is wound, rather than the entire silk-reeling configuration.
3. **Crank:** The crank enables the efficient rotation of the silk reel. The crank may be turned by hand or driven by a foot-powered treadle.
4. **Stationary guiding rod:** This horizontal rod is not a universal component, but when suspended or propped above the boiling pan serves as a way of guiding the silk strand out of the pan and onto the reel.
5. **Guiding eye:** This common, but also not universal component both guides and consolidates silk filaments into a single strand as they are unravelled from the cocoons. Guiding eyes also block any errant cocoons that might tangle in the reeled strand and affect the quality of the silk. One eye may be positioned over the boiling pan or attached to the front of the reeling device, and additional guiding eyes may be positioned along the frame.
6. **Ramping-board:** This is a term used by Dieter Kuhn (1988, 361) to describe a rod or narrow board designed to move side to side in order to guide the strand of silk evenly across the width of the reel as it turns. This distributes the silk evenly across the reel, encouraging more even drying, and reducing the risk of silk strands sticking to one another.
7. **Ramping-board guiding eye:** The strand of silk passes through this eye so that it will follow the path of the ramping-board.
8. **Rollers:** Rollers are often combined with a method of crossing the silk strand against itself to produce a rounder, smoother strand, but they may also serve as a simple guide.

3.2 Compilation of an Image Catalogue

As discussed in Chapter 2.1.1, the sources previous researchers (particularly Dieter Kuhn) have consulted in relation to the mechanics of medieval silk-reeling devices are wide-ranging, both geographically and chronologically. While textual and scant archaeological evidence are helpful in clarifying some aspects of reeling equipment construction, most of the evidence cited is pictorial. It was therefore crucial to revisit these artworks to understand the construction details of medieval silk-reeling devices, and to assess any chronological and geographic trends in form and function. A catalogue of these images (Appendix A) was compiled and organised chronologically. The foundational images included in the catalogue were cited by key authors such as Kuhn and Zhao, but further research utilising digitised museum, library and archive collections uncovered additional visual sources that aided in the analysis of reeling equipment design and construction.

The following criteria was established for the selection of suitable catalogue images:

Images of reeling equipment must be:

- Dated to within the Middle Ages (c. 400-1500 CE)

Or

- Have been referenced by a previous researcher as a possible continuation of an earlier piece of equipment

Or

- Be similar enough in form and apparent function to a device from the Middle Ages to suggest continuity and/or international exchange

Or (In one case)

- Be so different in design in comparison to medieval equipment that it provides a reference point for a clear break in tradition.

A second catalogue (Appendix B) was created of images of tools connected to silk-reeling and the production of silk thread, but are not themselves, reeling devices. This is a tricky category to define, as there are numerous multi-purpose textile production tools that could technically be used for silk production but may not be reflective of medieval silk textile traditions. The following criteria were therefore established:

- Images must be dated to the Middle Ages

Or

- Directly referenced as being used for silk production

Or

- From a region with a documented tradition of silk production

Ultimately, specific tool types were sought out, limited to the equipment required for silk yarn production, while excluding other multi-fibre tools

The final tool categories for this second catalogue were:

- Bobbins
- Spindle-wheels/spinning wheels
- Swifts/skein frames

3.2.1 Assessing Chronology of Silk-reeling Equipment

When considered chronologically, the silk-reeling depictions collected in the catalogue are consistent with the rough evolution (Figure 3.2) of silk-reeling equipment described by Kuhn, Zhao, and others, and summarised in chapter 2.1.

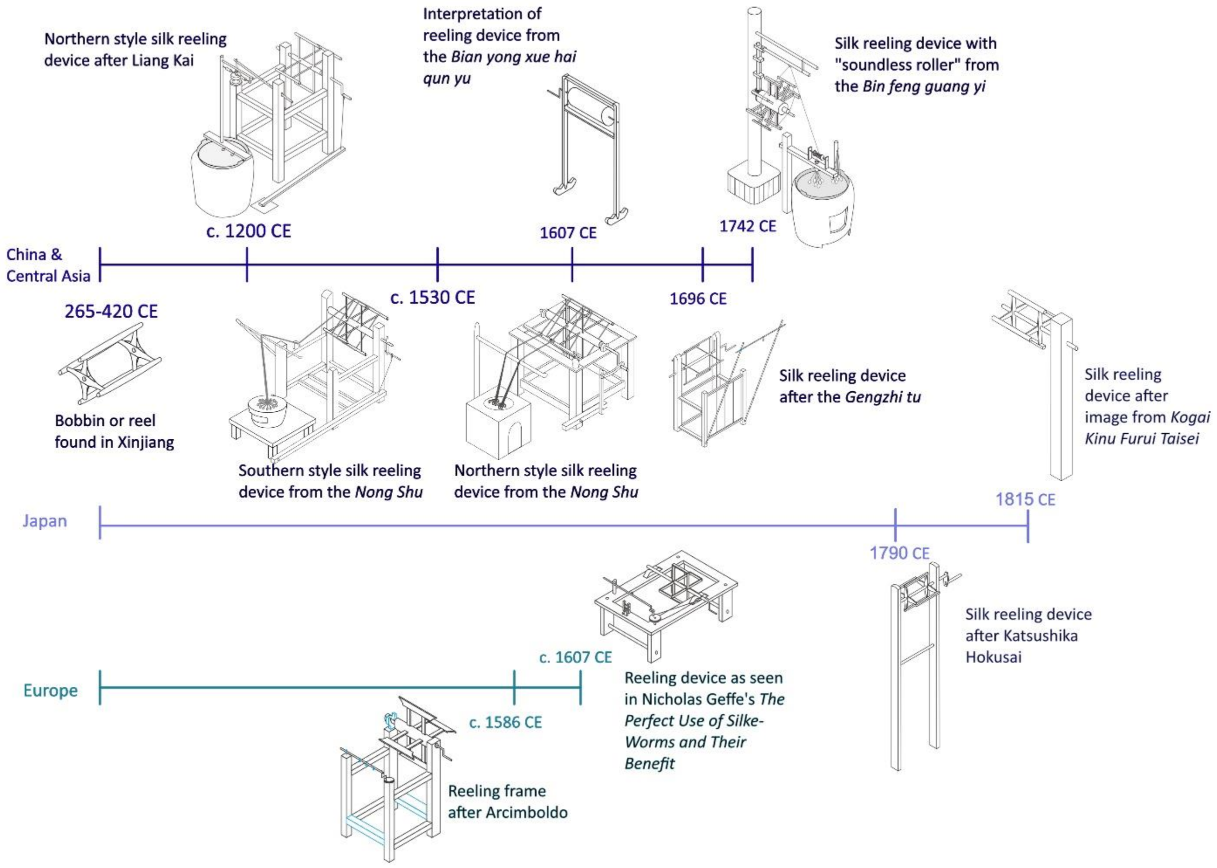


Figure 3.2: Timeline of silk-reeling devices from China and the Eurasian Steppes, Japan and Europe (Source: the author)

The earliest identified depictions (Figure 3.3) of silk-reeling show what may be simplified versions of a silk-reeling device dated to the Shang Dynasty (c. 1600 BCE-1046 BCE).

Figure 3.3: Reproduction of Shang Dynasty bronze engraving, possibly depicting silk-reeling equipment (Kuhn 1988, 347)

It is difficult to interpret the form of the reeling device in this relief as the plane along which this image is oriented is unclear, and no reeling frame or handle for turning a reel are visible. By the Han (202 BCE-220CE) dynasty, simple 4-armed bobbins are clearly depicted in stone reliefs (Figure 3.4) and the pictured bobbins appear to be of a style similar to the surviving bobbin (Figure 3.5) or reel dated to the Jin dynasty (c. 265-420 CE).

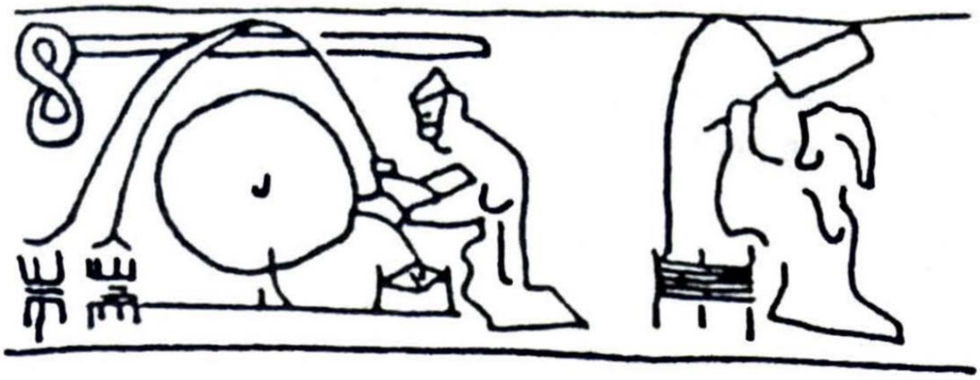


Figure 3.4: Reproduction of a Han Dynasty stone relief depicting silk throwing (Kuhn 1988, 161)

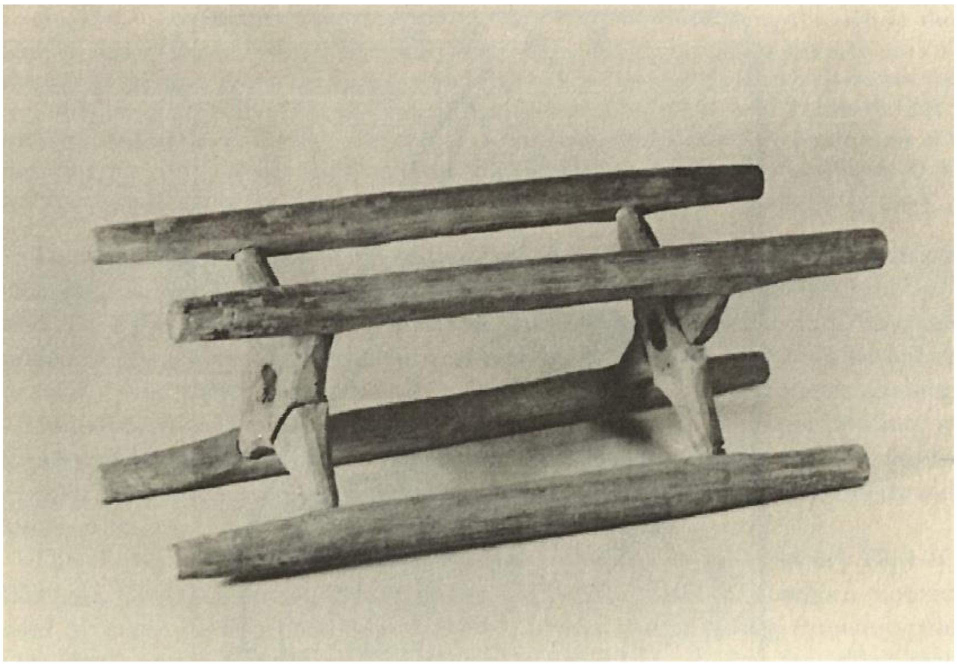


Figure 3.5: Wooden reel or bobbin found in Xinjiang, dated to the Jin dynasty (Kuhn 1988, 173)

This bobbin/reel was found in Xinjiang, which is home to more than 40 different ethnic groups, and has been claimed by a number of different kingdoms and dynasties throughout its history (Hsieh and Falkenheim 2021). This is relevant, as while Xinjiang is now considered to be part of the People’s Republic of China with nominal autonomy, its history is fraught, and except for a period during the Tang dynasty, this region had for the most part passed in and out of Han rulership by the 3rd century CE. Therefore, while the style of this object could be reflective of Han silk-reeling technology, this should not be assumed to be the case, as it might reflect a silk-reeling tradition external to the Jin dynasty, with an uncertain degree of Han Chinese influence. That said, this object is reflective of a common form seen in Chinese depictions of silk-reeling, as well as in later Japanese and European artwork.

The earliest clear depictions of Chinese silk-reeling equipment in the Reeling Catalogue date to the Southern Song Dynasty (1127-1279 CE). The first, (Figure 3.6) is a detail of a reeling device from a handscroll attributed to Liang Kai, and dated to the early 13th century. It depicts a complex reeling device that is treadle-operated, uses a cam-driven ramping-board, and has a roller frame that guides the silk filaments from the pan of water.

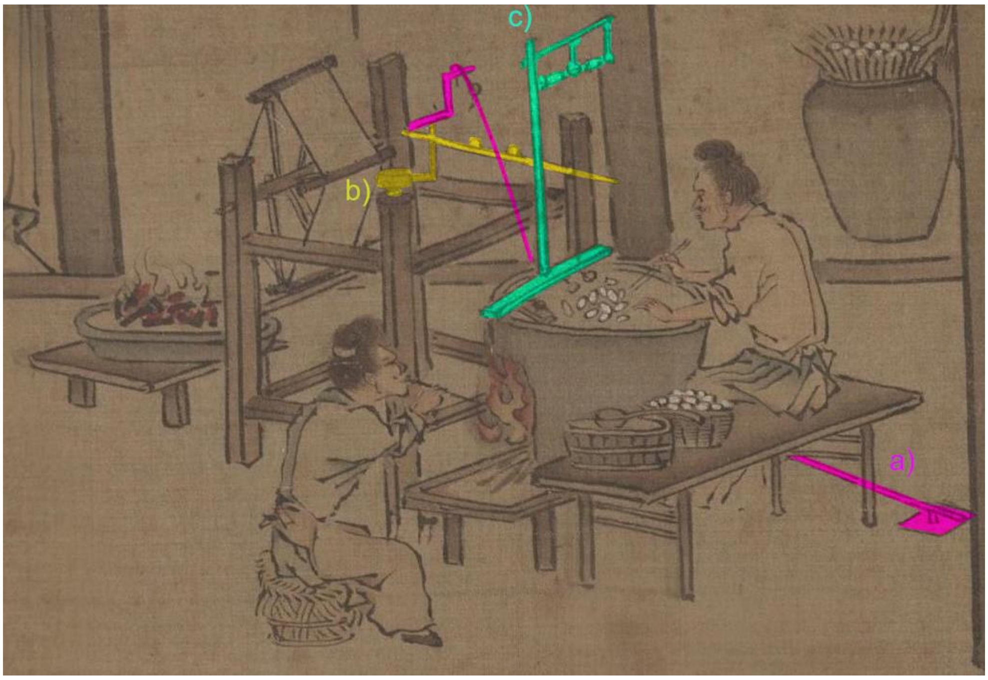


Figure 3.6:A treadle-operated silk-reeling device c. 1200. Treadle (a), moveable ramping-board (b) and roller frame (c) indicated with colour overlays (After Kai c.1200).

The second example (Figure 3.7) is roughly contemporary with Figure 3.6, and depicts a very similar device albeit with different proportions; this example is notably lower to the ground. Unfortunately, the ramping-board of Figure 3.7 is obscured, but aside from this, the key difference between the 2 frames is in the depiction of 2 guide eyes (rather than the rollers on the frame attached to the water pan in Figure 3.6).

Figure 3.7: Copy of an image of a treadle-operated silk-reeling frame from Empress Wu's annotated edition of Silkworm Weaving Pictures (Zhao & Liu 2020, 43). Guide-eyes indicated in green.

From the 13th century, depictions of treadled reeling equipment continue in Chinese sources, with some structural and aesthetic variations: most notably, between reels of the Northern and Southern styles (discussed in Chapter 2.1.1). In short, the depictions of the Northern style show 2 strands reeled simultaneously from 2 groups of cocoons, while depictions of the Southern style show only one strand of silk reeled at a time. Other features, such as the treadle form, may provide some indication of age, since the construction of the treadle mechanism depicted in Figure 3.6 and Figure 3.7 is notably different from the treadle mechanisms depicted in later images (Figure 3.8), which seem to show a series of interconnected shafts or planks rather than a cord connecting the treadle to the reel crank.

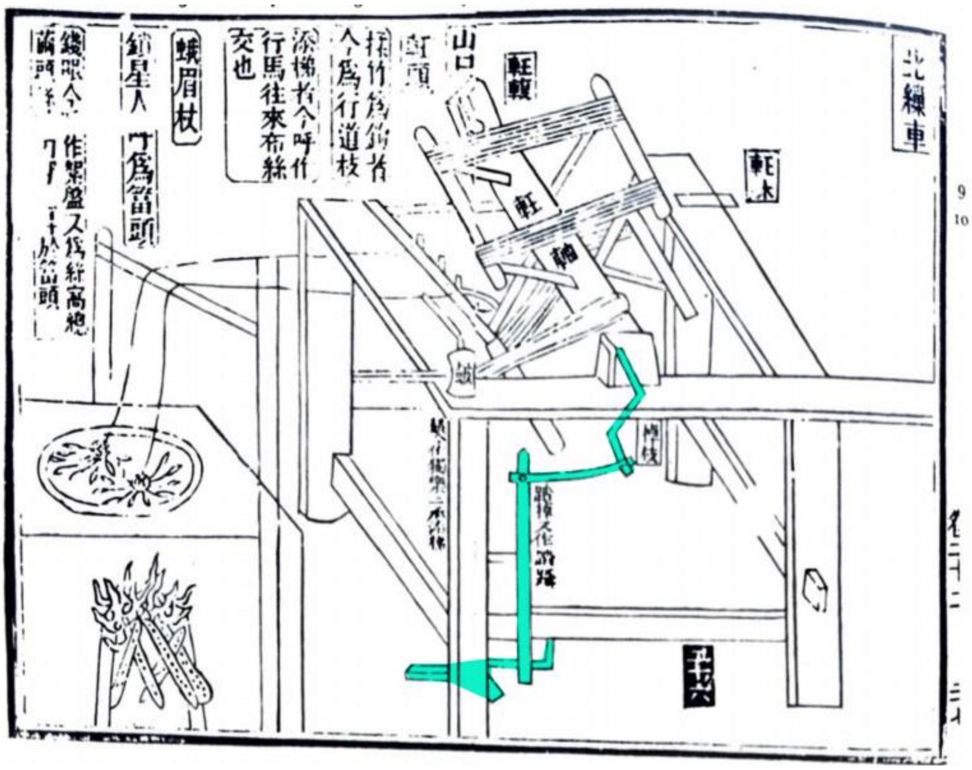


Figure 3.8:Silk-reeling device from the 1530 edition of Wang Chen's Nong Shu (Kuhn, 1988, p.368). Treadle indicated in green.

The earliest European image in the Reeling Catalogue that clearly references silk production is a detail from a 1440 Illuminated manuscript miniature, depicting the mythical figure of Pamphile. In the background of the image, she can be seen gathering yellow silk cocoons. In the foreground she is also depicted seated at a loom of geometrically impossible construction (Figure 3.9). Pamphile, or Pamphila, was a legendary figure appearing in the writing of both Aristotle and Pliny the elder, and is credited with inventing the practice of unravelling and weaving silk on the Greek island of Kos. Opinions have differed on whether the act of unravelling silk refers to reeling silk from the cocoons, or unravelling imported silk cloth and re-weaving it, although the latter has historically been a popular interpretation (Simmons 1950, 88; Jirousek 1998, 202; Burns 2009, 9). This miniature does not depict any type of silk-reeling device, and does not aid in the interpretation of medieval forms of silk-reeling equipment. That said, the image is reflective of an awareness of sericultural practices in 15th-century France.

Figure 3.9: Miniature detail depicting Pamphile gathering cocoons and weaving silk from Le livre de femmes nobles et renomées (The Talbot Master c.1440)

The earliest European image of recognisable silk-reeling equipment in the Reeling Catalogue is from a series of sketches and notes on the silk-reeling process by Giuseppe Arcimboldo, dated to c.1586 CE (Figure 3.10). This device resembles the Song-dynasty reeling frame pictured in Reeling Figure 3.6, and while there are notable differences such as the absence of a roller frame, the use of a hand crank rather than a treadle, and the reeling of 3 strands of silk simultaneously rather than 2, the reeling frame depicted by Arcimboldo has a ramping-board that appears to operate in the same way as the much older Chinese device.

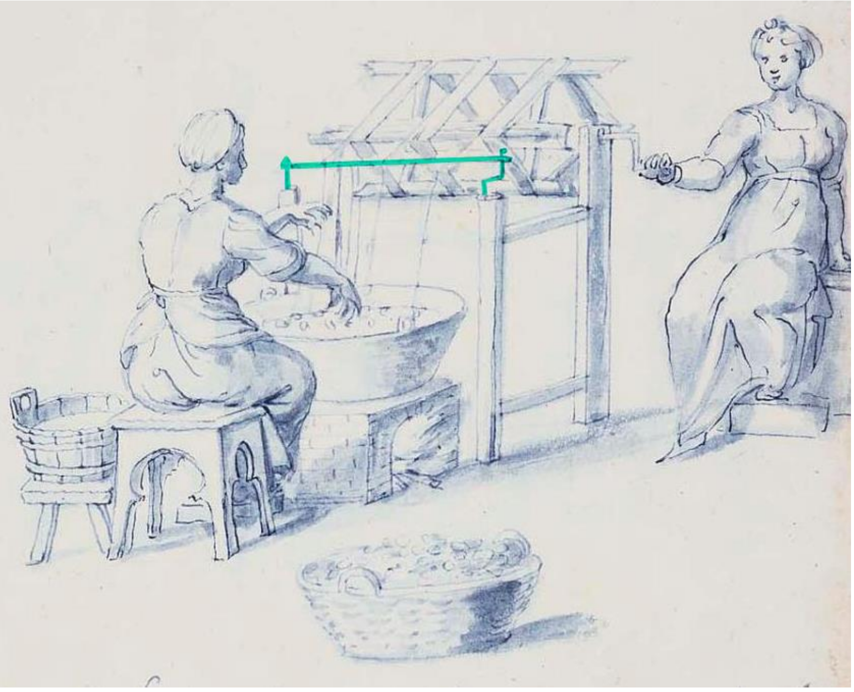


Figure 3.10: Study of a European hand-cranked silk-reeling device in use. Detail from page 7 of Giuseppe Arcimboldo's(c. 1586) *Treatise on Silk Culture and Manufacture. Ramping-board indicated in green.*

Later European examples vary more significantly in scale and proportion. Figure 3.11 shows a 16th-century silk-reeling factory rendered by Dutch artist Karel van Mallery. The exact location of the factory is not specified, but the wide trough set-up and numerous silk strands being reeled simultaneously suggest a very different production context from Arcimboldo's sketches. This may represent a move away from the possible influence of Chinese reeling-device forms.

Figure 3.11: Plate 6 of Vermis Sericus, by Karel van Mallery(c. 1595) *depicting silk-reeling in a factory setting*

17th- and 18th-century depictions, which are primarily from French sources or sources with French influence, do not appear to follow the more industrial form of van Mallery's engraving, and are more similar in proportions to Figure 3.7. These devices (Figure 3.12) also only appear to depict a maximum of 2 strands of silk being reeled simultaneously. These differences from the earlier works (which are also from a different geographic region), may indicate post-medieval French silk-reeling technology was developed under different influences than mechanisms in use in the Italian city states. Where Mallery's depiction fits into this narrative is uncertain and merits further investigation.

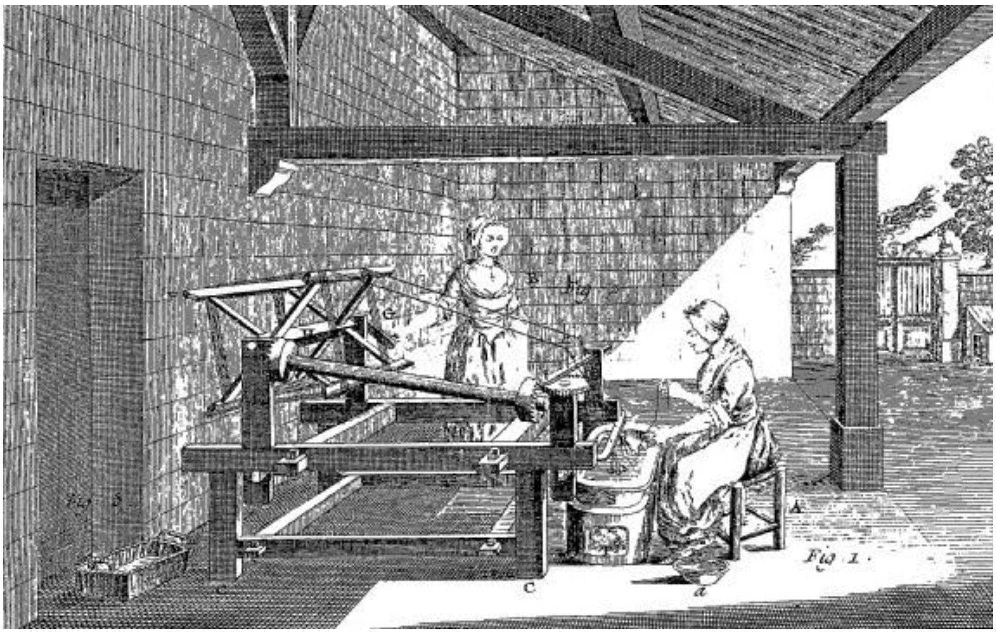


Figure 3.12: Detail of an engraving depicting a style of reel attributed to Piedmont, Italy from Plate I of L'art de la soie, (Diderot and D'Alembert 1751)

Perhaps the most notable variation in European silk-reeling devices is the method of crossing silk. The details of theorised Chinese crossing methods were presented in Chapter 2.1.1.1, and possible evidence for methods of crossing silk strands around rollers can be seen as early as the 13th-century depiction in Figure 3.6, though in this case the threads appear to simply pass over the roller. The clearest depiction of a crossing method comes from the 17th century (Figure 3.13), where the strands are seen to loop over top and bottom rollers on the reeling frame.

Figure 3.13: Woodblock print from the Tiangong Kaiwu depicting what Kuhn calls "the complete reeling frame" with crossing method circled in green.(After Golas 2015, 117)

The potential for the use of a similar method in Europe during the early 17th century is visible in Figure 3.14, where a small box frame housing 2 vertically stacked rollers is visible at the front of this device.

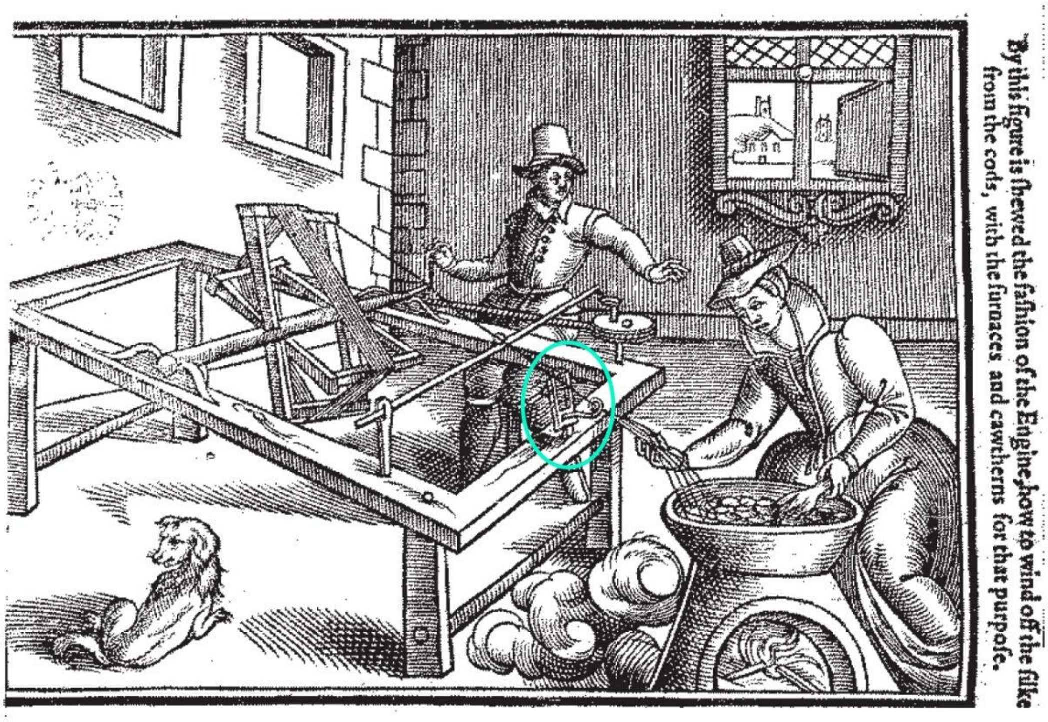


Figure 3.14: English depiction of a 17th century hand-cranked silk-reeling device (Geffe and de Serres, 1607). Box-frame with rollers circled in green.

This example is significantly more compact than the larger roller frames, and a nearly identical example is seen more than a century later in Pomier’s *L’art de cultiver les muriers-blancs, délever les vers a soye et de tirer la soye des cocons avec figures* (Figure 3.15).

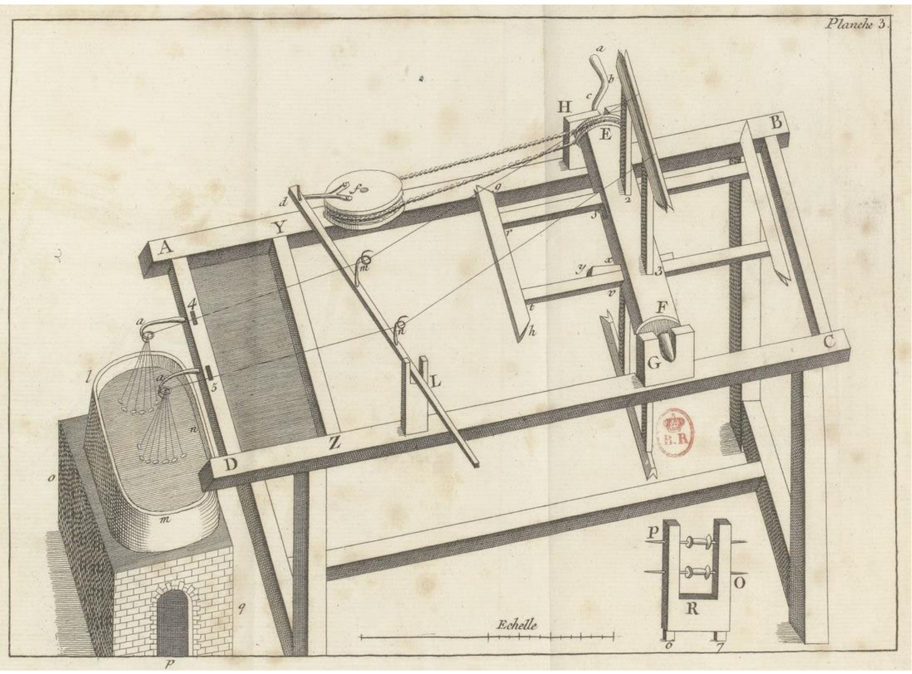


Figure 3.15: Engraving of an 18th century reeling frame equipped to reel silk "a la bobine" (Pomier 1754, 3)

Unfortunately, the way in which the strands would have interacted with these frames has not been clearly illustrated in either example. In the accompanying text, Pomier specifies that this method ("*a la bobine*") was no longer in use by the 1750s (Pomier 1754, 221). The next plate from this publication illustrates a method of reeling "*à la croisade*" (Figure 3.16) like the people of Piedmont, Italy, with the implication that this new method supplanted the older roller method, and indicating that these approaches filled a similar technical niche. This transition in thread-winding/crossing methods (the implications for the efficiency of which were discussed in Chapter 2.1.1.1) may indicate an increased Italian influence on the French silk-reeling industry of the 18th century, and further divergence from a Chinese technical influence.

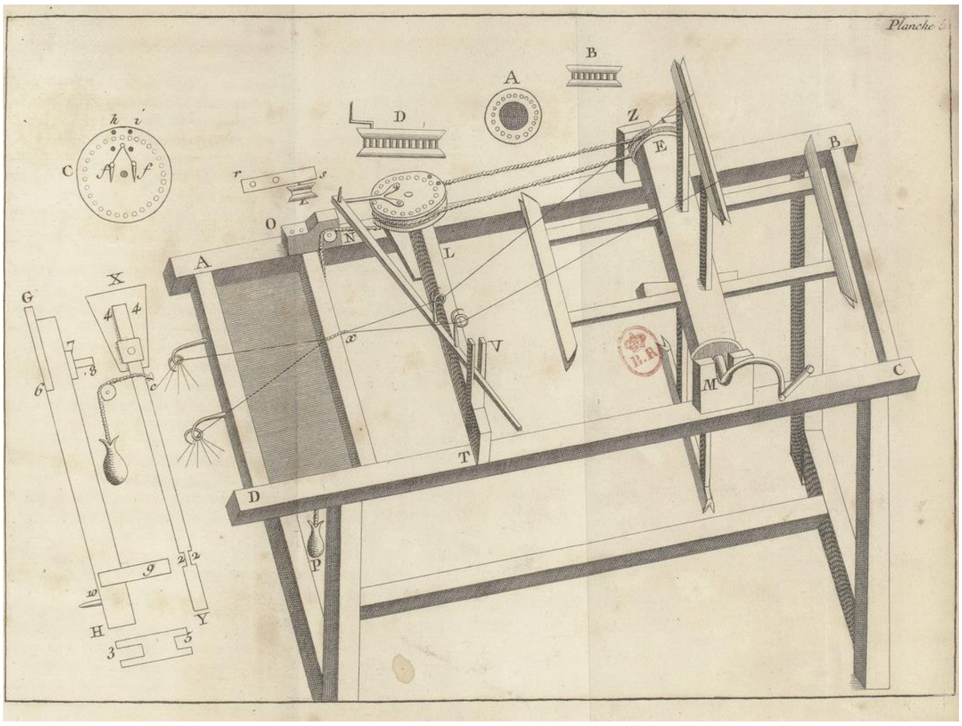


Figure 3.16: Engraving of an 18th century reeling frame equipped to reel silk " à la croisade (Pomier 1754, 5)

The most extreme example of this is “Mr. Vaucanson’s reel” (Figure 3.17), which uses a rocking arm rather than a cam-driven ramping-board, and a complex system of wheels to facilitate a double-twisted thread crossing, which may be considered an extension of the Piedmont method. This device is truly outside the scope relevant to the medieval silk industry but represents an important point in the history of European silk-reeling mechanisms where the devices are far enough removed from the forms of earlier devices that they may no longer be recognisable.

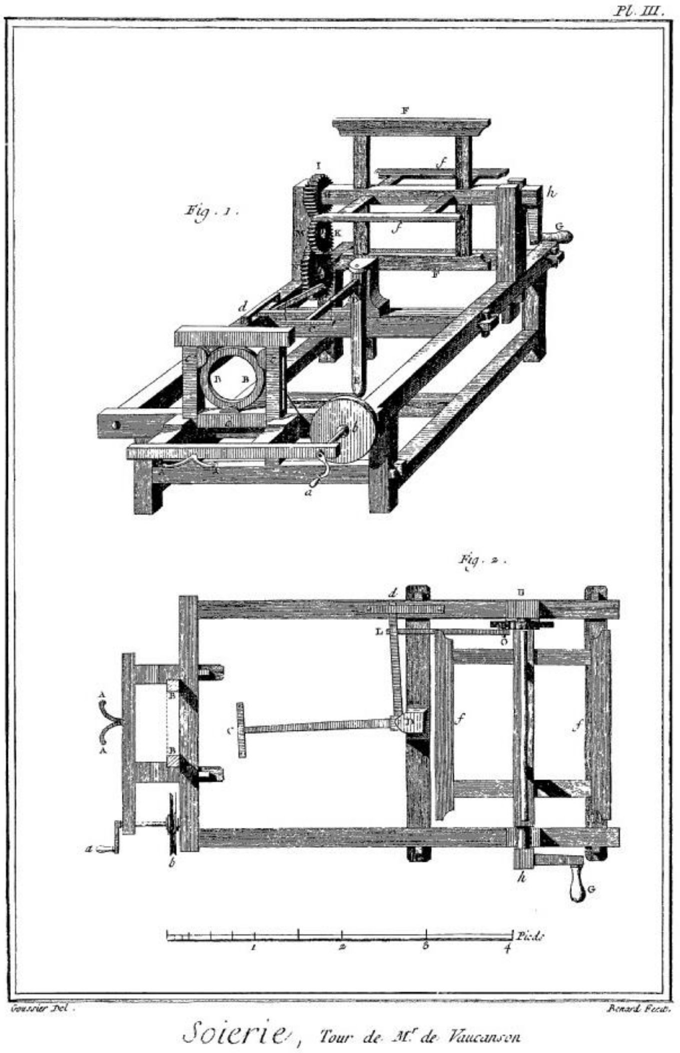


Figure 3.17: Engraving of "Mr. Vaucanson's Reel" (Diderot and D'Alembert 1751, III)

Figure 3.18 provides an example of Kuhn's use of later images to depict Song, or pre-Song reeling devices. In this case the reel is less important, and the focus is the small cage roller affixed over the water pan, around which the strand of silk is wrapped during the reeling process (this may be the earliest form of roller frame).

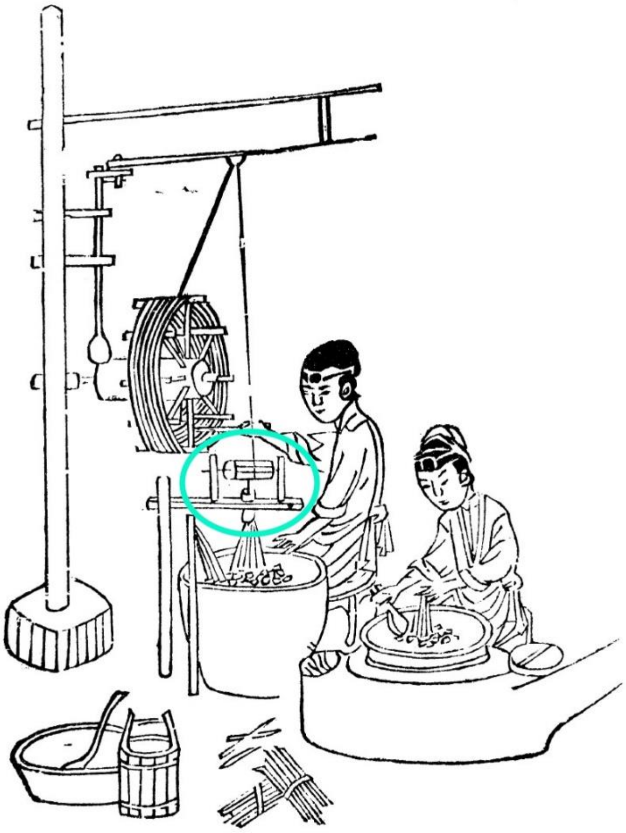


Figure 3.18: Woodblock print from the Bin feng guang yi depicting a simple roller frame (circled in green). (After Kuhn 1988, 380)

Both Kuhn and Zhao argue that versions of this roller frame (in some cases with 2 rollers) date to at least the Song dynasty if not earlier (Kuhn 1988, 379–384; Zhao 2020, 3/16). As Zhao has pointed out, this style of cage roller has continued in use in many countries in southeast Asia (Figure 3.19). In some cases, only the roller frame is used, and the operator pulls the strand from this roller cage into a basket at their feet (Figure 3.20). This style of roller does not appear to have been adopted in Europe, and therefore may be an important technical distinction between Chinese and European silk-reeling methods.

Silk processing from Cocoon to Golden silk

Figure 3.19: Screenshot from a Youtube video showing an example of a cage roller in use in Cambodia (Sok, 2016)

ก่อนจะเป็นผ้าไหมทอมือ - Silk Weaving

Figure 3.20:Screenshot from a Youtube video showing a basket of loose raw silk, just pulled from a roller (Queen Sirikit Museum of Textiles, 2016)

Meanwhile, further refinements of the treadle-operated silk-reeling device took place in China, the apogee of which might be considered the so-called “complete silk-reeling frame” (Kuhn 1988, 390), which incorporated all guides, rollers, and other parts onto the main body of the reeling frame, rather than affixing them to the water pan (Figure 3.13).

Parallel to this innovation, several simple, hand-operated devices are depicted in Chinese artwork from the 17th century onward. As has been discussed in Chapter 2.1, Kuhn used these Chinese examples in combination with some Japanese examples as pictorial aids to describe a simpler, intermediary style of reeling device that he believed was used prior to the development of the Song-dynasty treadled reeling-frame, and argues that these devices represent a continuity in the use of simple reeling equipment developed prior to the Song dynasty. Kuhn’s argument was based partially on the idea that there was a continuity between earlier forms of reeling device and those used particularly in more rural or cottage-industry settings, rather than workshops. I would argue that the case for continuity of form is more straightforward in the Japanese examples, as the treadle-operated silk-reeling device and other similar variations do not appear to have been adopted in Japan, and a more fruitful study in this context would need to take into consideration the scale of Japanese silk production throughout history, while also assessing more minute variations in form.

The continued use of certain silk-reeling tools up to the modern day brings this silk-reeling equipment chronology full circle. While there is a clear chronology that can be understood through the study of these historical depictions of silk-reeling equipment, the continuity of some of the simplest equipment forms is not only poetic, but extremely useful when trying to understand the mechanics of medieval silk-reeling devices that only survive through illustrations.

3.2.2 Devices for twisting silk

The silk processing catalogue features numerous wheel-driven devices that could be used to twist silk. Images from the Han dynasty (Figure 3.4) are more firmly linked directly to silk. Figure 3.4 is one of the earliest Chinese images of the device referred to as a spindle-wheel by Kuhn, or a throw wheel by Burnham. The mechanics of this device – a wheel connected by a drive band to a spindle with a whorl of a much smaller diameter than the wheel– appear to have changed very little between the Han and Song dynasties, although the arrangement and proportions of parts have. Early European forms (Figure 3.21) of what is often referred to as a "great wheel" or "walking wheel" are generally accepted to be the predecessor of the post-medieval, treadle-driven spinning wheel.

Figure 3.21: Detail from British Library Royal MS 10 E IV, f.137r depicting a medieval great wheel in use (Anon c.1300-1340)

Mechanically, the European medieval wheels function identically to the Chinese spindle-wheel. Prior to Burnham and Kuhn's research regarding the spindle-wheel, the proto-spinning wheel was described as having been invented in India (Lemon 1968, 87). Slightly more recent scholarship suggests that this technology was introduced to India around the 12th century (Khan 1996, 723), which does not exclude the country from having played a role in the introduction of the early spinning wheel to medieval Europe c. the 13th century (Crowfoot, Pritchard and Staniland 2006, 17). The European examples all appear to depict the spinning of wool, rather than the twisting of silk, and the proportions and method of construction distinguish these mechanisms visually from the examples from China and other parts of Asia. The apparent adaptation of a device originally used to twist silk and plant bast fibres to the spinning of wool is not surprising, particularly in an English context, given the importance of the wool trade in medieval England. This leaves the question of whether the great wheel –associated with spinning discontinuous textile fibres in medieval Europe –was subsequently re-adapted to the purpose of twisting silk, when silk processing as an occupation took hold in late-medieval Europe, particularly in England and France (Lacey 1987, 187). Furthermore, while the study of the introduction of this device to medieval Europe often separates the connection between the predecessor of these wheels and silk, it may be worth asking whether the association between silk and this type of wheel-driven twisting device was fully severed at the time of its introduction.

3.2.3 Frames for managing yarn

Skein winders (for transforming yarn on spindles or bobbins into skeins that may be washed, degummed, and dyed different colours) and swifts (for tensioning skeins of yarn after they have been removed from a reel or winder) can be easily overlooked in the study of textile production. These simple devices can be essential to textile production, as they keep all types of thread, yarn or reeled filament from tangling and becoming unusable. In terms of form, a 4-armed frame appears most common, and can be seen in the Han dynasty reliefs depicting silk processing (Figure 3.4), up to the range of devices depicted in late-medieval manuscripts (Figure 3.22).

Figure 3.22: Detail from illuminated manuscript showing a 4-armed skein frame (François c. 1475)

3.3 Construction Planning

3.3.1 Mechanism tests

While the simple silk-reeling devices depicted in the compiled catalogues are fairly straightforward in construction, some components of late-medieval and early-modern depictions of reeling devices required interpretation. Two specific parts first pictured in Chinese sources from 1200-onwards merited preliminary testing:

1. A moveable ramping-board (typically connected to the silk reel by a drive-band)
2. A treadle to drive the rotation of the silk reel

The absence of clear depictions of silk-reeling devices from medieval Europe necessitated the use of post-medieval European sources as a touchpoint reference for the construction and function of these parts. European silk-reeling devices depicted from the 16th century onwards (Figure 3.14) are visually and functionally similar to earlier Chinese devices (Figure 3.6), and typically include a moveable ramping-board, but compilation of the image catalogue revealed that most European depictions do not include a treadle, and the devices are instead shown to be cranked by hand. These similarities show an interesting continuity, and emphasise the importance of medieval Chinese silk reels as a base mechanism model. It was therefore essential to explore the mechanics of Chinese reeling mechanisms, as they appear to represent the most intricate examples of silk-reeling equipment in use during the Middle Ages.

Chinese depictions of reeling devices are typically very detailed, but due to image degradation, and/or obscured elements (see treadle in Figure 3.6) there remain some informational gaps. Other researchers have produced reconstruction drawings and 3D renderings based on early pictorial depictions and descriptions of medieval Chinese silk-reeling mechanisms (Hsiao, Chen and Yan 2010; Hsiao and Yan 2014; Kuhn 1988; Golas 2015) that may inform the design process, but these reconstructions are not always true to the original imagery. Given the potential for pitfalls in interpretations of historical mechanisms it became apparent that a method of testing the mechanics of the Chinese reeling devices was required before designs for full-sized wooden reconstructions could be finalised. K'NEX brand modular construction toys provided an efficient way to carry out these preliminary tests due to their ease of assembly and reconfiguration as needed.

Miniature reeling devices were assembled based on a surviving 13th-century depiction of a silk-reeling device attributed to Liang Kai (Figure 3.6), and reconstruction models (Figure 3.23, Figure 3.24) based on an illustration of a silk reel from Wang Zhen's *Nong shu,* originally published in 1313 (Hsiao, Chen and Yan 2010, 280) with subsequent editions published in later centuries (Kuhn 1988, 447).

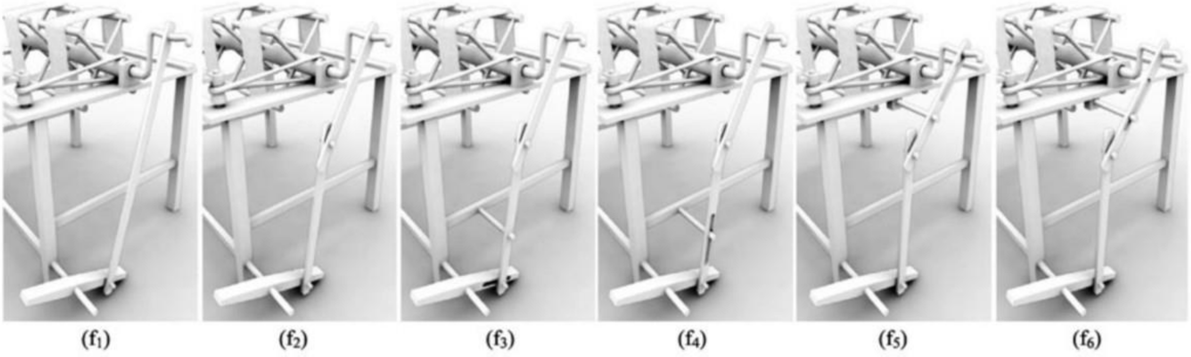


Figure 3.23: Theoretical (3D-modelled) reconstructions of the treadle mechanism depicted in Wang Zhen's Nong Shu (Hsiao et al. 2010, 284)

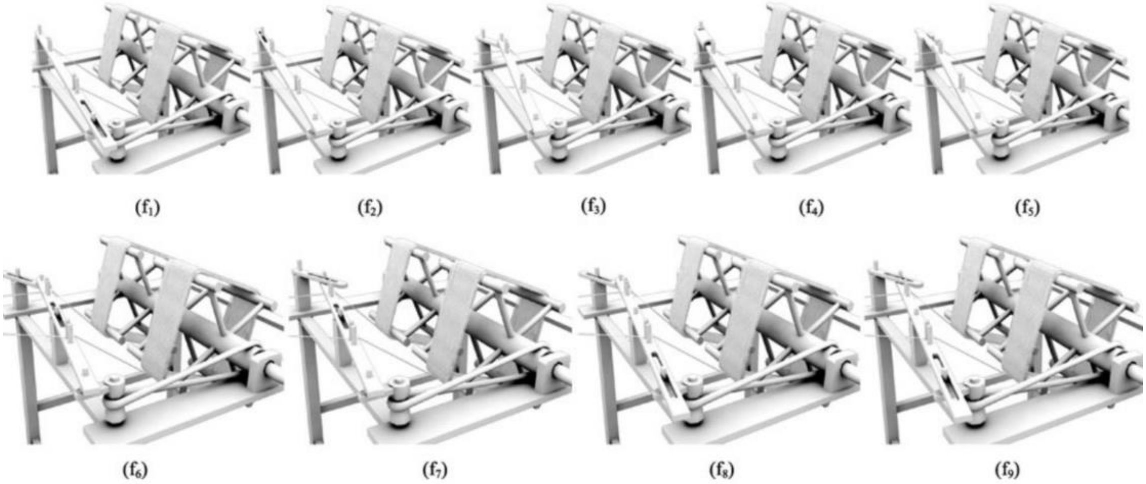


Figure 3.24: Theoretical (3D-modelled) reconstructions of the ramping-board depicted in Wang Zhen's Nong Shu (Hsiao et al. 2010, 287)

Hsiao et al. do not specify which edition of the *Nong shu* their diagrams come from, however their redrawing of the device (Figure 3.25) closely resembles a diagram from the 1530 edition (see Cat. 8), meaning that this depiction may not be accurate to Yuan dynasty (1271-1368 CE) reeling devices.

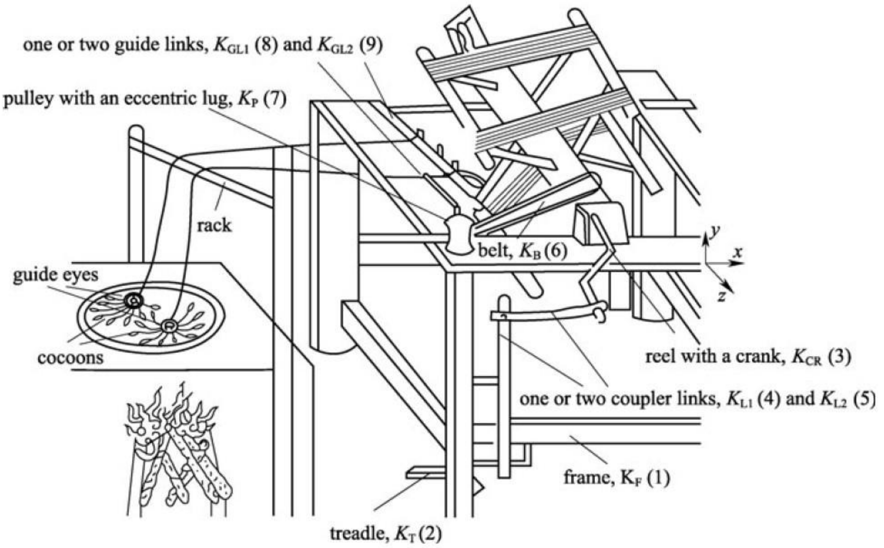


Figure 3.25: Annotated redrawing by Hsiao et al. of a treadle-operated silk-reeling device from an unspecified edition of Wang Chen's Nong Shu (Hsiao et al 2010, 280)

3.3.1.1 Method

After each model was assembled, it was photo-documented (Figure 3.26) and tested for functionality; the determining factor of functionality being whether the parts moved as intended. In cases where the model did not function, but modifications could be made to improve function, these modifications were made, noted, and recorded photographically in the event of significant modification. The functionality of the modified model was then re-tested and noted.

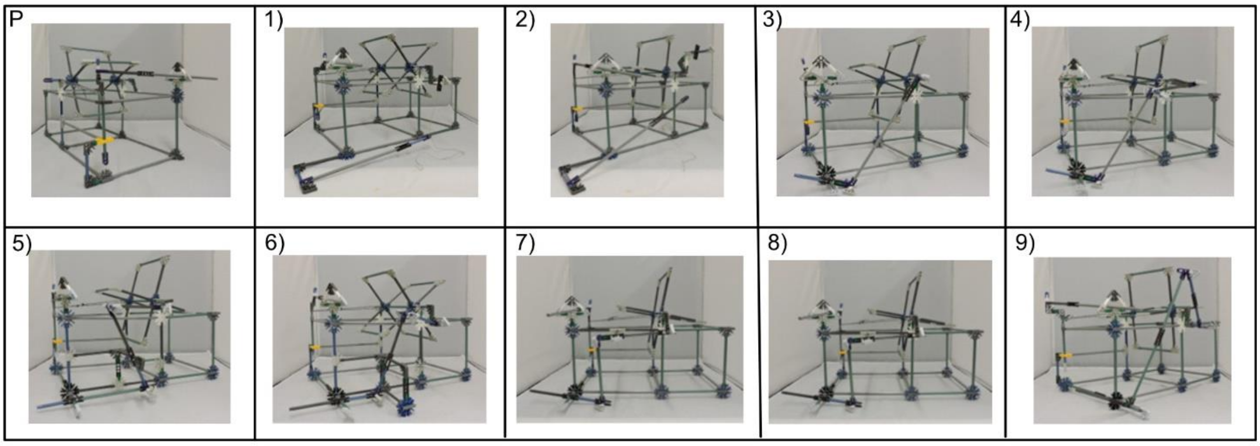


Figure 3.26: the Mechanical forms tested during each K'NEX trial. The preliminary construction test is labelled P (Source: the author)

3.3.1.2 Constraints

1. K'NEX have a limited number of standard piece lengths and sizes, which restricted the degree of fine-tuning that could be achieved during the mechanism tests, and in certain cases affected the scale accuracy of the trial models. This was partially mitigated with minor modifications to certain pieces, but this form of modification was not carried out in excess as it would undermine the structural integrity and potential for reuse of the K'NEX pieces.
2. The pieces tended to slip at joints, which inhibited the function of the replicated crank mechanisms. This was particularly problematic in instances where extra resistance was added to the reel, as was the case following the addition of a drive band connecting the reel to the ramping-board.

3.3.1.3 Results of the K'NEX Mechanism Trials

Despite the limitations of K'NEX as a construction material, the trials did indicate which styles of silk-reeling mechanism were best suited for full-scale replication (Table 3.1). Trials 1, 2, and 9 (See Appendix C) showed the greatest potential for success as full-scale wooden models. The results from trials 1 & 2 were particularly promising, since the models were more closely based on 13th-century source material.

The pattern of failure or requirement for extensive reworking during trials of the reconstructions proposed by Hsiao et al. (2010) suggests that many of the reconstructions are impractical and, in several cases, completely non-functional. Additionally, the slotted sections preferred by Hsiao et al. (Figure 3.23) do not appear to be reflective of the Chinese source material. The success of Trial 9, and a comparison of this mechanism with the illustration from the 1530 *Nong Shu* (Figure 3.8) suggests that the use of a lower connected rod, affixed at a 90° angle to the treadle may more closely reflect the structure of the treadle-crank mechanism depicted in the *Nong Shu,* although it has to be acknowledged that the treadle details in this image are somewhat unclear.

Trial #	Based on	Desired movement	Was movement successful?	Required modifications	Suitable for full-scale replication?
1	13th century handscroll	Side to side movement of ramping board	Partially	Materials	Yes, with modification
2	13th century handscroll	Rotation of reel	Partially	Materials	Yes, with modification
3	Hsiao et al. 2010	Reel rotation & Ramping board movement	No	N/A	No
4	Hsiao et al. 2010	Reel rotation & Ramping board movement	No	N/A	No
5	Hsiao et al. 2010	Reel rotation & Ramping board movement	No	Nature of treadle movement	No
6	Hsiao et al. 2010	Reel rotation & Ramping board movement	No	Nature of treadle movement, or (possibly length of treadle slot)	No
7	Hsiao et al. 2010	Reel rotation & Ramping board movement	No	Possibly length of slotted reel crank connection	Not without further trials
8	Hsiao et al. 2010	Reel rotation & Ramping board movement	No	Possibly length of slotted connection	Not without further trials
9	Hsiao et al. 2010; Nong Shu (1530)	Reel rotation & Ramping board movement	Yes	Materials	Yes, but chronology is uncertain

Table 3.1: Results of K'NEX silk mechanism trials 1-9.

The constraints caused by the material qualities of the K'NEX combined with the restrictive nature of their set lengths prevented these experiments from functioning as perfect replicas. That said, the process of reconstructing these mechanisms while working within the limitations of the K'NEX parts was a useful exercise in analysing the moving parts of the historical Chinese mechanisms and in working within the restrictions of a given material. This process also informed the planning of the full-scale wooden reconstructions by highlighting which characteristics of wood make it a desirable material for constructing these devices, and, most importantly, it has helped to determine which theoretical reconstructions are unlikely to function regardless of material, and which may function when fashioned out of wood, but ultimately are less practical considering the degree of effort and further experimentation required to make them function. Ultimately, the K'NEX models confirmed that the style of reeling device depicted in 13th-century handscroll was suitable for reconstruction.

3.4 Rationale for Equipment selected for Construction

Once these images had been compiled and studied, the next challenge was in determining how the silk-reeling mechanisms should be constructed at full scale. This led to the first set of practical trials.

Given gaps in information regarding silk equipment used during the early Middle Ages, particularly in Europe and the mediterranean, the types of reeling frame to be constructed were narrowed down to 2 basic forms:

1) A simple hand-cranked reel of the style that Kuhn suggested may have predated more complicated Chinese mechanisms, modelled after early-modern and modern source material.
2) A large reel with ramping-board and removable treadle, modelled after the 13th-century handscroll attributed to Liang Kai (Figure 3.6). When hand-cranked this reeling frame functions in the same way as the 16th-century reeling device depicted by Giuseppe Arcimboldo (Figure 3.10).

By choosing to construct these 2 styles of base reeling frame, it was possible to account for a broad geographic region, and a time span that extends beyond the Middle Ages.

A decision was made to construct the following additional reeling accessories:

1) The soundless-roller which, as previously mentioned, may predate the Song dynasty (960-1279CE), and continues in use in contemporary Thailand, Laos, and Cambodia.
2) The double roller frame, which, depending on the number of rollers used can be linked to reeling methods in China from the 12th century on, and (to some extent) a thread-crossing method in use in 16th- and 17th-century Europe.
3) The double-eyed copper-wire thread guide, which when used without crossing the threads allows for the 16th-century reeling method depicted by Arcimboldo (Figure 3.10), and if used to cross threads allows for the "Piedmontese" crossing method, which was certainly in use by the 18th century (Pomier 1754, 221) but has an uncertain chronology regarding its origin.

The construction of a simple reel and a more complicated treadled reeling-frame along with the 3 accessories described above allowed for a high degree of flexibility in experiment design, which accounted for regional and chronological specificity between different experiments.

In selecting the equipment to be used for silk throwing, the decision was made to construct the most commonly occurring tools:

1) A set of three 4-spoked bobbins;
2) a throwing rod;
3) a spindle-wheel, and;
4) a swift/skein frame.

The choice to construct 3 bobbins was based on descriptions of throwing processes by Kuhn and Burnham, which involved the twisting together of 2 or 3 reeled filaments at a time (Burnham 1968, 50–52; Kuhn 1988, 405). Of the throwing tools, the skein frame presented the highest number of possibilities in terms of design. Ultimately a 4-armed, horizontally oriented design (Figure 3.27) was selected. This style of swift, termed the "*Chekiang-Kiangsu* type" by Kuhn, appears to have been in use across a broad timespan and in many regions during the Middle Ages.

As the name suggests, this device is associated with Kiangsu and Chekiang provinces (or Jiansgsu and Zhejiang) on the Eastern coast of China, having been depicted in a 13th-century scroll by Liu Songnian (Kuhn 1988, 176). Stretching earlier and farther west, a strikingly similar swift was found in the Oseberg ship burial dated to the 9th century (Hoffmann 1964, 295; Walton Rogers 2007, 26), while similar swifts are also depicted in later medieval sources (Figure 3.28), suggesting this was a practical design for the purpose of holding skeins. The swift constructed for these experiments was based structurally on this style, but was not a direct replica of any one depiction, though it did incorporate adjustable tension pegs, as can be seen in the Oseberg swift (Figure 3.29)

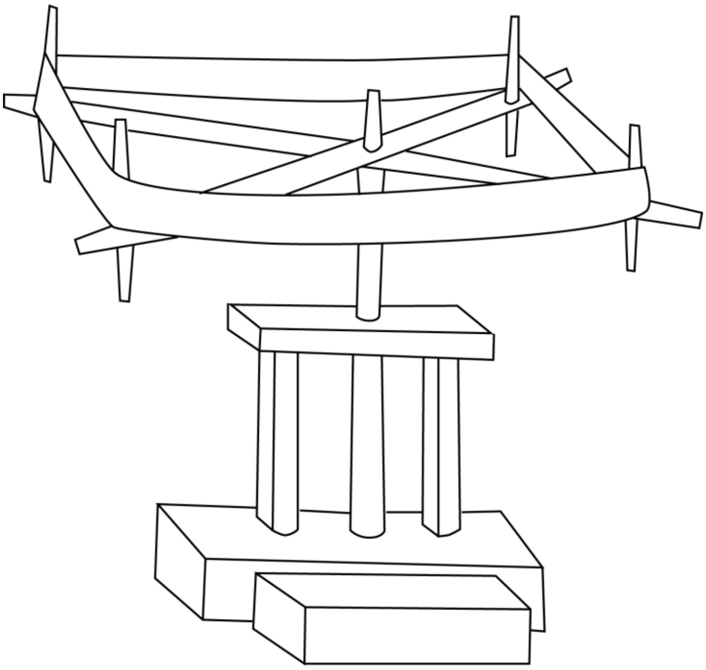


Figure 3.27: A horizontally-oriented swift of the "Chekiang-Kiangsu", after a 13th century scroll by Liu Songnian, held in the National Palace Museum, Taipei. (Source: the author)

Figure 3.28: 15th century swift from an anonymous French translation of Giovanni Boccaccio's De mulieribus claris, *Illuminated by Robinet Testard* (Boccaccio 1488)

Figure 3.29: Fragments of the swift or yarn winder form the Oseberg ship burial © Museum of Cultural History, University of Oslo, Norway (Anon 2007)

3.4.1 Equipment Selected for Construction

- Treadle-operated silk-reeling frame
- Hand-operated reeling frame
- Soundless-roller
- “Butterfly eyebrow” roller frame, with upper and lower rollers
- Copper-wire “eyes”
- Spindle-wheel
- Three 4-armed wooden bobbins
- 20+ Cylindrical bamboo bobbins, c. 5mm in diameter
- Throwing rod (handle) for bobbins
- Skein frame (swift)

3.5 Measurement synthesis

Once the mechanisms were clarified, the next puzzle was determining the scale of these tools and their components. It quickly became clear that a method for estimating the dimensions of the equipment was needed before detailed measured plans for silk-reeling mechanism reconstruction could be produced.

There are 3 key types of evidence that can provide information on the scale of medieval silk-reeling devices:

1. Silk-processing equipment uncovered from the archaeological record
2. Historical textual sources
    a. Sources that provide detailed measurements of silk-reeling parts appear to be exclusively Chinese. Given the language barrier, Kuhn’s (1988) research on Chinese silk-reeling mechanisms is a crucial source of translation.
3. Pictorial sources: European and Chinese Illustrations of silk-reeling equipment are extremely useful in understanding the scale of silk-reeling mechanisms.

Calculating the dimensions of medieval silk-reeling frames based on these 3 types of source material has proven to be challenging, due to the following factors:

1. A relative lack of physical evidence for silk-reeling equipment from the archaeological record;

2. Ambiguity in the translation of information on the dimensions of silk-reeling devices from medieval Chinese texts;
3. Uncertainty of the accuracy of scale when interpreting medieval illustrations of said equipment.

The information that can be gleaned from the 3 types of sources described, and the results of navigating the challenges listed above are addressed in the following sections.

3.5.1 The archaeological evidence

The most applicable piece of archaeological evidence for silk-reeling equipment is a 4-armed bobbin or reel (Figure 3.5) dated tentatively to the Jin dynasty (265-420 CE), which was found during an excavation at Xinjiang (Kuhn 1988, 171). Kuhn gives a measurement of 19.8 cm for the length of the object, but no other dimensions are noted (Kuhn 1988, 173).

3.5.1.1 Drawbacks

The main drawback in relying on archaeological evidence for silk-reeling mechanisms is an apparent lack of clearly identified silk production tools in the archaeological record. The bobbin or reel from the Jin Dynasty could arguably have been used as a bobbin for winding other yarns, but this object at least matches pictorial evidence for the bobbins and reels used in silk production, and therefore provides insight on the construction details of these objects. This object in isolation does not indicate a standard size for Jin dynasty bobbins and winders, let alone reels from later time periods, and it is unknown whether, at nearly 20cm long, this object represents a small reel, or a large bobbin, and whether the size of this object is anomalous or representative of other objects from the same era. Ultimately there appears to be little surviving archaeological evidence for styles of silk reels depicted in medieval Chinese illustrations.

3.5.2 Historical Chinese sources

Kuhn’s (1988) writing on medieval Chinese silk-reeling mechanisms references several contemporary Chinese sources on silk-reeling. Regarding the dimensions of Song dynasty (960-1279 CE) reeling devices, Kuhn provides a translation from the Yuan dynasty (1271 to 1368) source, Wang Chen’s *Nong Shu* (c. 1313), which in turn quotes the *Nong Sang Zhi Shuo* published between 1100-1300 CE:

“The pan (*ting*) is placed some thirty cm below the frame of the reel. The reel has a length of about 60cm, its diameter in the middle is nearly 12 cm, and at the ends of both sides about 6 cm. Elm (*yü*) and *Sophora japonica* (*huai*) are used to make the 4-or 6-sided reels. The length of the spokes is about 105 cm.” (Kuhn 1988, 365)

It should be noted that the units of measure were converted to centimetres by Kuhn during the translation process, which means that the measurements presented are one step removed from the *Nong Shu*, which is itself a secondary source to the original written record, and a tertiary source on the equipment being described. As presented in the above quote, the given dimensions are somewhat difficult to parse. The described position of the pan is clear, although whether the measurement given refers to the distance between the top of the pan and the base of the reel frame, the top of the pan and the top of the reeling frame, or some other configuration is unclear. More confusing are the dimensions of the reel as written. Given the distinction Kuhn makes between the term “reel” and the term “reeling frame”, it seems prudent to interpret the measurements in the quote as referring to just the reel, rather than the whole frame, meaning the dimensions given likely refer to a silk-reeling part that would resemble the Jin dynasty reel/bobbin (Figure 3.5) at a significantly larger scale. If the first set of dimensions given refer to the reel when viewed end-on, then this would describe a reel with a diameter of 60cm, with an axle diameter of c. 12cm, and cross-piece diameters of c. 6cm. Kuhn used the term “spoke” which might suggest the pieces that protrude from the axle of the reel, but from context appears to refer to the cross-pieces that connect the spokes, meaning the measurement of 105cm would apply to the length of the reel (Figure 3.30).

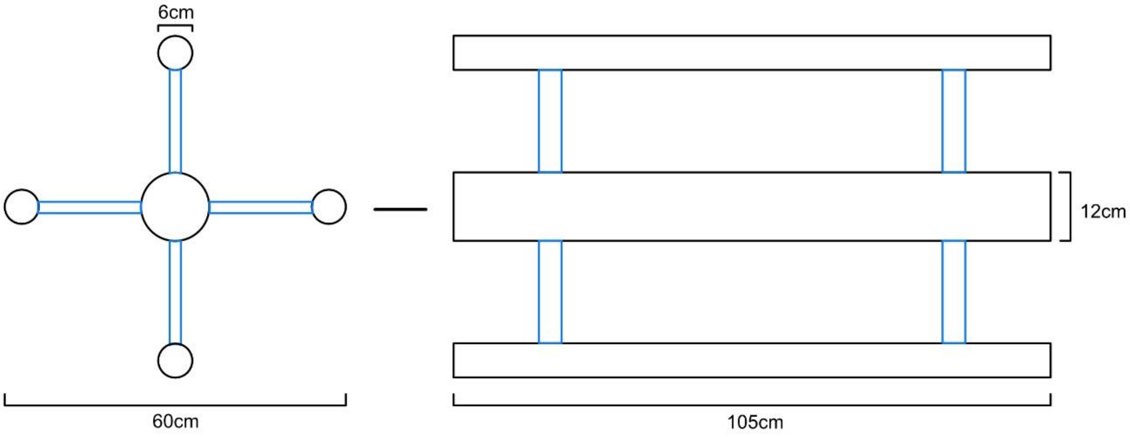


Figure 3.30: End-on view (left) and front view (right) of proposed reel dimensions based on Kuhn's translation. Parts for which no measurements were given are drawn in blue. (Source: the author)

Only a few other measurements of silk-reeling equipment are provided by Kuhn; the soundless-roller frame (Kuhn 1988, 382) dated to 1899 apparently sat 16-19cm above the rim of the reeling pan. It was held up by one upright stake, which was square in cross-section and measured 4.8cm across. The cross bar, also square in cross-section, measured 4.16cm across, but the length is not specified. It had a small hole drilled through it and a bamboo tube 9-12cm long fit snugly inside. The diameter of the hole and tube is not specified but is described as smaller than a bean. Two uprights attached to the crossbar held the roller; these were 12.8cm long and spaced 9.6cm apart. The roller itself is described as having 2 round end-pieces made of gourd that measured 3.2cm in diameter. These pieces were joined by fine lengths of bamboo to make a hollow cage-spool. The joining pieces are also described as measuring 9.6cm long, which seems unlikely, as this would mean that the spool would fit too snugly between the uprights to turn.

The final measurement, taken from the *Nong shu* (1313) is the length of the bamboo spindle (or quill of a quilling wheel) which is described as measuring 12.6cm long, and which Kuhn notes is shorter than the length of a spindle used to add twist (Kuhn 1988, 183).

3.5.2.1 Pitfalls

Reliance on translations

It would be preferable to consult the original works that Kuhn's translations come from. This has been precluded first by language barriers, but also by potential for access, as many of these sources have not been widely reproduced even in their original language.

Limited measurement detail

The measurements provided refer to only a few parts of a silk-reeling apparatus. It is unclear whether this is a result of limited focus on dimensions from the original authors, or selective translation on the part of Kuhn. Access to more thorough translations of these works would help illuminate this issue.

3.5.3 Estimated Measurements Using Open-source Image-Processing Software

While historical images of reeling devices can provide an approximate sense of scale, deriving specific measurements from such sources presents a particular challenge.

Using hand-drawn historical imagery with unreliable perspective and uncertain scale is not conducive to calculating accurate measurements. That said, trends in the overall size of a device in relation to the operator can be observed, and some estimates may be made based on this visual information. Image-processing software can be used to take measurements from scale-calibrated images, and it was concluded that it may be possible to derive measurement estimates by calibrating these historical images to a particular scale. An experimental approach was devised to test whether open-source image processing software could be used to set a scale and record the dimensions of illustrated silk-reeling devices and, whether a reasonable average of the recorded measurements could be determined, with the aim of using the averaged measurements as base dimensions for a set of measured plans.

3.5.3.1 Parameters

Only images of silk-reeling devices that incorporated an operator who could serve as a scale reference were selected for analysis. For the sake of consistency and in the interest of producing equipment suited to the person who would be operating it, the author's measurements were used to establish the scale of the figures in the selected depictions.

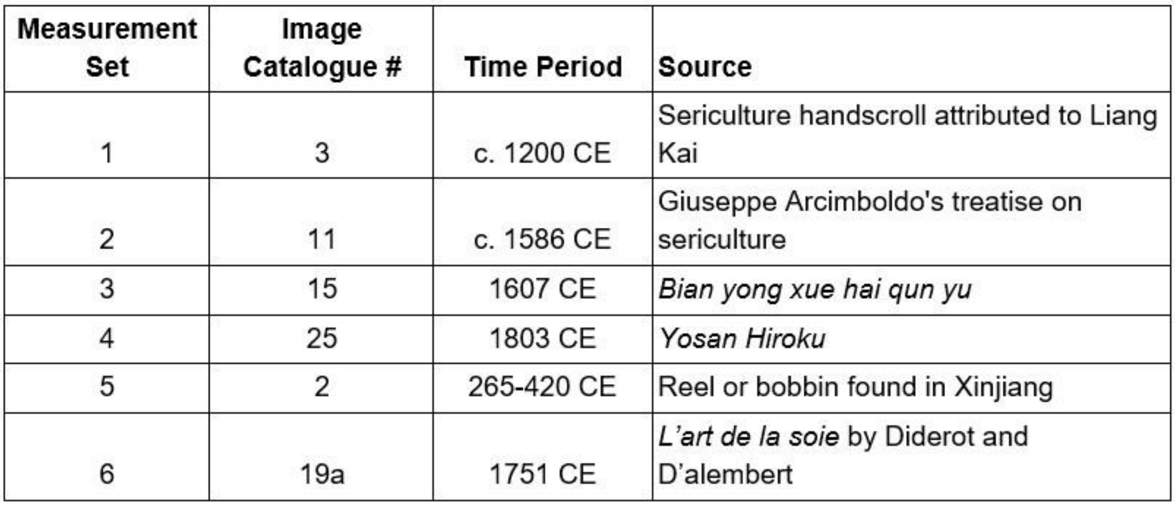
The following measurements were taken:

A) Measurement from top of head to seat of chair: 88cm
B) Hip to knee when seated: 55 cm
C) Knee to foot when seated: 46.5 cm
D) Slouched shoulder width: 43 cm

Ultimately only measurement A) could be consistently applied to the images, when factoring in the positions of each reel operator. The image processing program Fiji (ImageJ) was used to set the scale of the original images and take measurements of the silk-reeling devices depicted. All measurements were rounded to 1 decimal point.

3.5.3.2 Measurement Sets

A set of 6 images was extracted from the catalogue of reeling equipment. Five of the images were selected because they reflected a broad time span and depicted a reel operator who seemed roughly proportional to the equipment they were operating. The sixth image was selected because it depicted a surviving piece of equipment with one known measurement that could be used for calibration. The measurements taken from each selected image were compiled into measurement sets (Table 3.2).



Measurement Set	Image Catalogue #	Time Period	Source
1	3	c. 1200 CE	Sericulture handscroll attributed to Liang Kai
2	11	c. 1586 CE	Giuseppe Arcimboldo's treatise on sericulture
3	15	1607 CE	*Bian yong xue hai qun yu*
4	25	1803 CE	*Yosan Hiroku*
5	2	265-420 CE	Reel or bobbin found in Xinjiang
6	19a	1751 CE	*L'art de la soie* by Diderot and D'alembert

Table 3.2: Key of measurement sets, with corresponding image catalogue number, time-period and source.

3.5.3.3 Method

1. Each image was calibrated in Fiji by setting a calibration measurement reference on the pictured reel operator corresponding to measurement A, and substituting the corresponding measurement (this calibrated the seated figure to the author's torso height).
2. Measurements of the length of key parts of each silk reel were then taken manually with Fiji's line measurement tool.
3. The same process was repeated with the photo of the Jin dynasty reel/bobbin, using the length measurement of 19.8cm to calibrate.

3.5.3.4 Results of Measurement Interpretation

The calibrated images produced extremely varied measurements (Table 3.3), which in some cases were obviously internally inconsistent (for example, the length of the reel in Measurement Set 2 (Figure 3.32) exceeded the width of the frame). Some inconsistency was expected given the nature of these images, and carrying out this process confirmed that simply extracting measurements from any individual calibrated image and constructing a device based on said measurements would be unlikely to result in sensibly proportioned, or even functional reeling equipment. It was concluded that averaging the measurements would most likely be unhelpful, but the full range of the measurements extracted did nonetheless provide useful reference points during the design of the reeling mechanisms.

Measurement Set	Frame Height	Frame Width	Frame Depth	Leg Width	Leg Depth	Reel Length	Spoke Length	Reel Diameter	Ramping board length
1	105cm	66.6cm	61.2cm	7cm	5.1cm	33.1cm	27.7cm	67.5cm	74.3cm
2	88.6cm	65.4cm	35.5cm	3cm	6.7cm	78.7cm	15.5cm	45cm	69.8cm
3	76.3cm	44.9cm	N/A	N/A	3cm	31.9cm	N/A	8cm	N/A
4	90.7cm	74.7cm	36.7cm	N/A	3cm	52.1cm	N/A	13.7cm	N/A
5	N/A	N/A	N/A	N/A	N/A	19.8	7.8cm	10.2cm	N/A
6	70.9cm	N/A	177cm	N/A	N/A	68.1cm	N/A	N/A	N/A

Table 3.3:Key extracted measurements taken from calibrated images

It is worth noting that, even given the variability of the measurements and the need to account for inaccuracies, all reel dimensions taken were for the most part smaller than the dimensions translated by Kuhn, except for the reel diameter as depicted in Figure 3.31. This could indicate that the measurements provided by Kuhn correlate convincingly to a roughly contemporary depiction of a Song-dynasty reeling device, but given the nature of these measurements, this cannot be argued with complete certainty.

To improve the accuracy of a method like this, calculations would need to be made to compensate for perspective distortion, and the difference in the physical proportions of each reel operator depicted would need to be compensated for. Even so, the different priorities of each artist, and their own cultural and artistic context would need to be taken into consideration, as well as the conditions under which the images were produced (hurriedly sketching from life, drawing from detailed measurements, and so on.): information that is largely inaccessible.

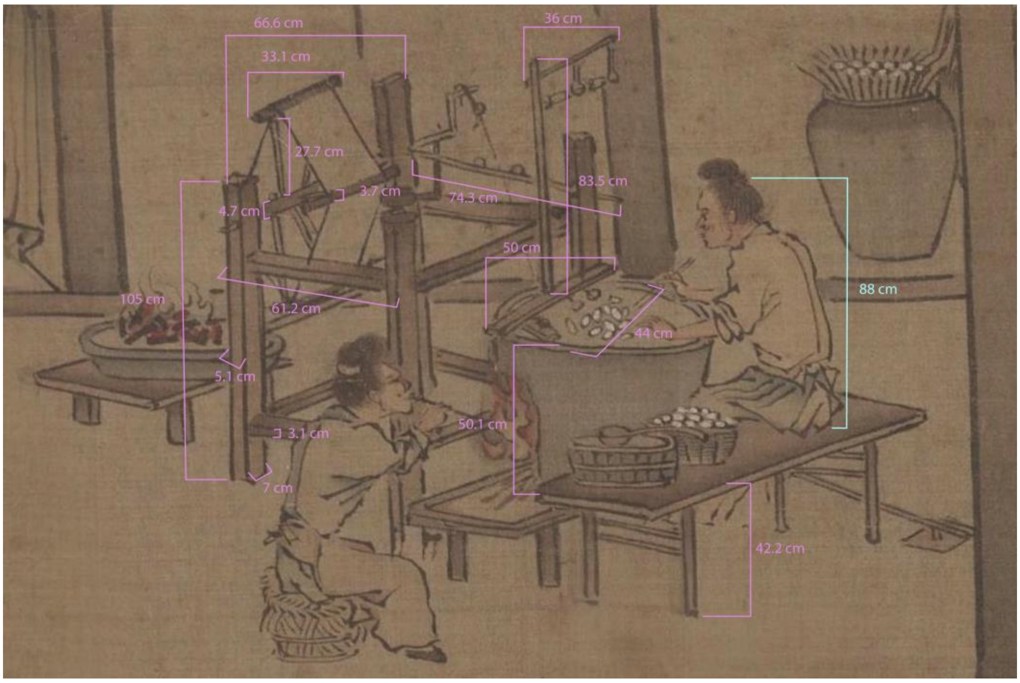


Figure 3.31:Measurement Set 1 from Sericulture handscroll attributed to Liang Kai

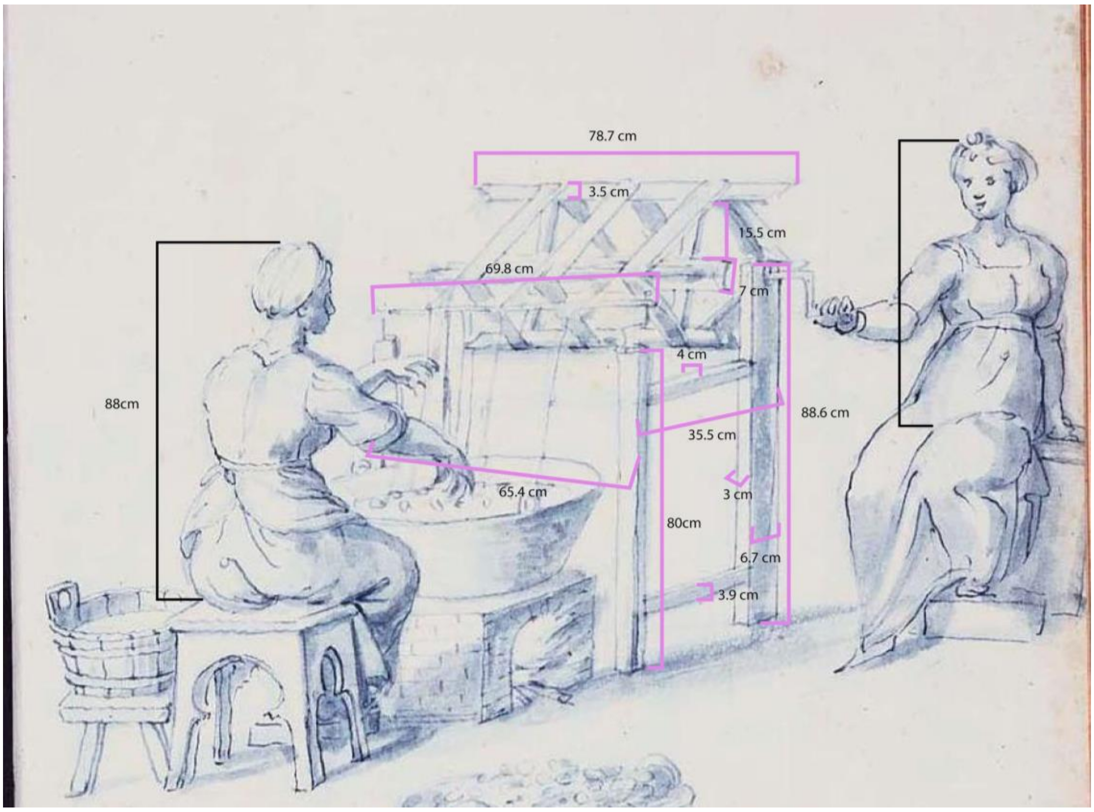


Figure 3.32:Measurement Set 2 from Giuseppe Arcimboldo's treatise on sericulture

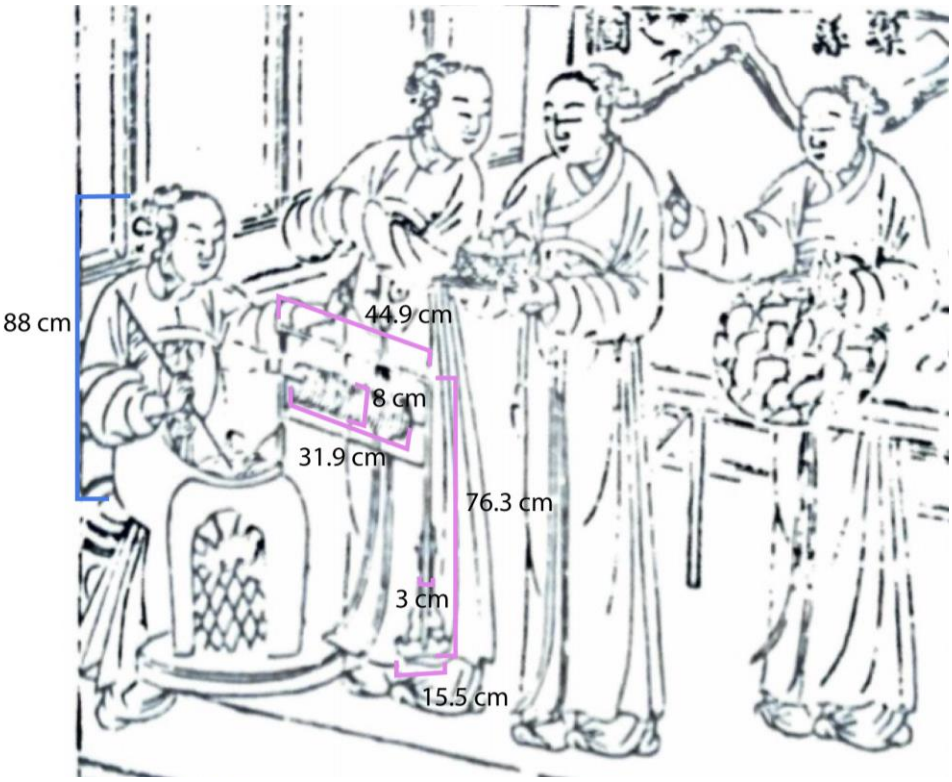


Figure 3.33:Measurement Set 3 from Bian yong xue hai qun yu

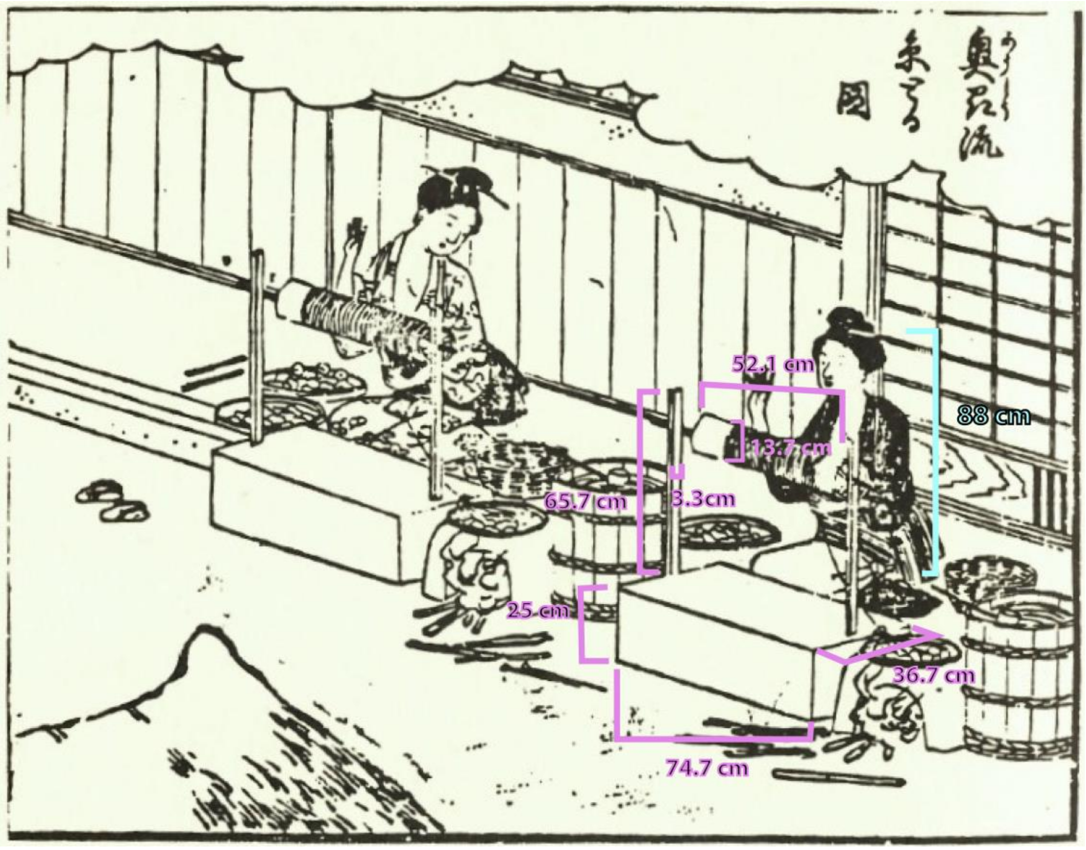


Figure 3.34:Measurement Set 4 from Yosan Hiroku

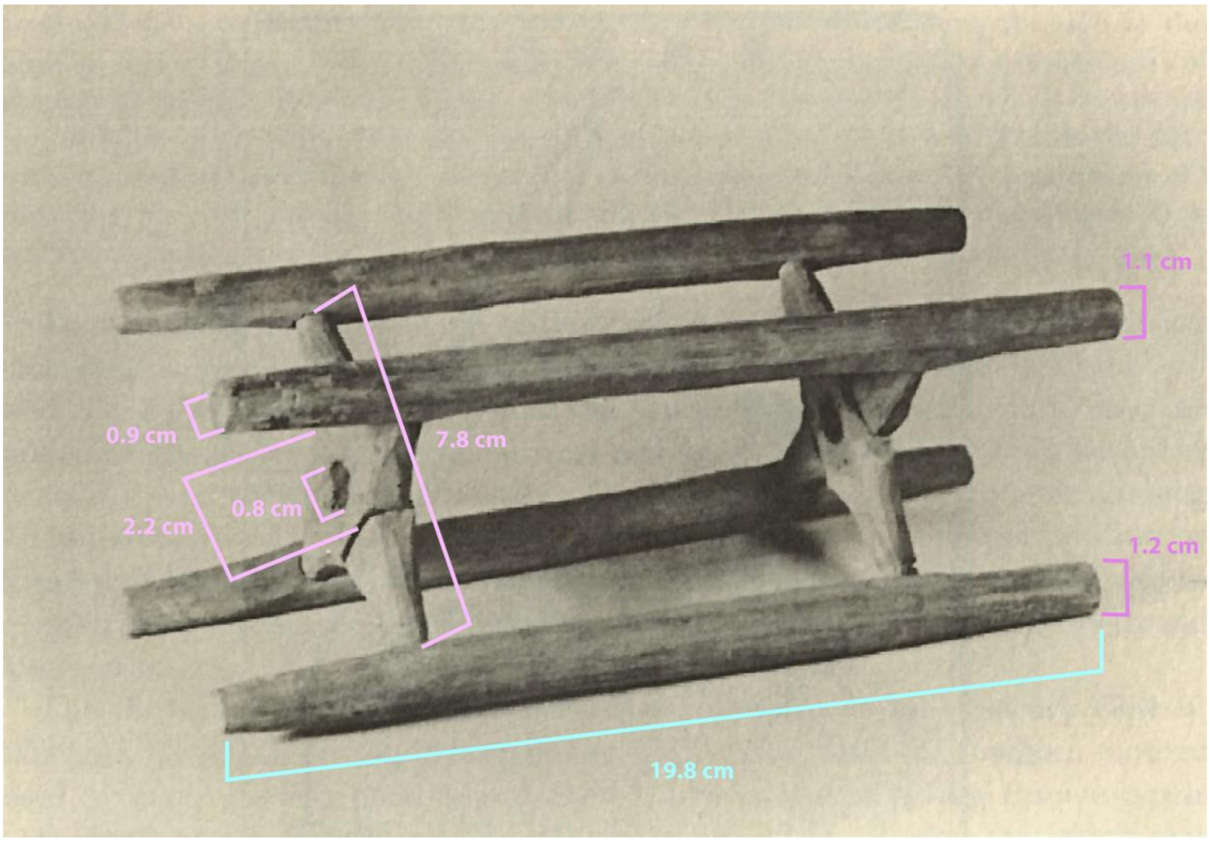


Figure 3.35:Measurement Set 5 taken from reel or bobbin found in Xinjiang

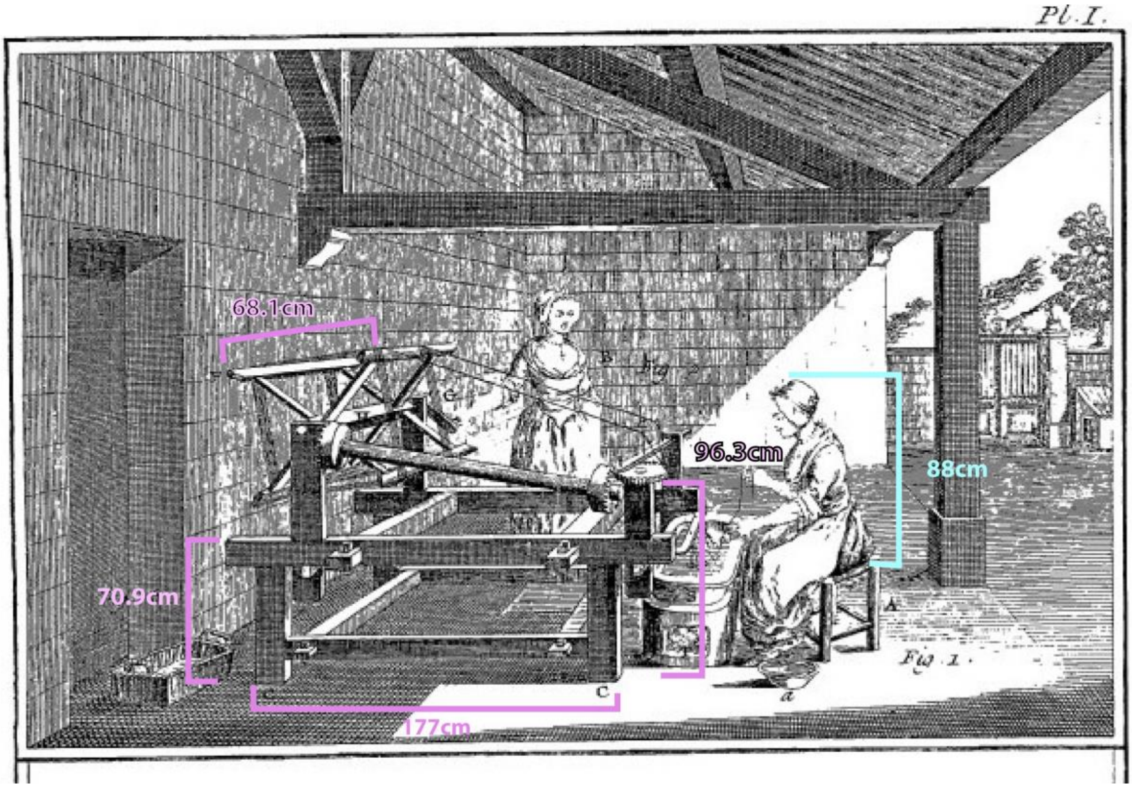


Figure 3.36:Measurement Set 6 from L'art de la soie by Diderot and D'alembert

3.5.4 Determining Final Measurements

Given the variability of measurements derived from pictorial and archaeological sources, final measurements for each piece of equipment were ultimately determined based on what would be ergonomically suitable for the reel operator, while remaining roughly within the dimension ranges derived from the measurement synthesis. Final considerations on the dimensions of the treadled reeling-frame accounted for the width of doorways in the locations where the frame would be constructed, stored, and used. A set of measured plans (Appendix D) was created to guide the construction process.

3.6 Equipment Construction

3.6.1 Materials list

- Planed square edge redwood timber, various dimensions
- Stainless steel rods 2mm diameter
- White and redwood dowelling, various diameters
- PVA wood glue
- Wooden Newel Cap
- Wooden pulleys
- 10mm x 300mm bamboo strips
- C. 200mm diameter bamboo rods
- Flax fibre (for drive band)
- Cotton twine

3.6.2 Equipment used

- Rotary Mitre saw
- Jig saw
- Handheld saws
- Pillar drill
- Hand drill
- Strap clamps
- C-clamps

3.6.3 Construction process

The methods used to construct the silk-reeling equipment were not directly based on Chinese or medieval European woodworking techniques.

This was determined to be a necessary and reasonable compromise for the sake of efficiency, as woodworking methods are not a research focus for this thesis. A dowel-and-socket method was used in combination with wood glue to produce equipment that would function in the same way as historical examples. Further modifications to this method were made using a hidden screw connections in the large reeling frame, to accommodate transportation and storage needs.

To safely construct the required equipment, workshop facility access was required. In response to a limited timeframe of access to the TSS workshop and Covid-related health and safety considerations, a "flat-pack" approach was taken while constructing the silk-reeling equipment required for the experiment. This involved pre-cutting and drilling all parts of the equipment on-site at the TSS facilities. The equipment was then assembled and finished off-site without the use of power tools, allowing for a more efficient workflow while taking appropriate precautions regarding health and safety.

Materials were selected to speed efficiency of construction; this included the selection of Plain Square Edge (PSE) timber and dowelling, both of which could be cut down to size with minimal additional finishing. Bamboo pieces were determined to be suitable for mechanism parts that required flexibility, such as the spokes of the spindle-wheel, and were also useful in constructing cylindrical rotating pieces such as the rollers for the roller frame. Prefabricated parts including small wooden pulleys and metal rods were used in the construction of the spindle-wheel quill, and the treadled reeling-frame ramping-board. The most important prefabricated piece was the wooden Newel cap, which was sliced horizontally to form the pulley section of the ramping-board cam. The alternative design for the spindle-wheel as shown in the measured plan (Figure 3.37) was selected for construction, as it was determined to be more likely to result in a stable wheel.

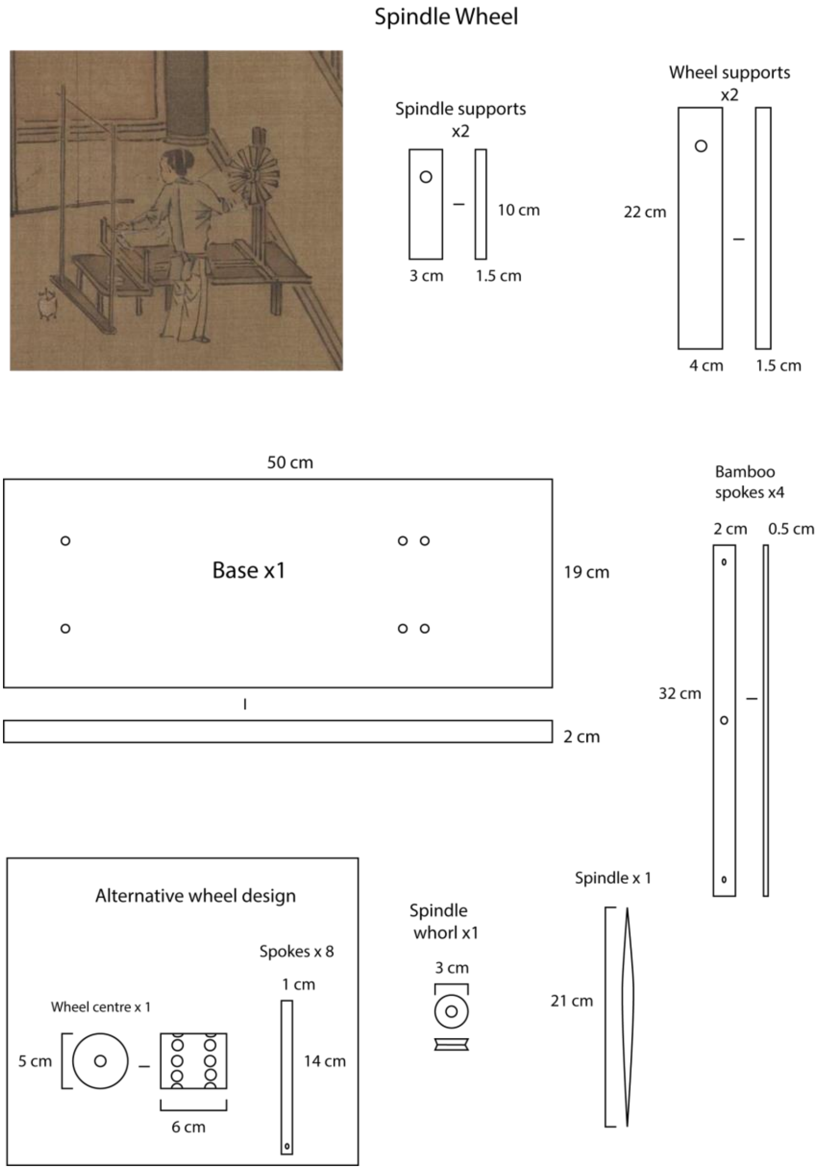


Figure 3.37: Measured plan for spindle-wheel with 2 potential styles of wheel construction (source: the author)

Sealing the reeling equipment

To reduce the risk of the wood swelling and splintering when exposed to moisture, waterproof wood finish was used on the parts of the equipment that were most likely to be exposed to water, including the reels, spools, and bobbins. This was a crucial consideration, as a splintered, uneven surface would cause the silk to catch on the wooden reels, increasing the risk of filaments breaking. Tung oil was selected as an ideal wood finish as it is non-toxic and has been used as an ingredient in waterproof sealants in China since at least the 6th century CE (Fang et al. 2014).

3.6.4 Observations

Construction of most equipment was carried out without complication, particularly in the case of equipment with fewer components such as the simple reel (Figure 3.38), bobbins (Figure 3.39), and swift (Figure 3.40).

Figure 3.38:Simple Reel in use at the YEAR centre (Photo: Eleanor Johnson)

Figure 3.39:Completed bobbins in use at the YEAR Centre (Source: the author)

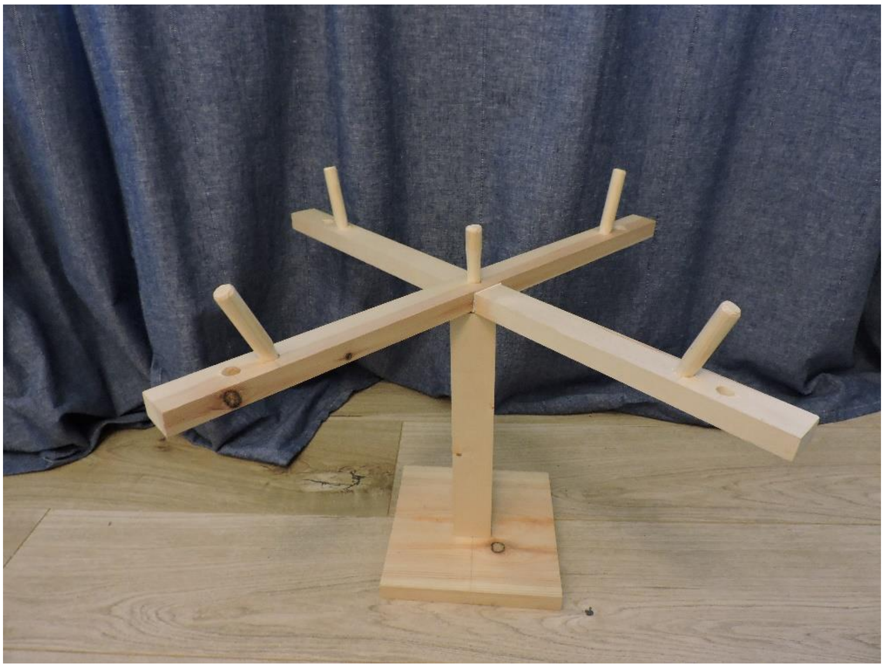


Figure 3.40: The 4-armed swift (Source: the author)

Some complications arose during the construction of the treadled silk reel (Figure 3.41), as this piece of equipment comprised the most moving parts by far. In one instance the axle of the reel was remade to correct for drilling errors in its first iteration. Hand-sanding post-construction was also crucial to finely adjust the movement of the ramping-board.

Figure 3.41:The completed treadled reeling-frame in use at the YEAR Centre (Source: the author)

Size was also an important consideration during construction, as it became clear at an early stage that the larger size of the treadled silk reel meant that it would need to be constructed in such a way that it could be taken apart for storage and transport on and off-site. A maximum exterior width of 70cm was selected for the large reeling frame so that it could fit through doors when fully assembled. The need to disassemble and reassemble the treadled reeling device resulted in a minor deviation from the appearance of historical silk-reeling apparatus of similar construction due to the inclusion of a system of bolts and locknuts in the frame. These could be unscrewed to separate the front and back sections from the side supports for flat storage and transport.

A complication with the ramping-board was also addressed, as the original placement of the cross-piece stopped the rotation of the cam by catching on the drive-band. This was rectified by repositioning the cross piece higher and at a slight upward angle.

Figure 3.42:The completed spindle-wheel in use at the YEAR Centre (Photo: Andy Needham)

3.6.5 Heat Sources

A variety of styles of clay stoves were noted during the visual analysis of the reeling equipment catalogue. A set of stoves were experimentally constructed for the experiments (Figure 3.43) by Dr Gareth Perry following designs based on historical images. A detailed account of the stove construction process and attempted firing can be found in Appendix E.

Figure 3.43: The stoves constructed by Dr Gareth Perry preheating by the fire at the YEAR centre (Source: the author)

Unfortunately, these stoves did not survive the firing process due to temperature shock (Figure 3.44). Following their structural failure, several options were discussed including building new stoves and firing them in a modern kiln, which would allow for better temperature control. The possibility of modifying terracotta chimney pots was investigated, but this was ultimately not viable due to covid-related shipping delays. Trials with a hotplate used in an indoor setting (detailed in reeling experiment logs) produced unsatisfactory results and provided no frame of reference for conducting silk-reeling in an outdoor setting. A gas-fuelled camp stove was ultimately identified as the most suitable choice of heat source in terms of temperature control and accessibility.

Figure 3.44: Collapsed remains of one of the clay stoves (Source: the author)

3.7 Further modifications to equipment

Given the complications inherent with conducting experiments in an outdoor environment, an additional stage of minor modification to the reeling equipment was necessary during the experimental reeling stage. This primarily took the form of sanding parts by hand, replacing the Treadle reeling-frame drive band, and the additional use of Tung oil and/or beeswax, and sap to increase or reduce friction on specific moving parts. The complications that arose during use, and corresponding amendments made to the reeling mechanisms have been detailed in the silk-reeling experiment logs (Appendix G) rather than in this chapter.

Ultimately the construction of the equipment was successful, as functional tools were produced and used to reel silk and produce silk yarn.

Ongoing troubleshooting did emphasise the importance of skilled woodworking in the construction of specialist equipment. The subsequent reeling and throwing experiments, while successful, would likely have run more smoothly if conducted with more skilfully constructed equipment.

3.8 Summary

Although designed to support the silk-processing experiments to be discussed further in Chapters 4 & 5, the construction of the silk-reeling and processing equipment became a significant research undertaking in itself. The combination of visual analysis, experimental construction and virtual measurement estimation allowed for functional equipment to be purpose-built and used in the subsequent silk production experiments. As explained above, there were significant barriers to this undertaking, as many gaps in information needed to be addressed. Notwithstanding these difficulties, the research described in this chapter has clarified aspects of the linear chronological development of silk-reeling equipment in use in Eurasia, which supported the selection of reeling archetypes suitable for reconstruction.

4 Development of the Silk-Processing Experiments

The design of silk-processing experiments was a core part of this research. The creation of a comprehensive reference collection of reeled silk samples was essential to the development of an analytical protocol (discussed in chapter 6). The silk processing experiments (based on the information regarding technology and operational sequences compiled in Chapter 2) were divided into 3 production stages. The first stage, **reeling** produced raw silk filaments that were also used during the subsequent stages of **throwing**, and **degumming**. Each stage of experiment produced samples for the reference collection, allowing for a focus on the effects of variation in technique and equipment at each stage of production.

The **silk-reeling experiments** were designed to assess the impact of variations in equipment and reeling methods on the morphology of the silk produced. The **throwing experiments** were designed to test a set of theorised throwing methods to determine their effect on the morphology of silk yarn. The **degumming experiments** in contrast were primarily designed to assess the efficacy of different approaches to "cooking" raw silk and observe the tactile and visual differences between raw, degummed, and partially degummed silk yarn.

This chapter will describe the design and execution of the silk-processing experiments. The recording methods and experiment locations will first be introduced. The equipment and materials, methods, and complications encountered will be discussed for each of the 3 experiment categories. Sampling approaches will also be discussed in the reeling and throwing sections. The chapter will close with a summary.

4.1 Experiment recording and Locations

To document each experiment, a team of volunteers assisted with photographic and video recording of the experiments. In addition to photo and video documentation, a notebook log was kept for each experiment. Volunteers also provided help with other tasks including water temperature measurements and hand-cranking the treadled reeling-frame, when necessary.

Most reeling experiments were conducted at the YEAR centre. The decision to conduct the reeling experiments in an outdoor setting was informed primarily by practical concerns, particularly fire safety, as the planned heat sources would involve the use of either a gas- or wood-fuelled flame. An outdoor setting also presented an excellent opportunity to observe how weather conditions might influence the silk-reeling process, a relevant consideration as a number of historical depictions of silk-reeling indicate an outdoor or only partially sheltered setting [Reeling Catalogue #s 16, 17, 19, 23-26], while many others are ambiguous in their settings [Reeling Cat #s 6,7,9-12, 18, 21-22]. The YEAR centre was ideal to test these conditions, as the experiments could be conducted completely in the open on a dry day, while the Henson teaching huts provided a partial shelter when necessary (Figure 4.1).

Figure 4.1: The treadled reeling-frame in use under one of the Henson teaching huts on a rainy day (Source: the author)

A preliminary reeling experiment was conducted in an indoor laboratory setting with an electric heat source. Complications with this experiment will be discussed in further detail, but in addition to the safety considerations, this experiment setting was ruled out due to concern that the experiments would be too sheltered for an actualistic approach to medieval silk-reeling.

Throwing experiments were conducted in both indoor and outdoor settings, as there were no heat-source requirements or other safety concerns regarding either location. Historical depictions of silk-throwing processes do suggest both indoor and outdoor settings (For example, Silk Reeling Catalogue #s 3,4 17, 19a), so it was useful to compare the process of throwing silk under various weather conditions to doing so when completely sheltered from the elements.

Degumming experiments were initially conducted outdoors, given the same heat-source related considerations as the reeling experiments, but were subsequently conducted in an indoor setting with an electric element, due to weather-related complications, which will be discussed in further detail.

4.2 Reeling

The reeling experiments were first divided by the 2 categories of reeling equipment: (1) the simple reel, and (2) the treadled reeling-frame with ramping-board. The 2 equipment categories were used in combination with 3 categories of independent variable (Table 4.1): (1) The number of cocoons reeled at one time, (2)the temperature of water used during reeling, based on historical records, and (3) the manner of crossing, or not crossing threads.

Number of Cocoons	Water Temperature	Crossing methods (simple reel)	Crossing Methods (Treadled Reel)
3	**80°C**	**None**	**Single Winding (No cross)**
6	Boiling	Soundless roller	Double Winding
15			Complete Winding
30+			Piedmont Crossing

Table 4.1: The key variables determined for each reeling method, control methods are in bold

The selected control methods comprised 6 cocoons reeled together (x2 for treadled reeling-frame), a water temperature of 80°C, and no thread crossing (the silk passing over, but not wrapping around, a roller for the treadled reeling-frame). The control methods were established based on historical evidence for commonality of use, or earliest established technique.

The control **number of cocoons** were established as 6 because this falls within the middle of the range of cocoon numbers listed in historical texts, particularly sources from China, with significantly higher, or lower numbers being remarked upon as outside of the norm. 3 cocoons were tested to compare strength and ease of reeling to higher numbers of cocoons, while 15 and 30+ cocoons were tested to approximate European silk-reeling approaches.

The **water temperature** of 80°C was selected because it is the only numerical temperature value that has been recorded, and both colder temperatures and boiling are presented as outside of the norm in historical texts (Chapter 2.2.1.2). Boiling water was tested to determine the impact of high water temperatures on silk strength and appearance. The impact of water temperature on speed of reeling was also of interest.

Finally, reeling methods that did not **cross or wrap the silk** filament were chosen as the control for each reeling frame because all methods of crossing or wrapping have been discussed as later innovations or solutions to the "problem" of filament shape and strength. For the simple reel this involved no apparatus, for the treadled reeling-frame this used the "single" winding method wherein the filament simply passes over a roller. The double, complete, and soundless-roller variables are all reflective of techniques developed and used in China or central Asia. The double winding method may also have been used in medieval Europe. The Piedmont method is the earliest European crossing method that is distinct from the roller methods. A key consideration was the impact of these variables on filament shape and cohesion.

Upon establishing control methods and formulating the combinations of variables to be tested, a total of 14 reeling experiments were designed: 4 to be conducted with the simple reel, and 10 to be conducted with the treadled reeling-frame. This was determined to be a suitable number of experiments to produce a range of silk samples reflecting variations in reeling methods from multiple regions, spanning the early to late Middle Ages. Importantly, this was also determined to be a reasonable number of experiments to complete within the time constraints of the PhD. As will be discussed in section 4.2.4, complications arose during the experiments that led to 6 experiments being conducted with the simple reel (Figure 4.2). Other complications also led to the incorporation of hand-cranking the treadled reeling-frame in select experiments (Figure 4.3).

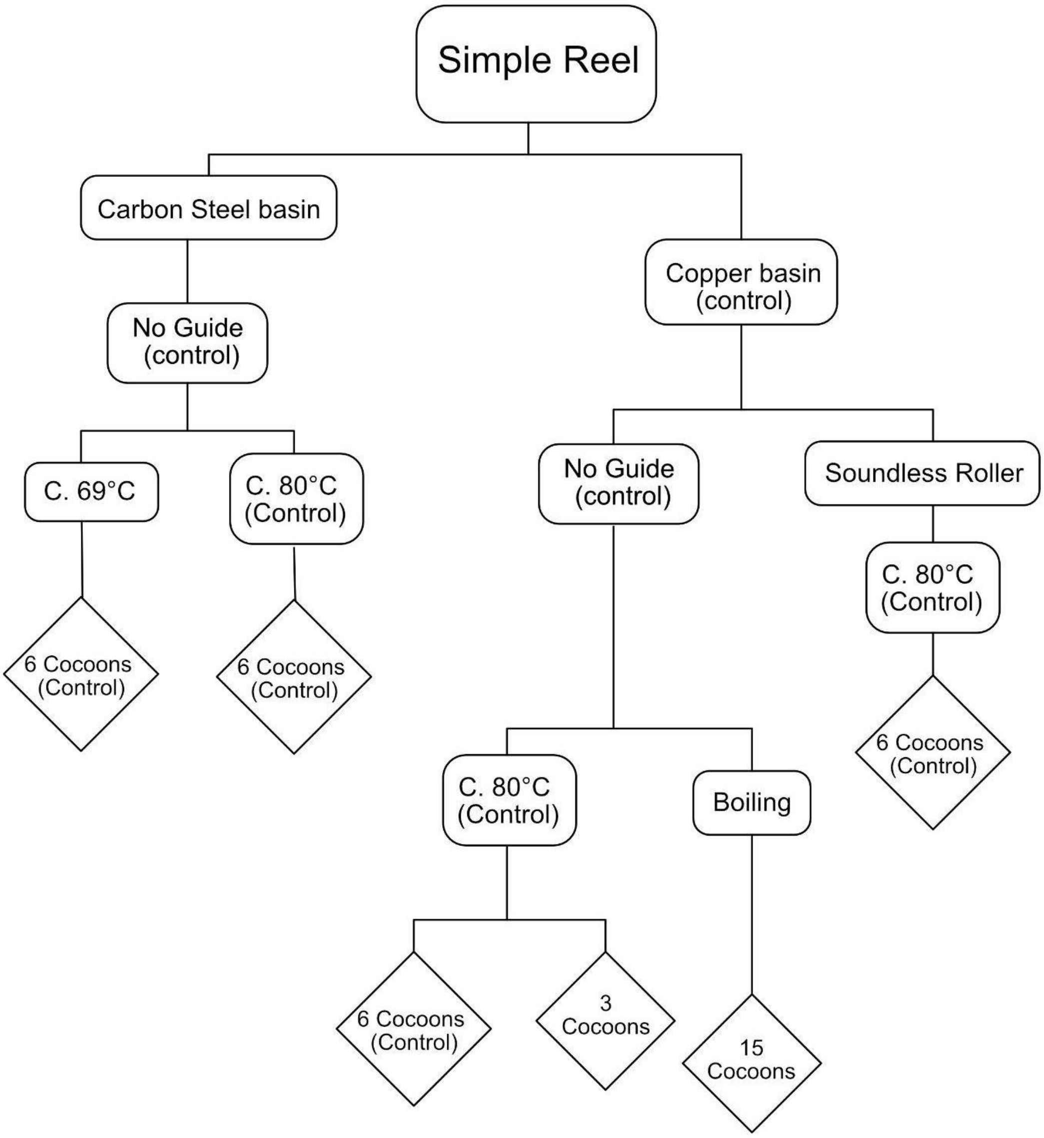


Figure 4.2: Flow chart of independent variables applied to reeling experiments conducted with the simple silk-reeling frame. (Source: the author)

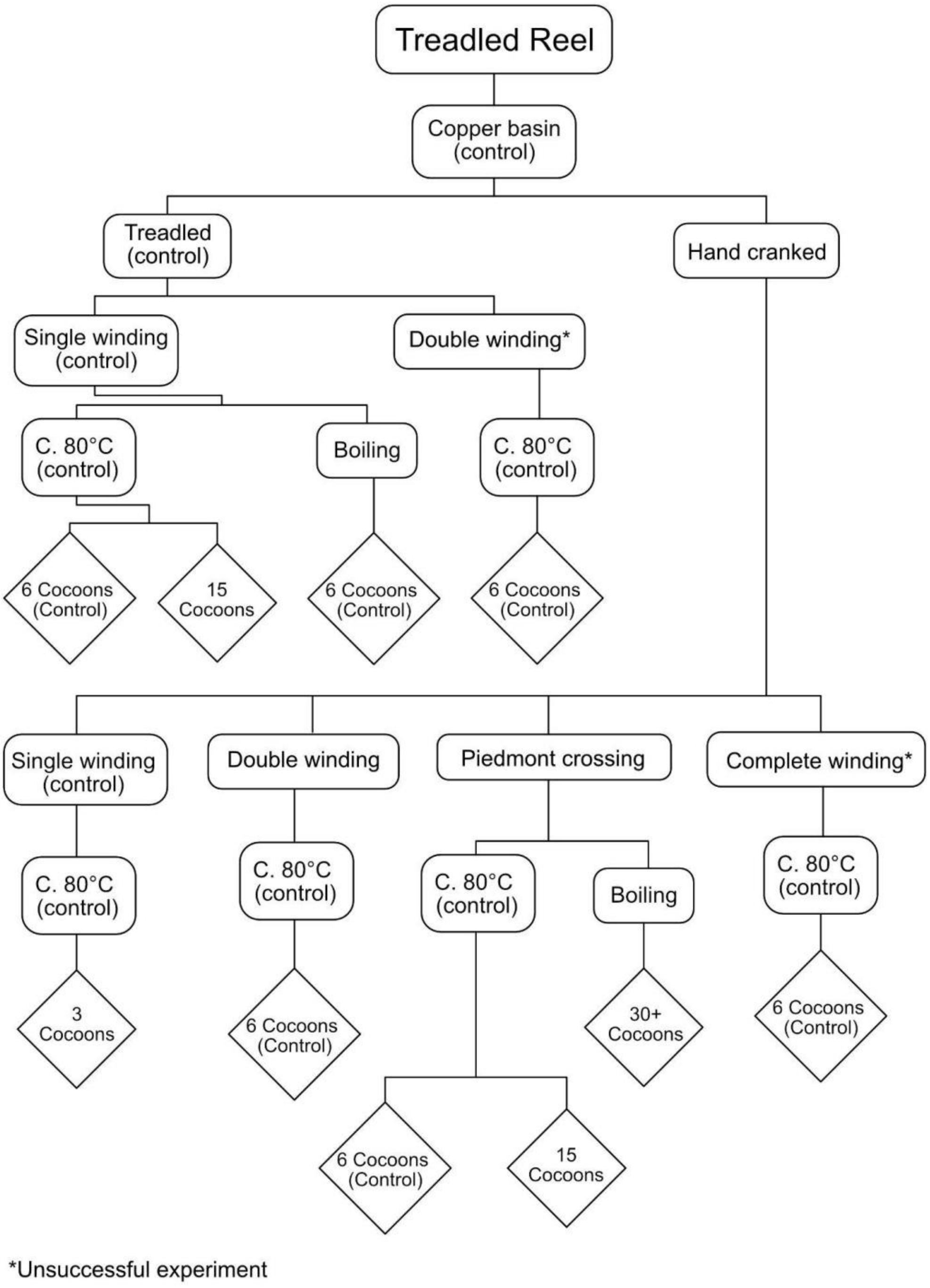


Figure 4.3: Flow chart of variables applied to reeling experiments conducted with the treadled silk-reeling frame. (Source: the author)

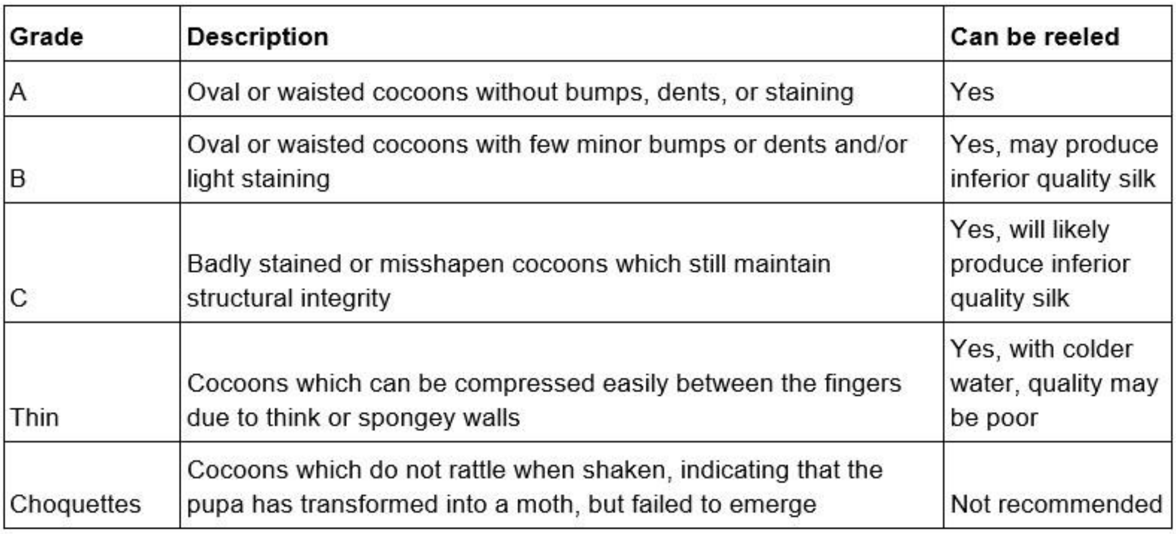
4.2.1 Equipment & Materials

The silk-reeling equipment was used in a variety of combinations for each experiment (Table 4.2). In addition to the purpose-built reeling equipment, some additional purpose-suited equipment was purchased.

Date	Samples Generated	Reeling Equipment	Water Pan	Heat Source	Materials
04-08-2021	Sr_001-Sr_003	Simple Reel	Carbon Steel Wok	Electric Hot Plate	6 Grade A cocoons
30-08-2021	Sr_004-Sr_006	Simple Reel	Carbon Steel Wok	Gas Camping Stove	8 Grade A cocoons
06-09-2021	Sr_007-Sr_009	Simple Reel	Copper Jam Pan	Gas Camping Stove	8 Grade A cocoons
08-09-2021	Sr_010-Sr_014	Simple Reel, Soundless Roller	Copper Jam Pan	Gas Camping Stove	8 Grade A cocoons
14-09-2021	Tr_001-Tr_008	Treadled Reel, Double roller frame	Copper Jam Pan, copper bowl	Gas Camping Stove	32 Grade A cocoons
16-09-2021	Tr_009-Tr_014	Treadled Reel, Double roller frame	Copper Jam Pan	Gas Camping Stove	16 Grade A cocoons
17-09-2021	Tr_015-Tr_020	Treadled Reel, Double roller frame	Copper Jam Pan	Gas Camping Stove	36 Grade A cocoons
21-09-2021	Sr_015-Sr_017	Simple Reel	Copper Jam Pan	Gas Camping Stove	5 Grade A cocoons
22-09-2021	Tr_021-Tr_026	Treadled Reel, Double roller frame	Copper Jam Pan	Gas Camping Stove	8 Grade A cocoons
24-09-2021	Tr_027-Tr_038	Treadled Reel, Copper guide eyes	Copper Jam Pan	Gas Camping Stove	36 Grade A cocoons
29-09-2021	Tr_039-Tr_044	Treadled Reel, Copper guide eyes	Copper Jam Pan	Gas Camping Stove	C. 70 Grade B&C cocoons
06-10-2021	Tr_045-Tr_050	Treadled Reel, Double roller frame	Copper Jam Pan	Gas Camping Stove	16 Grade A cocoons

Table 4.2: Variations in reeling equipment and materials used during each experiment.

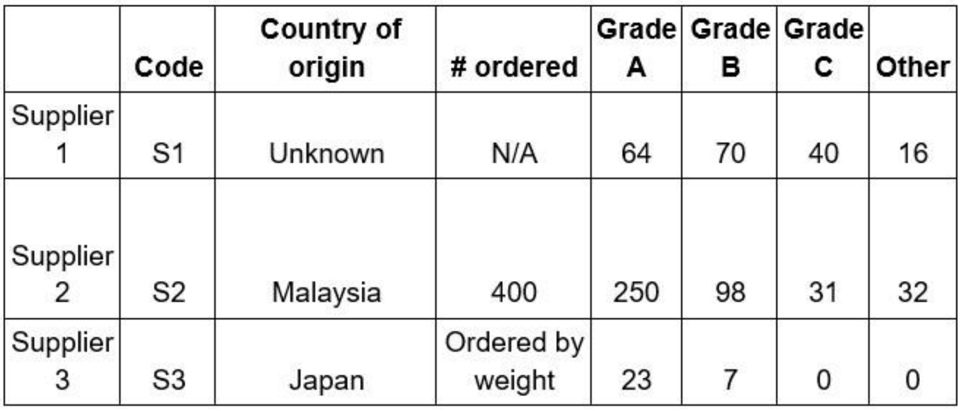
Silk cocoons from 3 different sources were inspected to assess their quality and suitability for the experiments. The cocoons from each supplier were separately sorted according to defined grades (Table 4.3).



Grade	Description	Can be reeled
A	Oval or waisted cocoons without bumps, dents, or staining	Yes
B	Oval or waisted cocoons with few minor bumps or dents and/or light staining	Yes, may produce inferior quality silk
C	Badly stained or misshapen cocoons which still maintain structural integrity	Yes, will likely produce inferior quality silk
Thin	Cocoons which can be compressed easily between the fingers due to think or spongey walls	Yes, with colder water, quality may be poor
Choquettes	Cocoons which do not rattle when shaken, indicating that the pupa has transformed into a moth, but failed to emerge	Not recommended

Table 4.3: Cocoon Grade quality key

Each batch of cocoons presented different benefits and drawbacks regarding quantity and quality (Table 4.4), and ultimately the cocoons from Supplier 2 were selected for all experiments, as this batch contained the highest quantity of A and B grade cocoons suitable for the experiments.



	Code	Country of origin	# ordered	Grade A	Grade B	Grade C	Other
Supplier 1	S1	Unknown	N/A	64	70	40	16
Supplier 2	S2	Malaysia	400	250	98	31	32
Supplier 3	S3	Japan	Ordered by weight	23	7	0	0

Table 4.4: Cocoon Suppliers with number of cocoons sorted into each quality grade

Grade A cocoons were selected for all experiments except one (See section 4.2.2), which used A, B, and C grade cocoons. While it is not possible to perfectly replicate or even know the precise rearing conditions of Bombyx mori silkworms in various geographic locations and time periods throughout the Middle Ages, confirming a single origin for the cocoons was important to determining whether variations in reeling methods and equipment influence reeled silk-fibre morphology. Sorting the cocoons by quality was equally necessary in terms of controlling for natural variables that may impact the morphology and mechanical properties of silk fibres.

4.2.2 Method

The range of equipment used for each experiment was primarily influenced by the reeling methods. The key variables, previously summarised as variations in water temperature, crossing methods, and number of cocoons reeled at a time were tested using both styles of reel. The thread crossing or wrapping variable influenced the equipment choices for each reel, as the double roller frame, soundless-roller, and copper wire “eyes” were required for specific cross methods, while the decision not to cross or wrap threads eliminated the need for such equipment.

A variation of hand-cranking the treadled reeling-frame was also incorporated into the experiments as certain crossing variations and low numbers of cocoons resulted in a strand that was too fragile to withstand the jerking motion of the reel when treadled. Hand-cranking was also used during the experiment reeling 30+ x 2 mixed quality cocoons from supplier 2 in boiling water, to match descriptions of c. 16th century Veronese reeling methods (Molà 2000, 245).

Each experiment required a slightly different approach, but the overall reeling method for each experiment can be described in the following steps:

1. Ignition of heat source;
2. Water poured in Boiling pan; pan placed on heat source;
3. Water brought up to desired temperature, monitored with a probe thermometer;
4. Upon water reaching desired temperature, number of cocoons required for reeling, plus an additional 2-5 placed in the boiling pan, stirred and allowed to simmer for a minimum of 5 minutes;
5. Following 5-minute period, cocoons brushed regularly to check if fibres come away from cocoon core;

6. Once fibres are taken up with brush, they are pulled manually until desired number of cocoons unravel consistently;
7. Gathered filament fed through/around any guiding eyes or rollers and tied to reel with a square knot;
8. Reel turned manually with crank or by foot with treadle, while silk filament guided back and forth across reel ;
9. During reeling, cocoons monitored to ensure correct number are unravelling at all times. Cocoons that drop away or are exhausted are replaced with others;
10. Reeling stops when there are no more cocoons left to replace finished cocoons and filament is becoming noticeably thin;
11. Silk filament removed from reel by winding from end of reel onto 3 bobbins with throwing rod, or by tying skein of silk with cotton ties before sliding the skein from the reel;
12. Silk filament either;
    a. Thrown immediately, or;
    b. Stored for later processing.

The control method utilised with the simple reeling frame follows the above steps without interacting with any guiding eyes or rollers (Figure 4.4), causing the reel operator to act as the intermediary between the silk filament and the reel, with no automation.

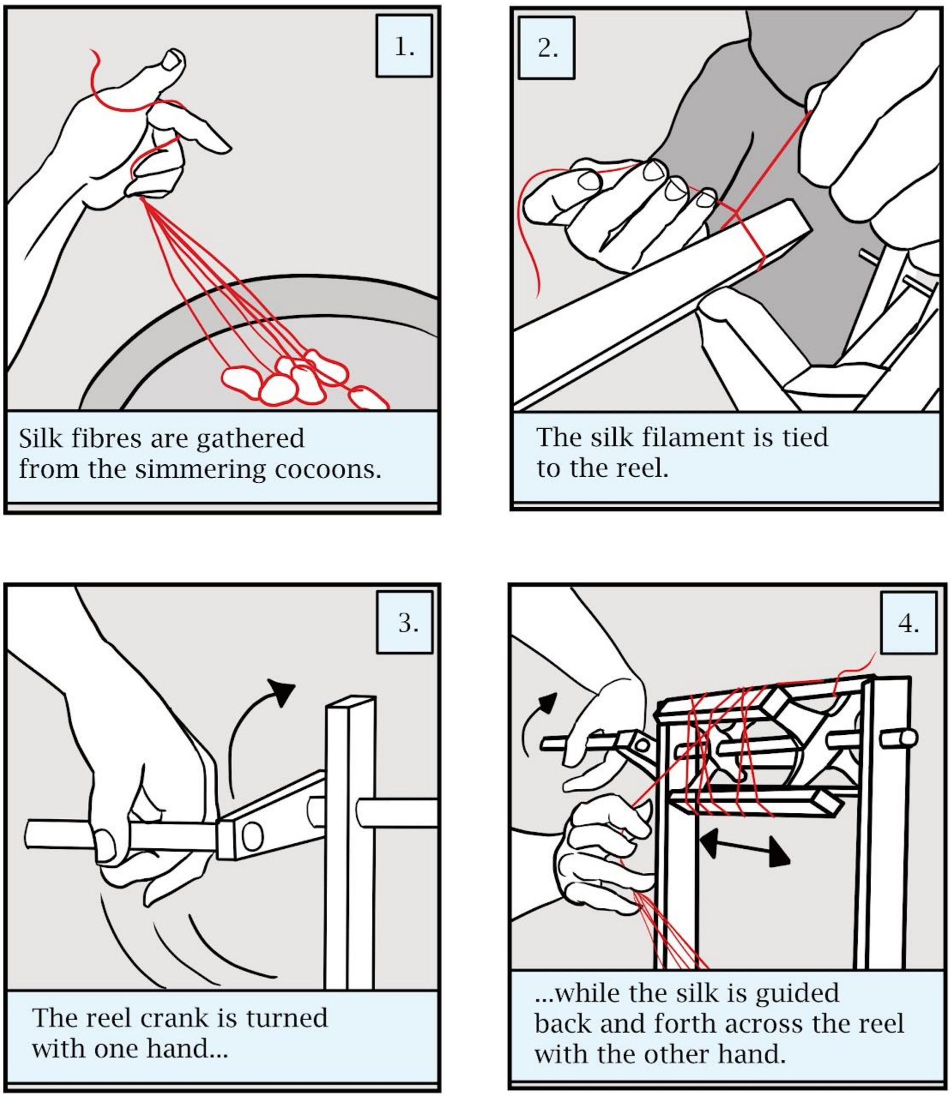
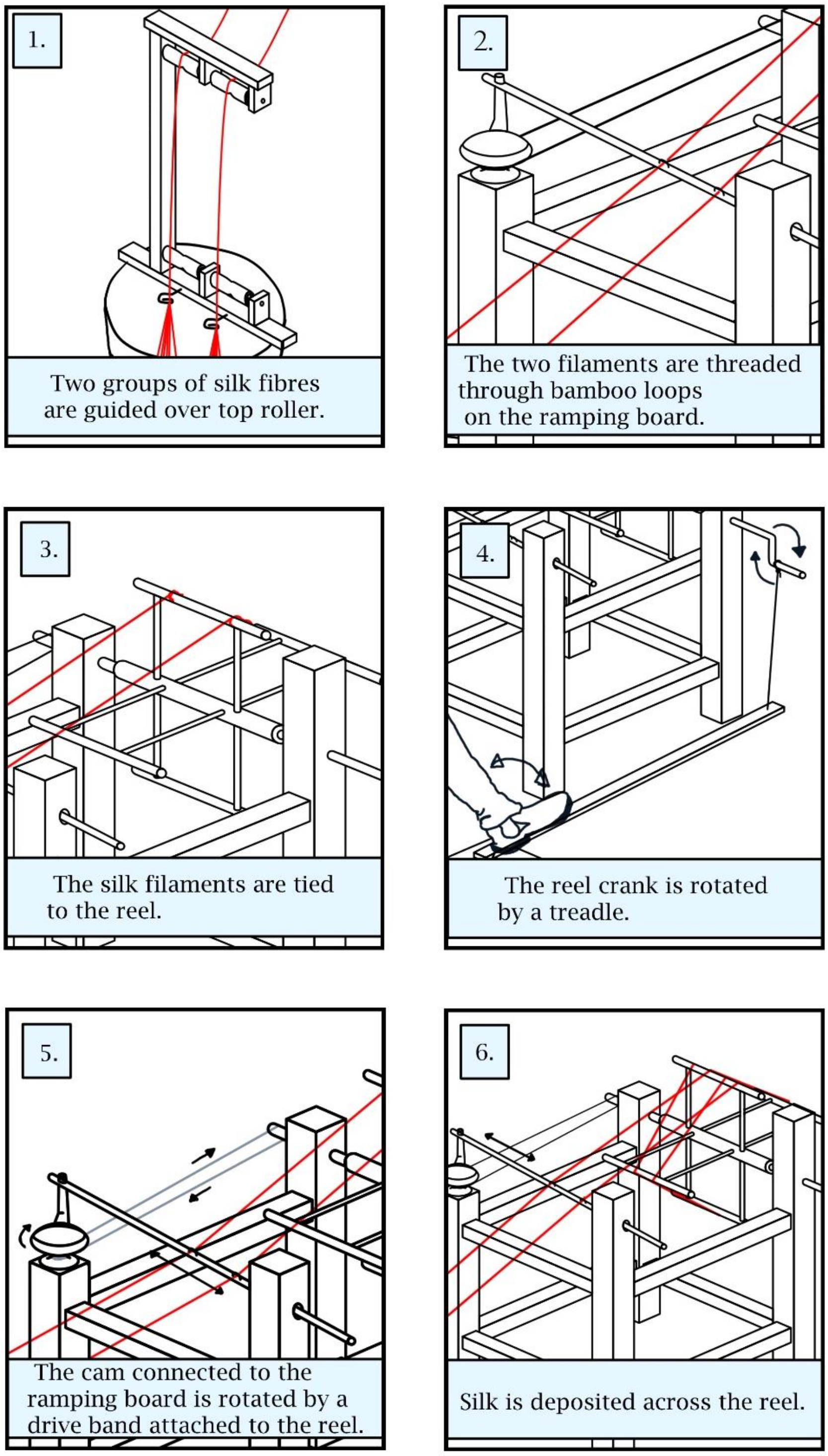


Figure 4.4: Illustrated reeling process for simple reeling frame control method (Source: the author)

In contrast, the control method utilised with the treadled reeling-frame is guided onto the reel through a series of semi-automated processes (Figure 4.5). This leaves the operator free to focus on driving the reel with a treadle, while tending to the cocoons.



1. Two groups of silk fibres are guided over top roller.

2. The two filaments are threaded through bamboo loops on the ramping board.

3. The silk filaments are tied to the reel.

4. The reel crank is rotated by a treadle.

5. The cam connected to the ramping board is rotated by a drive band attached to the reel.

6. Silk is deposited across the reel.

Figure 4.5: Illustrated reeling process for treadled reeling- frame control method (Source: the author)

4.2.3 Sampling Approach for Reeled Filaments

A minimum of 3 samples were collected from each reeling variation. In almost every case, the samples corresponded to sections of reeling from the exterior, middle, and interior of the cocoons and were labelled accordingly. In the case of the treadled reeling-frame, the same approach was taken, but 3 samples were taken from each of the 2 skeins produced simultaneously during reeling. The 2 skeins were distinguished by noting the position of each skein on the reel, when viewed while seated in front of the reeling frame. The skeins were labelled “Left” and “Right” accordingly. Any exceptions to the established sampling procedures were noted in the experiment logs (Appendix G) with an explanation for this deviation.

In most instances the samples from the exterior, interior, and middle of the cocoons were collected from the simple reel experiments immediately following the reeling session, as the division of the skein onto 3 bobbins correlated with the interior, exterior, and middle of the cocoon, and supported the direct collection of these samples prior to throwing. To aid this process, the bobbins were labelled with the corresponding section of silk they held.

The approach to collecting samples from the skeins of silk reeled with the treadled reeling-frame differed in that sample collection typically took place on a separate day from the reeling experiments. To aid with accurate sampling, the end of the silk corresponding to the exterior of the cocoon was marked with a small piece of cotton string tied around the silk filament. Even without this marker it was typically easy to distinguish between the interior and exterior ends of the silk, as the silk from the exterior of the cocoon was visibly thicker than that from the interior.

Treadled-reel sample collection was carried out according to the following steps:

1. The skein was tensioned on the swift;

2. The tied ends were located and untied, but the cotton strings holding the centre of the skein were not cut;
3. The exterior cocoon end was identified, a sample was collected onto a labelled card and place in a labelled sample bag;
4. The interior cocoon end was identified, a sample was collected onto a labelled card and place in a labelled sample bag;
5. The ends were tied together again and marked with cotton string;
6. A strand from middle of the skein was selected, cut, and one end was secured with cotton string to swift so it was not lost;
7. The middle sample was carefully wound onto a labelled card and placed in a labelled sample bag;
8. The 2 ends from the middle section of silk were tied back together;
9. The remaining skein was then twisted back together for storage (Figure 4.6) and returned to its sample bag.

This method allowed for the collection of several metres of each sample for further analysis, while leaving several hundred metres of the silk produced during each reeling experiment, which could be utilised for throwing and degumming experiments.

Figure 4.6: 4: Skeins of raw reeled silk twisted for storage following an experiment day (Source: the author)

4.2.4 Complications

4.2.4.1 Finding the Control Method for the Simple Reel

Two partially successful reeling experiments were conducted before the desired controls for the simple reeling experiment were successfully executed. The first experiment took place on 04/08/2021 and used a carbon steel wok as the water basin in combination with an electric hotplate as the heat source. The experiment was conducted in the Palaeohub Material Culture Lab at the University of York and was designed to trial an already available heat source following the unsuccessful firing of the custom-built terracotta stoves. Two key complications arose:

1) The hotplate was unsuccessful at raising the temperature of the water in the wok to above 69°C, meaning that the desired control temperature of 80°C could not be reached
2) During the extended period spent heating the water, the carbon steel wok began to oxidise, staining the cocoons (Figure 4.7)

Figure 4.7: Carbon steel wok with visible rust spots and stained cocoons (Photo: Andy Needham).

The first complication resulted in a much slower reeling time, as the cocoons required a longer period of simmering prior to reeling, and the resulting silk was much more prone to breaking during the reeling and throwing process than in most subsequent experiments. The water temperature obstacle could not be overcome, which eliminated the hotplate as a viable heat source. The second complication may have arisen from improper seasoning of the wok prior to use. To address this, the wok was cleaned and properly seasoned prior to the second attempted control experiment.

The second experiment took place on 30/08/2021 and was conducted outside at the YEAR centre using a gas-burning camp stove. This experiment was successful in raising and holding the water temperature within 3 degrees of 80°C for the duration of the reeling process, establishing the camping stove as a viable control heat source. Because the wok had been properly seasoned and the process of heating the water was more efficient, little oxidation occurred, but the problem was not eliminated, resulting in a more subtle, but still visible rust stain on the cocoons and reeled silk. The carbon steel wok was therefore eliminated as a suitable water basin.

The above complication led to the development of the actual control experiment, which was conducted outdoors using a copper jam pan in combination with the camping stove.

4.2.4.2 Silk Shrinking/Breaking on the Simple Reel

Following a successful silk-reeling session using the soundless-roller (Figure 4.8) in combination with the simple reel, the reeled filament broke while being wound onto bobbins.

Figure 4.8: Reeling silk with the soundless-roller (Photo: Skye Ennis)

A significant amount of time was spent trying to find the broken end, which appeared to have become trapped under another strand of silk. It became clear that the end would not be easily located while the silk was under tension; the best option was to remove the entire skein from the reel by pulling it over one end. The diameter of the simple reel meant that it could not be removed and re-tensioned with the custom-built swift. This was a design flaw resulting from the assumption that the silk from the small reel would always be wound from the end of the reel without complication. Were this the case a swift would not have been necessary; this highlights the potential for unforeseen errors in actualistic experiments. A modern swift with a more flexible diameter was retrieved to resolve this issue, however, by the time it had been brought onto site, the silk had shrunk to the point that it could not be pulled from the reel, and the increased tension had caused the silk filament to break at multiple points in the skein. The strength of the silk was significant and while some strands broke (Figure 4.9), the constricted skein also began to create dents in the arms of the reel.

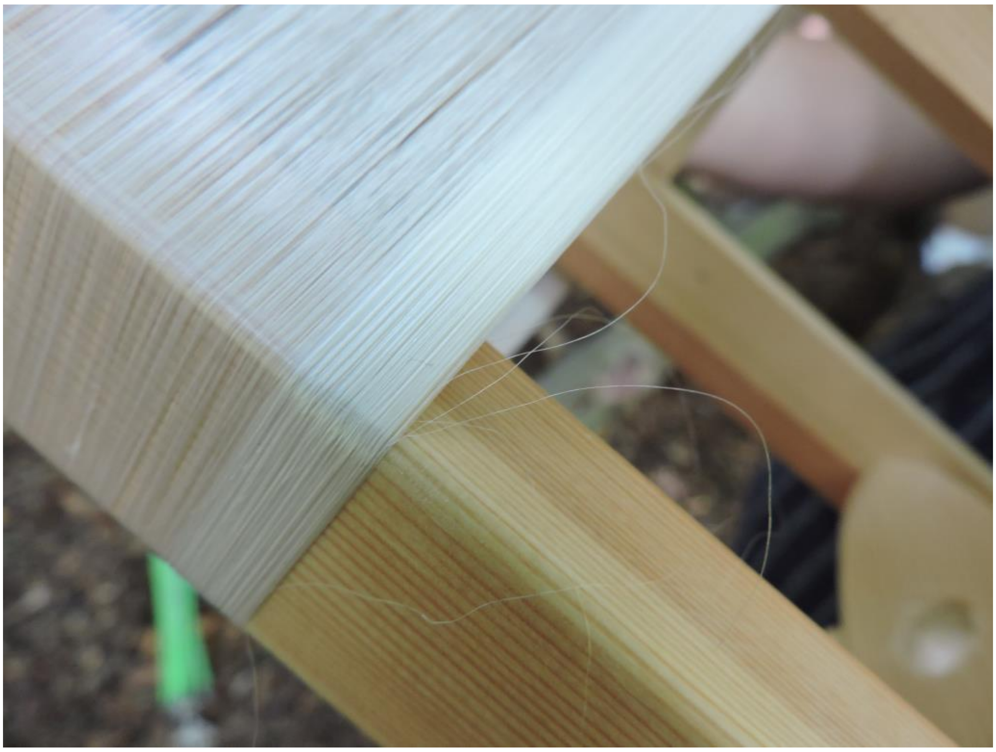


Figure 4.9: Silk filaments breaking while shrinking on the reel (Photo: Skye Ennis)

To mitigate the risk of further equipment damage, the skein was cut from the reel (Figure 4.10), and samples were taken from the first spooled section as well as several sections of the cut skein. Broken fragments resulting from the process of trying to pull the silk from the reel were also collected and labelled as separate samples.

Figure 4.10: Silk cut from the reel, showing creases in the fibres formed due to tension (Photo: Skye Ennis)

It is unclear why the end of the silk snapped so easily or why it could not be found after the break, although it was noted that the end of this filament was very fine, as the silk at the end in question was from the interior of the cocoons. The problem was exacerbated by further delay in pulling the silk from the reel, resulting in the silk shrinking to the point that it could not be removed without cutting it from the reel. The width of the silk reel arms may have put additional strain on the silk, though this is uncertain, and the reel arms were not modified in favour of maintaining consistency of equipment across the experiments.

To prevent this loss of silk material from recurring, in subsequent experiments greater care was taken to prevent the filament from being reeled too thin, thus reducing the risk of the strand breaking. Care was also taken to pull the small skein of silk immediately from the reel if the end broke, or at the first sign of drying and shrinking. In these occurrences, the silk was dried and then spread under lesser tension, using a modern swift to accommodate the narrow diameter of the skein.

The silk could then be sampled and/or thrown under reduced time pressure with a lower risk of broken filaments.

4.2.4.3 Unsuccessful and Partially-successful Winding Variations Using the Treadled Reeling-frame

Following descriptions of silk-reeling methods discussed in Chapter 2, a decision was made to pre-emptively simmer the full quantity of cocoons (Figure 4.11) required for 2 separate experiments conducted on 14/09/2021. A copper mixing bowl was set up on one of the 2 camp stove burners, filled with water and brought to the desired 80°C temperature prior to adding the 32 cocoons. After these cocoons had simmered, the ends of silk from 16 cocoons were gathered. As only one basin could fit on the stove at a time, the first 16 cocoons were transferred to cold water in the copper jam pan. The copper bowl was then set aside and the jam pan was moved to the stove.

Figure 4.11: Cocoons for 2 separate reeling experiments set up to simmer (Photo: Abbie Evans)

While heating the water, silk strands that broke away from the cocoons during the transfer process were gathered again and the reel was threaded using the “single winding” technique (Figure 2.5). This first reeling experiment was carried out without difficulty, and the use of the treadle was successful.

Meanwhile, the remaining 16 cocoons had been left to soak during the first reeling experiment and had cooled in the copper bowl. The remains of the first 16 cocoons were removed from the heated water in the Jam pan and were replaced with the pre-soaked cocoons. Finding the ends of these cocoons took half an hour, after which point the reel was threaded using the "double winding" method described by Kuhn (Figure 2.4) that employed the top and bottom rollers of the roller frame. This winding method resulted in both filaments immediately snapping, and the silk would not reel until an adjustment was made, with the silk wrapped solely around each of the top rollers (Figure 2.3). This adjustment allowed for somewhat successful reeling if the reel was hand-cranked, but the filaments snapped and had to be re-tied whenever the treadle was used.

After some successful reeling, the filament feeding into the left-hand skein repeatedly snapped, and inspection determined that large quantities of silk were being deposited on the left roller (Figure 4.12), resulting in a weakened filament. This issue could not be resolved, so only one full skein of silk was produced during this experiment. The partial left-hand skein was labelled and stored.

Figure 4.12: Silk deposited on one of the top rollers during unsuccessful attempt at double winding method (Photo: Abbie Evans)

To mitigate the problem of silk clinging to the roller, the roller frame was sanded to remove any possible sharp edges, with particular focus on the rollers, and the entire apparatus was treated with tung oil. Humidity was also taken into consideration in relation to silk strength, as the experiments were conducted under cover in rainy weather, which may have impacted the mechanical properties of the silk. Notably, the process of pre-soaking cocoons was not found to promote efficiency, given that the 2 bases could not be heated simultaneously, and the prolonged soaking time of the second batch of cocoons discoloured the fibres and may have weakened them. The decision was therefore made to simmer only the required number of cocoons for each experiment moving forward.

The “Complete Winding” technique (Figure 2.2) was the only wholly unsuccessful experiment. The fibres from 2 assemblages of 6-8 cocoons were wrapped around the rollers according to Kuhn’s “complete wrapping” description. Before reeling could begin, it became clear that the method as described by Kuhn would not work with the equipment constructed, as the number of times the silk wrapped around each roller prevented them from turning, which trapped the silk filaments and prevented reeling from progressing.

A modification of this method (Figure 4.13) that implemented fewer wraps around the rollers themselves allowed initially for the successful movement of thread on the right assemblage, but still resulted in the lower left roller jamming. To mitigate this problem the experiment was split, and the left side of the roller frame was used to repeat the double winding method, while the right side was used to attempt the modified version of the complete winding method. Not long after the reeling resumed the complete wrap on the right jammed, and the strand repeatedly broke as the top and bottom rollers would not turn sufficiently.

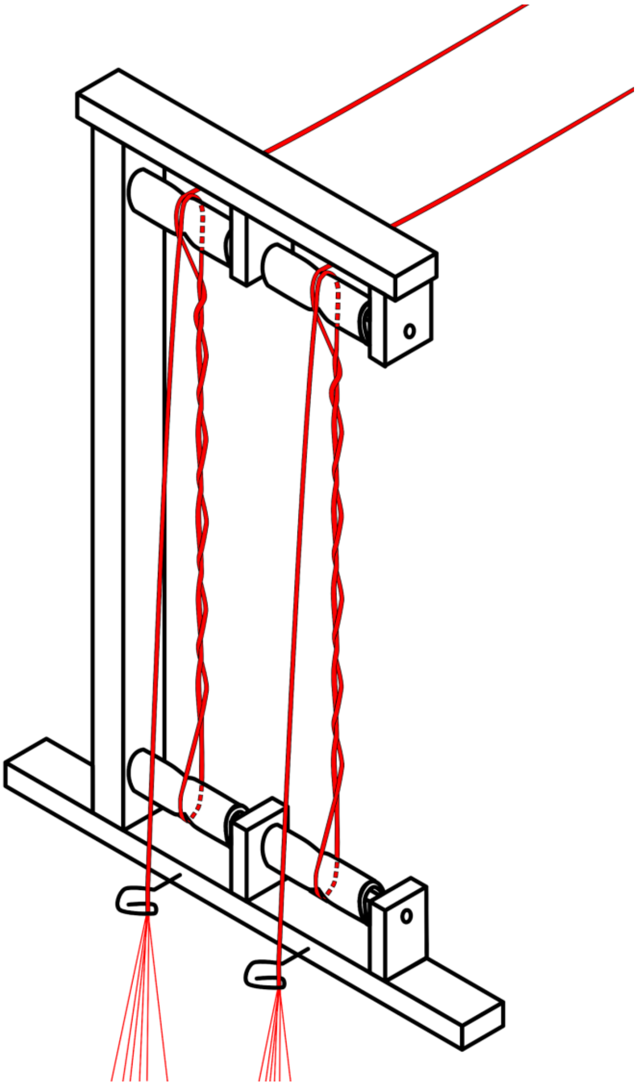


Figure 4.13: Complete Winding method modified with fewer wraps around the top and bottom rollers (Source: the author)

After multiple unsuccessful attempts to continue with the modified complete winding method, the decision was made to proceed with both rollers double wrapped, thereby repeating the previous attempt that had been executed with only limited success. This repeated experiment progressed smoothly but could not be treadled without the silk fibres snapping. A few breaks occurred even when hand-cranked, and a notable quantity of silk was deposited on rollers. That said, the silk was less inclined to shred when the reel was turned more quickly.

Following this experiment, no further attempts were made at replicating the Complete Winding method, but it was noted that the mechanical properties of the custom-built equipment may have resulted in the described complications.

4.2.4.4 Sticking Ramping-board Cam

During the later experiments using the treadled reeling frame, the rotating cam that drove the ramping-board from side to side began to stick increasingly frequently, ceasing rotation while the reel continued to turn. This problem, if left unresolved, would result in the deposit of silk on the same spot on the reel rather than an even distribution of silk across the whole reel. The primary cause of this issue was a loss of tension in the drive band, resulting in insufficient friction to drive the cam. This was typically attributed to a minute expansion of the drive band on humid days, or the gradual stretching or loosening of the cord when under tension. Several mitigations were attempted, including deliberate roughening of the wooden channels, the tightening of the drive-band, and the use of substances to increase friction (including Rosin and residual birch tar recovered from a stump at the YEAR centre). It was also determined that the need for such a high degree of drive-band tension could also be due to a lack of ease in the cam's rotation. Measures were therefore taken to smooth the wood of the rotating parts with fine grit sandpaper and the application of tung oil. All mitigations were executed with mixed success, which allowed the reeling experiments to continue, but the problem of occasional ramping-board jams continued and have highlighted the need for skilful construction of these moving parts.

4.3 Throwing

Because detailed technical descriptions of throwing methods are scarce and often leave significant room for variation, the process of narrowing down a set of throwing techniques for experimentation was daunting, particularly when analysis of archaeological silk samples had not yet been conducted for the purposes of comparison. Additionally, the amount of time required to test a full range of throwing methods in each reeled silk sample was too large for the scope of this project. Therefore, following the production of a sufficient number of samples to observe patterns of variation in the different throwing methods, the remaining raw silk was stored. This approach allows for the possible use of the remaining reeled samples in future throwing experiments informed by further analysis of medieval silk textiles.

4.3.1 Equipment & Materials

Most of the experiments used the spindle-wheel to combine the silk filaments, with or without twist. It was therefore important to set up some clear parameters regarding the use of this piece of equipment, as the speed of operation arguably has a more significant impact on the characteristics of the yarn produced than is true of the reeling process. Another style of equipment discussed in Chapter 2 was the *filatoio* or silk mill, the mechanics of which were approximated during these experiments. This section will first describe the operation of the spindle-wheel as applicable to these experiments, and the development of the "false silk mill" method.

4.3.1.1 Spindle Wheel Operation

As discussed in Chapter 2.2.2.2, the spindle-wheel allows for the alternate twisting and winding of silk onto a bobbin, depending on the angle at which the silk is held in relation to the horizontal spindle (Figure 2.11). Cylindrical bobbins made of bamboo were sized to fit the shaft of the spindle, in some cases stuffed with flax fibre to ensure a proper fit. When a bobbin was placed on the spindle (Figure 4.14) the silk could be wound onto the bobbin as it was twisted and then be removed for storage or further processing.

Figure 4.14: Bamboo bobbin with silk placed on the shaft of the spindle-wheel (Photo: Andy Needham)

To achieve a relatively consistent degree of twist between samples, the number of times the handle of the spindle-wheel made a full rotation was counted, while a set length of 0.5 metres was held in the twisting potion. The length of twisted yarn was then wound onto the bobbin and the process was repeated. When combining silk filaments to produce I (without twist) yarn, the strands were held at a 90° angle to the spindle shaft, to wind the filaments together without introducing twist.

4.3.1.2 Devising the "Mock Silk Mill" method

This method was developed as a way to compare the differences between silk twisted with the spindle-wheel and that twisted by the late-medieval Italian silk-twisting mill or *filatoio* (Figure 4.15), as this distinction is highlighted as an important factor by authors such as Desrosiers (2019) when discussing the differences between silk yarn manufactured in China and that produced in Europe.

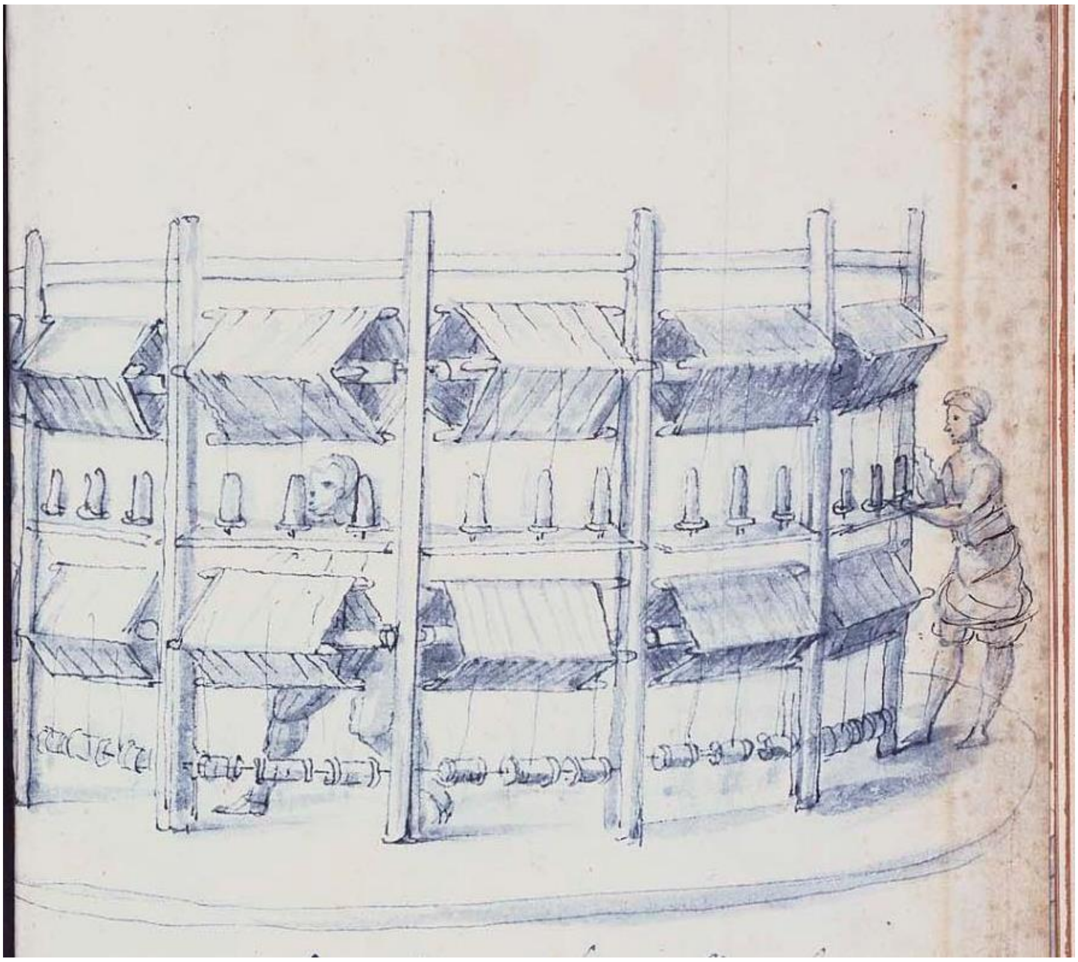


Figure 4.15: Detail of sketch of a probable silk twisting mill by Guiseppe Arcimboldo(c. 1586)

It was impractical to attempt the re-construction of even a scaled-down water-powered silk mill, but the basic principle of silk being twisted as it is pulled from a rotating bobbin or quill and deposited on a turning reel could be manually replicated by combining the simple reel and a piece of modern technology: an e-spinner (Figure 4.16), This compact electronic spinning-wheel flyer can be used in place of a traditional treadle-operated spinning wheel. The e-spinner chosen for this experiment was selected based on its portability and the fact that the manufacturer encourages “modding” of the e-spinner to suit users' needs. This meant that there were a large number of open source 3D-printable attachments for this piece of equipment, which allowed it to be easily and temporarily converted from a horizontally-oriented flyer suitable for traditional spinning, to a vertically oriented, spinning quill, serving as a simplified version of the rotating bobbins found on medieval silk-twisting mills (Figure 4.17).

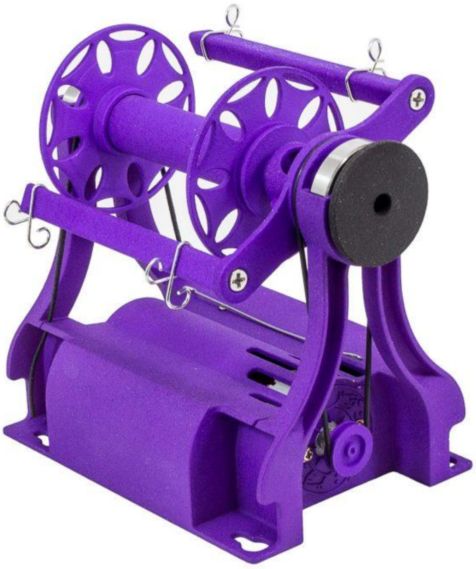


Figure 4.16: Photograph of the EEW Nano e-spinner (Ribble 2018)

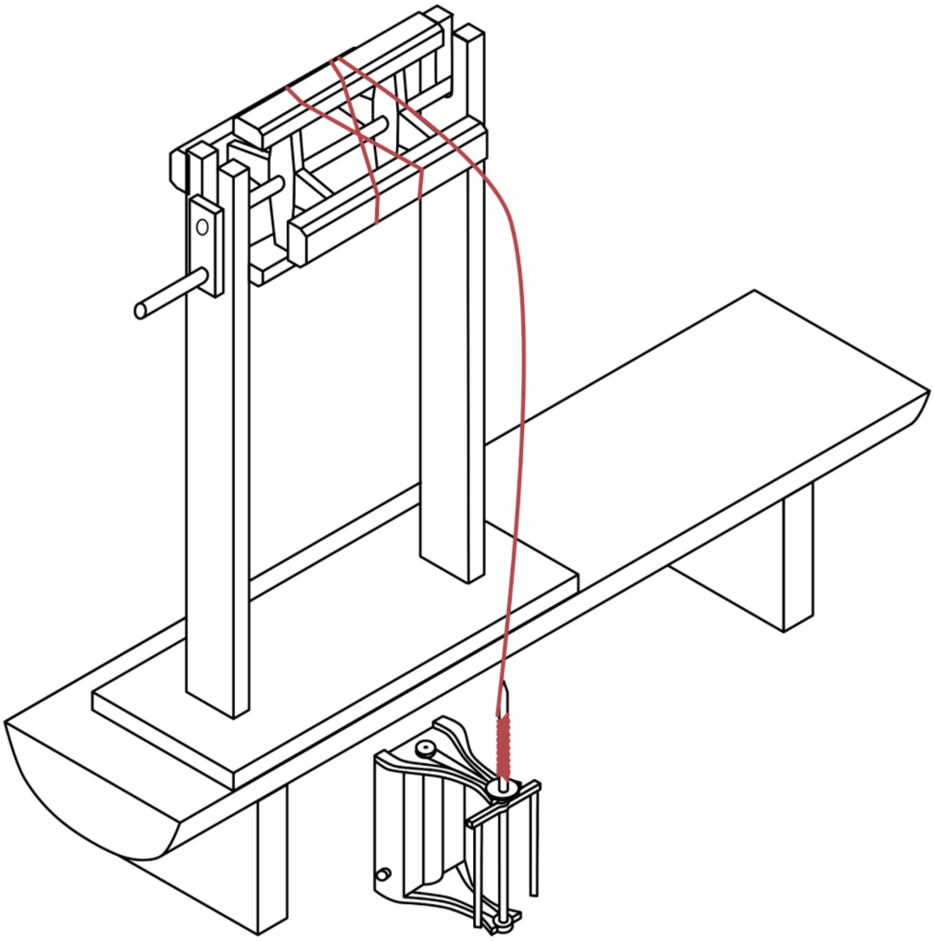


Figure 4.17: Diagram of the Mock silk mill configuration (Source: the author)

Preparation and use of the “Mock silk mill” is summarised in the following steps:

1. Simple reel set up on a bench so that it was elevated above ground level;
2. 2 or more silk filaments wound either clockwise or counterclockwise around the e-spinner quill attachment;
3. The quill attachment inserted into the front orifice of the e-spinner;
4. E-spinner set by edge of bench below simple reel, with quill attachment oriented vertically;
5. Two strands to be combined tied one arm of the simple reel;
6. E-spinner switched on at selected speed setting and rotation;

   a. Rotation direction must be set to opposite direction in which the silk was wound onto the quill;

7. The handle of the reel slowly cranked counterclockwise with one hand, while the other hand guided the silk from the quill to the reel, keeping the silk to be twisted parallel to the quill.

4.3.2 Method

The silk from the first partially successful reeling experiment was used to test multiple approaches to combining silk filaments using the spindle-wheel (Figure 4.18). This initial approach, based primarily on descriptions from Kuhn (1988, 405), produced samples consisting of 2 strands of silk combined while adding a low level of clockwise (Z) twist, 2 strands combined with anticlockwise twist, and 3 strands combined without twist (I). 2 bobbins of each of these samples were produced, and following the collection of samples of each, further samples were created: twisting the 2 strands of Z-twisted silk in the S direction, twisting the S-twisted silk in the Z direction, and combining the I silk without twist. This produced samples that could be notated as I2Z2S, I2S2Z, and I2I2I, respectively. The twisted samples were created with a relatively low level of twist, in the interest of replicating the purportedly lower levels of twist found in samples from China and central Asia.

Following this trial, it was concluded that it would be more valuable to test a broader range of approaches to twisting silk, as well as differences in degree of twist, rather than focussing on producing samples following the same method but altering the direction of twist. While variations in direction of twist were still to be tested, it was concluded that twist direction, given that it is visually identified relatively easily, did not need to be varied as extensively as it was during the initial experiment.

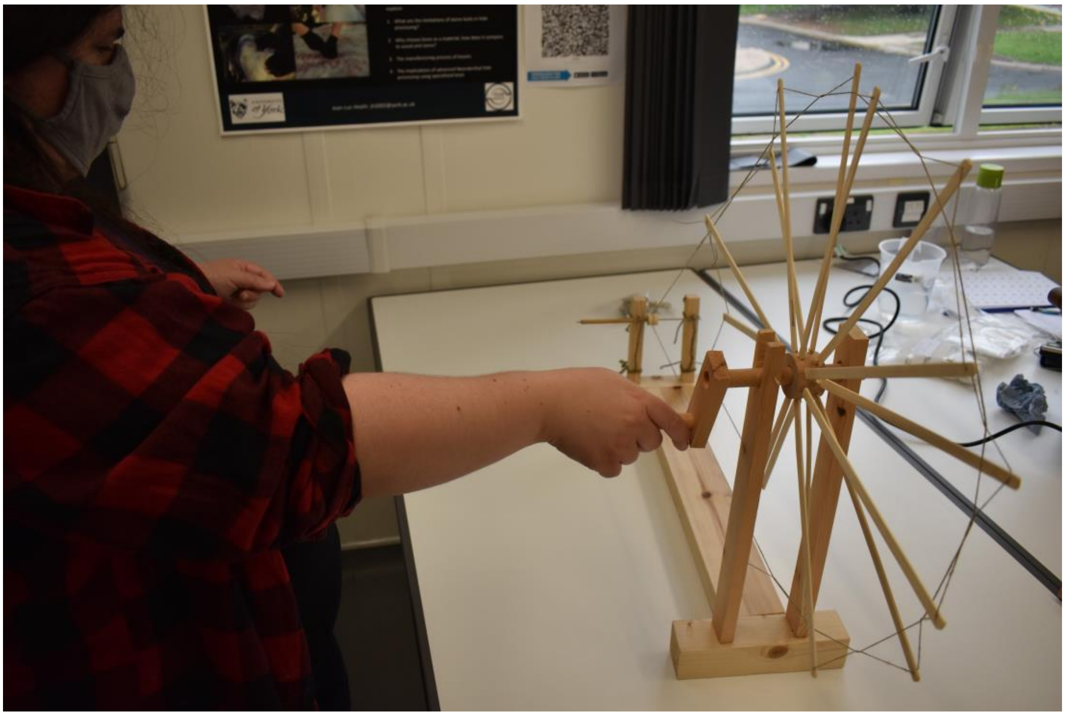
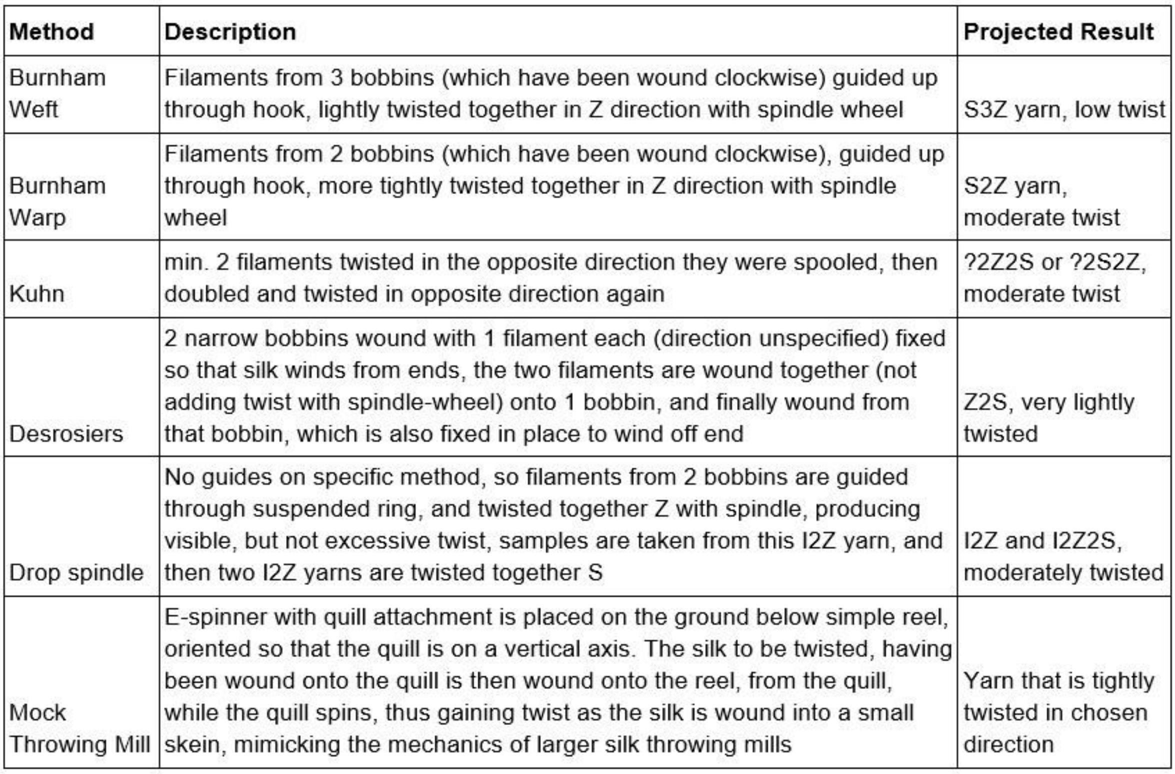


Figure 4.18: The spindle-wheel in use in an indoor setting (Photo: Andy Needham)

The subsequent throwing experiments were designed to test several descriptions of throwing methods by different authors (Table 4.5). Three core methods used the spindle-wheel to add twist, and have been named after the authors who described them (Burnham 1968; Kuhn 1988, 405; and Desrosiers 2019). The methods, also discussed in Chapter 2, are based on overlapping principles but aim to produce different degrees of twist, using different numbers of combined filaments. An additional method not described by a specific author used the spindle-wheel to combine multiple strands of silk without the intentional addition of twist, as silk with no discernible twist is found in many surviving silk textiles. In addition to the spindle-wheel method, select samples were twisted using a drop spindle, creating samples of 2 strands twisted together in the Z direction, and 2 of these Z-twisted strands twisted together in the opposite direction (S). The use of a drop spindle is based on numerous suggestions that the drop spindle may have been used in some contexts for silk throwing, particularly in Europe (Dixon 1895, 220; Lacey 1987, 187; Kuhn 1988, 90). Finally, the previously described mock “silk mill” method was tested to mimic the mechanical operations of late-medieval silk-throwing mills. This did not perfectly duplicate the process, but did allow for useful observations regarding the degree of twist resulting from different speed ratios between the reel and the quill.



Method	Description	Projected Result
Burnham Weft	Filaments from 3 bobbins (which have been wound clockwise) guided up through hook, lightly twisted together in Z direction with spindle wheel	S3Z yarn, low twist
Burnham Warp	Filaments from 2 bobbins (which have been wound clockwise), guided up through hook, more tightly twisted together in Z direction with spindle wheel	S2Z yarn, moderate twist
Kuhn	min. 2 filaments twisted in the opposite direction they were spooled, then doubled and twisted in opposite direction again	?2Z2S or ?2S2Z, moderate twist
Desrosiers	2 narrow bobbins wound with 1 filament each (direction unspecified) fixed so that silk winds from ends, the two filaments are wound together (not adding twist with spindle-wheel) onto 1 bobbin, and finally wound from that bobbin, which is also fixed in place to wind off end	Z2S, very lightly twisted
Drop spindle	No guides on specific method, so filaments from 2 bobbins are guided through suspended ring, and twisted together Z with spindle, producing visible, but not excessive twist, samples are taken from this I2Z yarn, and then two I2Z yarns are twisted together S	I2Z and I2Z2S, moderately twisted
Mock Throwing Mill	E-spinner with quill attachment is placed on the ground below simple reel, oriented so that the quill is on a vertical axis. The silk to be twisted, having been wound onto the quill is then wound onto the reel, from the quill, while the quill spins, thus gaining twist as the silk is wound into a small skein, mimicking the mechanics of larger silk throwing mills	Yarn that is tightly twisted in chosen direction

Table 4.5: Throwing methods key with desired results

As indicated by Table 4.5, the methods tested varied in approach but followed a common set of steps:

1) Raw silk filaments were wound onto 4-armed bobbins;
2) The silk from 2 or 3 bobbins were passed through a smooth sanded bamboo ring (Figure 4.19), a stand-in for the “hook” described by Kuhn (1988, 169);
3) The silk strands were then combined with or without twist using the appropriate equipment and method;
4) Samples were collected by winding several metres onto a labelled card and winding the rest (if not set aside for plying) into a small skein using one of the 4-armed bobbins for later degumming;
5) Samples were stored in labelled bags and recorded in the sample catalogue (Appendix F);
6) Thrown samples were twisted together in opposite direction (plied) if method called for this;

a) Plied samples were also collected and labelled as per steps 4 & 5.

Wherever possible, the degree of twist added to each sample was based on the written descriptions consulted.

Figure 4.19: Silk filaments passing through a bamboo ring suspended from the roof of a Henson teaching hut (Photo: Andy Needham)

4.3.3 Rationale for Sampling of Thrown Silk

During the throwing process, samples of raw thrown silk were collected for each throwing variation, and a skein of the same silk was wound and secured with cotton ties for later degumming. 39 samples of thrown silk were produced from silk reeled using the simple reel, while an additional 7 samples were produced using silk produced with the treadled reeling-frame. The notably higher number of thrown samples produced from silk reeled with the simple reel is a result of practical considerations during the reeling and spooling process: as previously mentioned, the smaller diameter of the reel meant that the skein could not simply be pulled from it and transferred to the custom-built swift for processing at a later time. This meant that silk had to be wound off the end of the reel and onto spools in-situ and immediately after reeling, in order to avoid the silk constricting against the reel and breaking as it dried. Once the silk was wound onto the spools it was also practical to throw it immediately. In contrast, silk samples pulled from the reels as a whole skein were easily stored for later processing, which removed the time pressure of throwing in-situ, and allowed for more careful and intentional sampling to be carried out. Some experiments using the simple reel gave rise to complications that required a modified sampling approach. In these cases, the silk either could not be thrown (but reeled filament samples were gathered), or the silk was removed from the reel as a skein and transferred onto a modern swift with more flexible dimensions than the custom-built version.

4.3.4 Complications

4.3.4.1 Drive-band Slipping off Spindle-wheel

The flexibility of the bamboo spokes of the spindle-wheel resulted in a tendency for the drive-band to slip out of its cord support. As was the case with the drive band of the treadled reeling-frame, this complication particularly arose on humid days, either because of a loss of rigidity in the spokes, an expansion of the drive band increasing the risk of slipping, or a combination of these factors. This meant that while the spindle-wheel was used to twist silk in a relatively efficient manner when operating smoothly, the process was significantly slowed down on days where the drive band was prone to jump out of place.

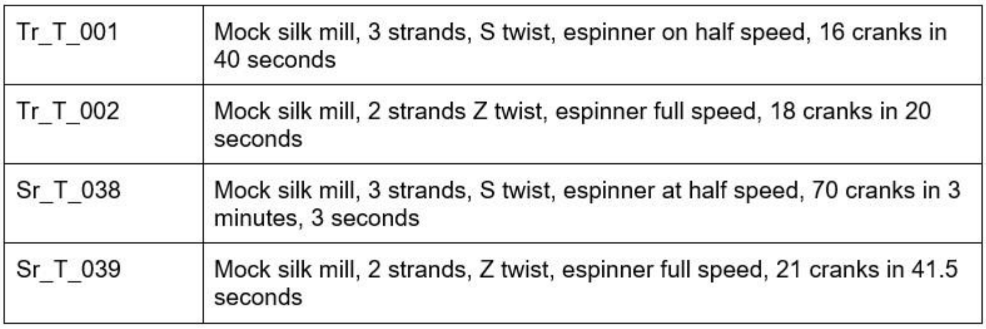
This issue was partially resolved with the use of small bamboo wedges to adjust the position of the spokes and reduce the risk of shifting. This would likely not be an issue on a wheel with more rigid spokes.

4.3.4.2 Documenting twist per metre

The approach to estimating the number of twists per metre achieved with the spindle-wheel has been described. This same approach could not be easily taken with the other throwing methods that used either a drop spindle or e-spinner. In the case of the drop spindle, twisting was primarily done by feel while standing, by gradually feeding more length of silk filament until the rotating spindle was close to the ground (Figure 4.20) and then allowing the spindle to continue to rotate for 5-10 seconds until there was a visible twist in the filaments. This allowed some control but meant that the number of twists per metre could not be estimated during the experiment and could only be assessed during the analysis stage.

Figure 4.20: The drop spindle in use (Photo: Andy Needham)

More control was possible with the mock silk mill and the number of times the simple reel was cranked in a set time interval was recorded, as was the e-spinner speed setting (Table 4.6). That said, a still unknown variable is the RPM of the e-spinner motor, meaning that the number of rotations made by the quill during the time interval could not be estimated.



Tr_T_001	Mock silk mill, 3 strands, S twist, espinner on half speed, 16 cranks in 40 seconds
Tr_T_002	Mock silk mill, 2 strands Z twist, espinner full speed, 18 cranks in 20 seconds
Sr_T_038	Mock silk mill, 3 strands, S twist, espinner at half speed, 70 cranks in 3 minutes, 3 seconds
Sr_T_039	Mock silk mill, 2 strands, Z twist, espinner full speed, 21 cranks in 41.5 seconds

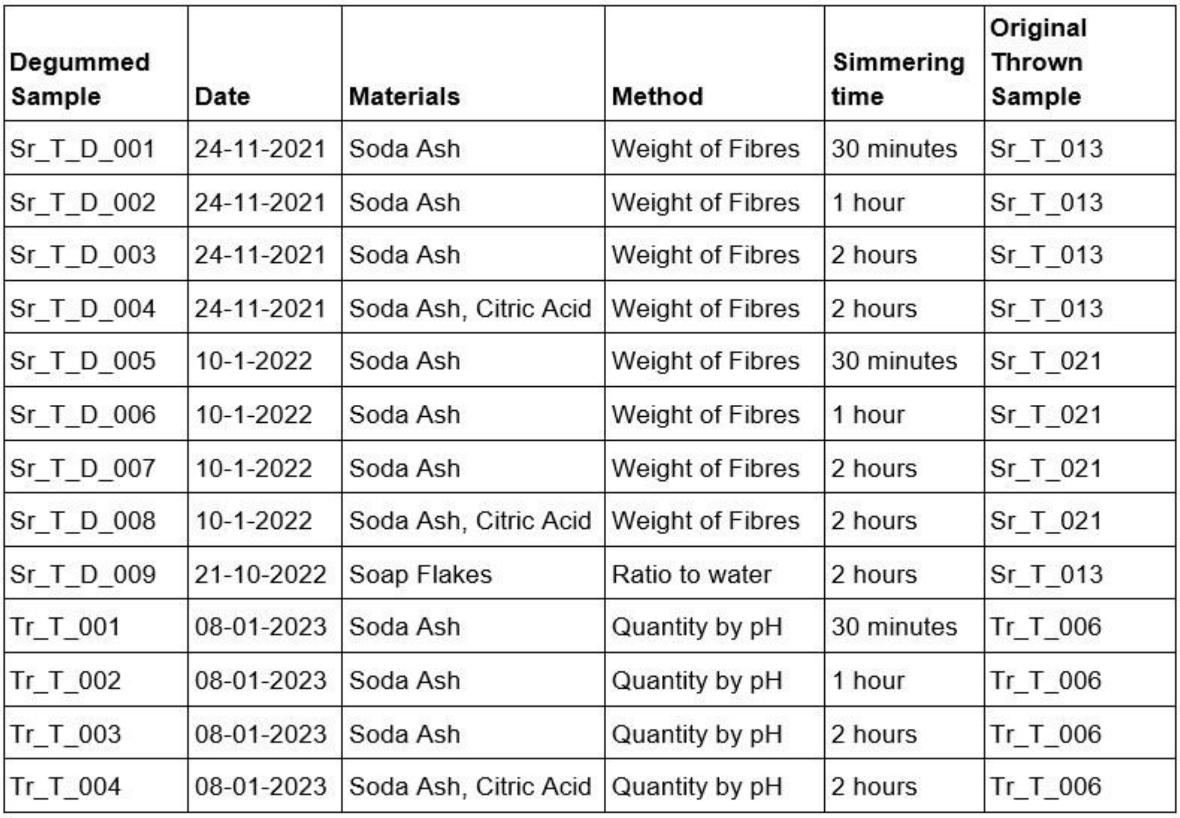
Table 4.6: Specifications of thrown silk samples produced using the Mock silk mill method

4.4 Degumming

Degumming was determined to be an important process to trial early in the experiments, as the change to the visual and haptic properties of silk resulting from the process are significant and require documentation to form a complete reference collection. As has been previously discussed, there are some surviving descriptions of the degumming process from historical records, although in some cases the degumming methods described addressed the preparation of cocoons for spinning rather than degumming reeled silk. Additionally, these descriptions are not always explicit about the quantities of chemicals used, or, if they are, they are often described in relation to a process carried out at a significantly larger scale than the planned experiments. Establishing a base quantity of degumming agent was crucial to avoiding severe damage to the fibres and mitigating the potential health risks resulting from overuse of an alkaline additive. The degumming experiment designs therefore incorporated additional information from contemporary degumming recipes to fill in information gaps from earlier sources.

4.4.1 Equipment & Materials

No specialist equipment was constructed for the degumming process. Instead, a range of common kitchen items were used including a stainless-steel pot, a borosilicate glass bowl, and a set of measuring spoons. A jeweller’s scale was used to weigh out the degumming agents used in different combinations and quantities during the experiments (Table 4.7) and litmus strips were used to test water pH.



Degummed Sample	Date	Materials	Method	Simmering time	Original Thrown Sample
Sr_T_D_001	24-11-2021	Soda Ash	Weight of Fibres	30 minutes	Sr_T_013
Sr_T_D_002	24-11-2021	Soda Ash	Weight of Fibres	1 hour	Sr_T_013
Sr_T_D_003	24-11-2021	Soda Ash	Weight of Fibres	2 hours	Sr_T_013
Sr_T_D_004	24-11-2021	Soda Ash, Citric Acid	Weight of Fibres	2 hours	Sr_T_013
Sr_T_D_005	10-1-2022	Soda Ash	Weight of Fibres	30 minutes	Sr_T_021
Sr_T_D_006	10-1-2022	Soda Ash	Weight of Fibres	1 hour	Sr_T_021
Sr_T_D_007	10-1-2022	Soda Ash	Weight of Fibres	2 hours	Sr_T_021
Sr_T_D_008	10-1-2022	Soda Ash, Citric Acid	Weight of Fibres	2 hours	Sr_T_021
Sr_T_D_009	21-10-2022	Soap Flakes	Ratio to water	2 hours	Sr_T_013
Tr_T_001	08-01-2023	Soda Ash	Quantity by pH	30 minutes	Tr_T_006
Tr_T_002	08-01-2023	Soda Ash	Quantity by pH	1 hour	Tr_T_006
Tr_T_003	08-01-2023	Soda Ash	Quantity by pH	2 hours	Tr_T_006
Tr_T_004	08-01-2023	Soda Ash, Citric Acid	Quantity by pH	2 hours	Tr_T_006

Table 4.7: Degummed samples with corresponding methods, materials, and number of original thrown samples

4.4.2 Method

Several methods of degumming were trialled to assess the effects of both the length of time simmering, and the quantity of degumming agent on sericin integrity.

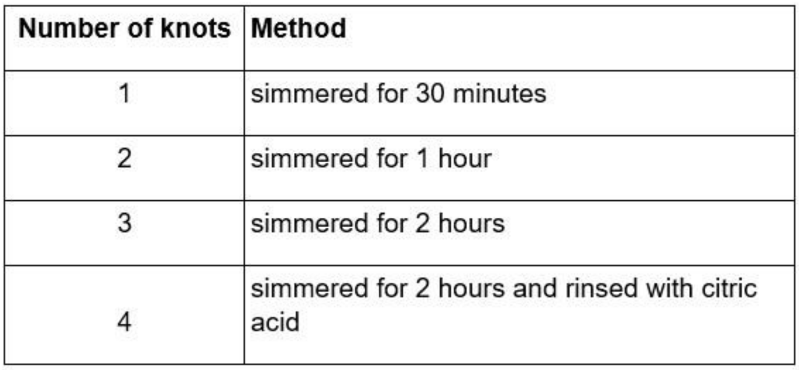
In preparation for conducting the degumming experiments, several parameters were established:

- The goal temperature for degumming was set at 80°C based on an estimate from Kuhn (1988, 85), and directions from 2 contemporary sources, one that urges that the silk not be boiled, the other that discourages a temperature exceeding 95°C (Holland 2015; Kumar 2018).
- Lengths of time for simmering were set depending on the method used and in reference to both contemporary and historical sources, which vary widely in the suggested simmering time. A minimum of 30 minutes (Cook 2004; Kumar 2018) and a maximum of 2 hours (Hooper 1900, 49) provided the range for simmering times.
- An alkalinity maximum of pH 9 was established based on precautions from contemporary sources (Holland 2015; Kumar 2018).
- Soda Ash was selected as a primary degumming agent for these experiments, as it is noted by Kuhn as being described in the *Bin Feng Guan I* from 1756 (Kuhn 1988, 84). “Washing Soda” is also a key ingredient in a degumming solution described by Michael Cook(2023), an experienced textile artist and silk-reeler.
- Soap flakes were selected as a secondary degumming agent, as the use of soap in this process is described in several post-medieval European manuals, as well as in degumming descriptions from present-day sources (Lardner 1831, 173; Hooper 1900, 49; Holland 2015)

4.4.2.1 First set of experiments, quantity of degumming agent determined by weight of yarn

The first degumming trials were conducted using a quantity of sodium carbonate (also called soda ash or washing soda) equivalent to ⅓ of the weight of the silk to be degummed. This quantity was based on a written source from 1831, which was the only source to provide a measure of degumming agent based on the weight of silk (Lardner 1831, 173).

Four small skeins of Sr_T_013 were prepared for simultaneous degumming during the first trial. Each skein was then removed from the bath at successive time increments of 30 minutes, 1 hour, and 2 hours. The third and fourth skein were both to simmered for 2 hours. The 4th skein was to be rinsed in a mild citric-acid solution, a method not mentioned in historical sources, but which is described by Michael Cook (Cook 2004) as a way to balance the silk’s pH post-degumming, and prevent fibre deterioration. The simultaneous degumming of the skeins combined with incremental removal ensured that all 4 skeins were exposed to the same degumming conditions, in order to more accurately assess the importance of the length of simmering time. To differentiate between the skeins, each was coded with a cotton string tied with a set number of knots, corresponding to its simmering time and any additional treatment (Table 4.8).



Number of knots	Method
1	simmered for 30 minutes
2	simmered for 1 hour
3	simmered for 2 hours
4	simmered for 2 hours and rinsed with citric acid

Table 4.8: Coded string key showing the number of knots correlating to specific degumming methods.

The total weight of the 4 skeins equalled 0.356g, therefore 0.119g (⅓ of the weight of the silk rounded to 3 decimal places) of soda ash was required for the experiment. Precision measuring of such small quantities proved difficult, and the total quantity of soda ash measured outweighed 0.122g. A citric-acid solution was also mixed in advance, comprising 75 ml of water and 3g of citric acid crystals. The resulting solution had a pH of 3.

The string-coded skeins were soaked in warm water prior to degumming; this was based on 2 descriptions (Kuhn 1988, 83; Hooper 1900, 37) that mention soaking or washing the silk prior to degumming. Three litres of tap water were added to the Jam pan, and the initial PH was measured to be 6. This first experiment was conducted in an outdoor setting using a camp stove. In this setting the water temperature could not be raised above 75°C due to weather conditions, so the soda ash was added once this temperature was reached. Following the addition of the small quantity of soda ash, the pH did not shift from 6. This was cause for some concern, as one contemporary source stated that an alkaline degumming reaction would occur at a pH of 9 (Kumar 2018). In the interest of shifting the pH of the water to at least slightly higher than 6, an additional 0.130g of soda ash was added, which just shifted the pH to 7. After each skein was removed at the appropriate time increment it was rinsed twice in tap water at pH 6, with the exception of the fourth skein, which was rinsed once in tap water with pH 5-6, a second time in water shifted to pH 4-5 with citric-acid solution, and finally rinsed once more in unaltered tap water.

Once the skeins of silk had dried it was clear from their texture that these trials did not fully strip the sericin from the fibres. It was hypothesised that this was due to the water maintaining an alkalinity below pH 6, but the difficulty in controlling the water temperature added an undesirable variable that also needed to be addressed. The experiment was therefore repeated with the same quantity of soda ash in an indoor setting using an electric hotplate. The repeated experiment produced similar results, with possibly marginally improved sericin removal. The fibres were, however, determined by touch to be more heavily coated in sericin than desired, which highlighted the need for additional experimentation to explore the influence of water pH on the degumming process.

4.4.2.2 Soap Degumming method

An experiment trialling a method of degumming soap flakes had already been planned prior to the disappointing result of the first sets of experiments with soda ash. This experiment was based primarily on instructions from the George Weil website, which advises a quantity of 8g of soap flakes per litre of water, while the simmering time was based on Hooper’s instructions, which advise that the silk be “boiled gently for two hours" (Hooper 1900, 49). Notwithstanding Hooper's description, the temperature of the water was kept to 80°C.

No time variations were trialled for this experiment, so a single skein of silk (Sr_T_013) weighing 0.219g was soaked in tap water prior to degumming and added to the litre of soapy water once a temperature of 80°C had been reached. Prior to adding the skein of silk, the pH of the soapy water was measured to be 9. Following 2 hours of simmering, the skein was removed and rinsed with tap water in a bowl until it was no longer slippery in texture. The resulting sample was dried and wound onto a labelled acid-free card. This method was observed to have stripped the sericin, and the silk was also noted to tangle more easily than previous samples when wound onto a sample card.

4.4.2.3 Soda Ash Degumming by PH

A final degumming experiment was carried out indoors, following the same steps as the first 2 soda ash experiments, including testing 3 time-increments and contrasting the rinsing of one skein of silk with a citric acid rinse. In contrast to the previous soda ash experiments – which based the quantity of degumming agent on the weight of the silk – quantity was determined by water pH. Prior to beginning the experiment, 2 measuring spoons were used to measure and weigh quantities of soda ash. A levelled ¼ teaspoon of soda ash was determined to weigh 0.616g, and a smaller levelled spoon (less than 1/16 of a teaspoon) of soda ash was determined to weigh 0.092g. These 2 measures were used to incrementally add the soda ash to 3l of 80°C tap water (pH6 unmodified), testing with pH indicator strips between each addition until the pH measured 9. The total quantity (¼ teaspoon + 5 smaller spoons) of soda ash added to reach pH 9 weighed 1.076g. Following the addition of the requisite quantity of soda ash, the 4 string-coded skeins of Tr_T_006 were added to the water, suspended by strings from a bamboo skewer, and removed incrementally and rinsed as previously described.

4.4.3 Complications

Weather proved to inhibit temperature regulation of the degumming process significantly, which may be the result of conducting the experiments in late autumn in contrast to the reeling experiments, which, while vulnerable to some weather-related disruptions did not suffer nearly as much when it came to water temperature control. Other factors to consider are the difference in material of the water pan (copper for the reeling experiments, stainless steel for the degumming experiments). However, this was a necessary change as the risk of soap or soda ash residue on the copper reeling basin impacting future reeling experiments was taken into consideration. Regardless, moving the degumming experiments indoors was a reasonable accommodation to ensure the success of the trials.

Another important consideration was the adaptation of recipes typically designed for much larger-scale silk production, to the experiments that trialled degumming with very small skeins of silk. This is significant particularly when adapting a recipe based on the weight of the silk itself, as ⅓ the weight of larger quantity of silk, may equate to enough degumming agent to properly strip the sericin from the silk fibres. This highlights the need for flexibility and the consideration of disparate material quantities when adapting historical recipes and/or methods.

A final complication encountered during these experiments was the tangling of some degummed silk samples once they had dried. It is worth noting that mitigations for silk tangling were necessary during this process, which in some cases involved cutting the silk yarn and winding the remaining silk on a new labelled card.

4.5 Summary

There is a potentially infinite number of variations of reeling, throwing, and degumming methods, particularly when considering the combination of the 3 steps to produce a finished skein of yarn. It was, therefore, a daunting task to narrow the number of methods and combinations of methods trialled to an achievable number, while also trialling a wide enough spread of approaches to produce a useful reference collection. The reference collection produced through this series of experiments should therefore be regarded as a starting point, upon which future research and experimentation may be built. The methods described, along with the identified pitfalls and areas for improvement should provide a framework for designing solid, repeatable silk-processing experiments, helping to further improve our understanding of silk production throughout history. The information that can be gleaned specifically from this set of experiments will be discussed further in Chapter 5.

5 Results of Silk-Processing Experiments

5.1 Introduction

This chapter will discuss the results of the silk-reeling, throwing, and degumming experiments, starting with an explanation of the reference collection the experiments generated. The results of the analysis of this reference collection will be discussed in detail in Chapter 7. The focus of this chapter is on the often less tangible results, in the form of observations gathered throughout the experimental process. This includes the tactile and visual aspects of the reeling process that will be discussed in relation to certain aspects of craft. The 3 stages of production will also be discussed in relation to the existing literature on silk manufacture covered in chapter 2.

5.2 The Reeled-Silk Reference Collection

The silk-processing experiments generated a collection of silk samples corresponding to different silk-reeling, throwing, and degumming methods. In total the experiments yielded 73 raw silk samples, 46 thrown silk samples, and 13 thrown and degummed samples. Of the raw silk samples, 23 were reeled with the simple reeling frame, and 50 were reeled with the treadled reeling frame. Within this collection, the reeled and degummed samples were particularly useful for comparison with the archaeological silk fibres, while the throwing experiments generated less comparable results.

5.3 Observations from Silk-processing experiments

The silk-processing experiments generated 2 types of observation overall:

1. Observations on the products of the experiments
2. Observations on the actual processes

The 3 stages of reeling, throwing, and degumming allowed for a variety of different observations applicable to the study of archaeological silk textiles. The key observations are described below.

5.4 Reeling

5.4.1 The Reeled Silk

Prior to any microscopic analysis, the silk-reeling experiments were observed to have a clear influence on the appearance and texture of the silk produced. This was particularly clear following the treadled reeling-frame experiments, due to the approach taken in collecting and storing the reeled silk. The different experimental conditions were observed to influence the colour of the silk generated (Figure 5.1), wherein lower water temperature leading to longer cocoon soaking times darkened the colour of the silk, as did reeling with higher numbers of cocoons. The brightest white silk generated was reeled from only 3 cocoons at a time (Tr_024-026) and had a relatively short soaking time. Higher numbers of cocoons also resulted in noticeably thicker silk filaments, which were also coarser and stiffer to the touch and noticeably more resistant to breaks.

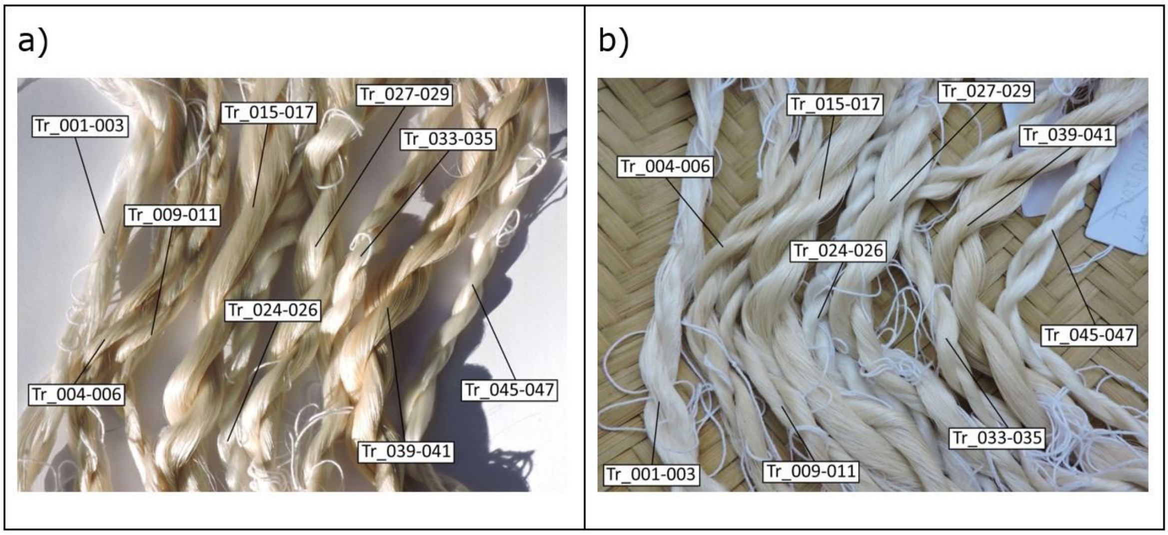
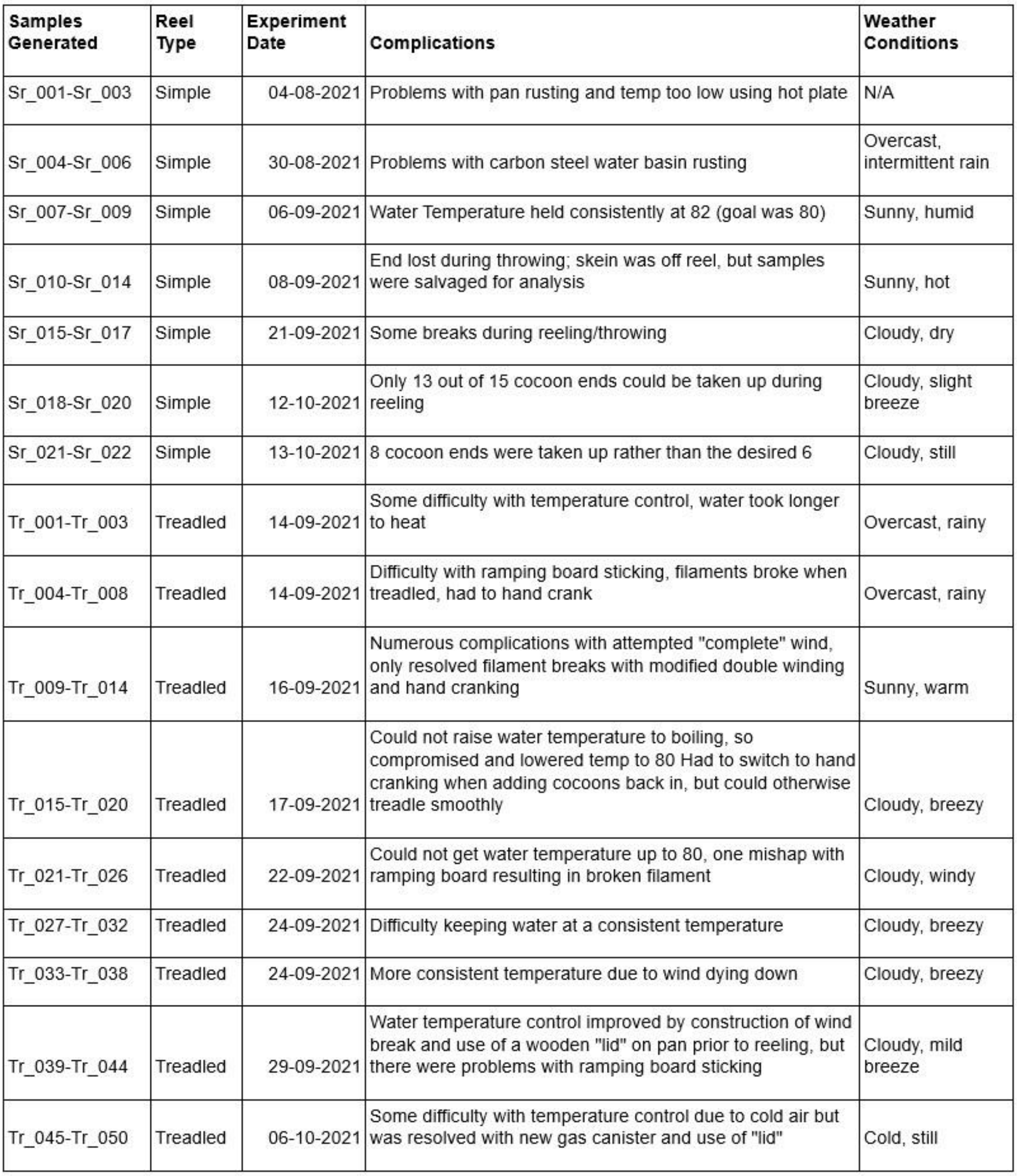


Figure 5.1:Skeins of raw silk reeled using the treadled reeling-frame pictured in bright sunlight (a) and shade (b) showing variation in colour and texture (Source: the author)

5.4.2 The Process

Certain complications were encountered during the reeling process (Table 5.1) that can be linked in part to external variables. The treadled reeling-frame was more prone to equipment-related complications given the higher number of moving parts. Additionally, certain wrapping methods were more likely to result in filament breaks, as these methods increased the tension placed on the filaments.



Samples Generated	Reel Type	Experiment Date	Complications	Weather Conditions
Sr_001-Sr_003	Simple	04-08-2021	Problems with pan rusting and temp too low using hot plate	N/A
Sr_004-Sr_006	Simple	30-08-2021	Problems with carbon steel water basin rusting	Overcast, intermittent rain
Sr_007-Sr_009	Simple	06-09-2021	Water Temperature held consistently at 82 (goal was 80)	Sunny, humid
Sr_010-Sr_014	Simple	08-09-2021	End lost during throwing; skein was off reel, but samples were salvaged for analysis	Sunny, hot
Sr_015-Sr_017	Simple	21-09-2021	Some breaks during reeling/throwing	Cloudy, dry
Sr_018-Sr_020	Simple	12-10-2021	Only 13 out of 15 cocoon ends could be taken up during reeling	Cloudy, slight breeze
Sr_021-Sr_022	Simple	13-10-2021	8 cocoon ends were taken up rather than the desired 6	Cloudy, still
Tr_001-Tr_003	Treadled	14-09-2021	Some difficulty with temperature control, water took longer to heat	Overcast, rainy
Tr_004-Tr_008	Treadled	14-09-2021	Difficulty with ramping board sticking, filaments broke when treadled, had to hand crank	Overcast, rainy
Tr_009-Tr_014	Treadled	16-09-2021	Numerous complications with attempted "complete" wind, only resolved filament breaks with modified double winding and hand cranking	Sunny, warm
Tr_015-Tr_020	Treadled	17-09-2021	Could not raise water temperature to boiling, so compromised and lowered temp to 80 Had to switch to hand cranking when adding cocoons back in, but could otherwise treadle smoothly	Cloudy, breezy
Tr_021-Tr_026	Treadled	22-09-2021	Could not get water temperature up to 80, one mishap with ramping board resulting in broken filament	Cloudy, windy
Tr_027-Tr_032	Treadled	24-09-2021	Difficulty keeping water at a consistent temperature	Cloudy, breezy
Tr_033-Tr_038	Treadled	24-09-2021	More consistent temperature due to wind dying down	Cloudy, breezy
Tr_039-Tr_044	Treadled	29-09-2021	Water temperature control improved by construction of wind break and use of a wooden "lid" on pan prior to reeling, but there were problems with ramping board sticking	Cloudy, mild breeze
Tr_045-Tr_050	Treadled	06-10-2021	Some difficulty with temperature control due to cold air but was resolved with new gas canister and use of "lid"	Cold, still

Table 5.1:Complications encountered during reeling process and the associated weather conditions

Weather conditions were observed to have a notable impact on the reeling experiments. Damp conditions had a particularly negative impact on the treadled reeling-frame as the swelling of the wooden parts hindered the function of the ramping-board and slowed down the reeling process. That said, the most clearly measurable impact of weather conditions was the influence of windy conditions on the water temperature in the reeling basin (Figure 5.2). Windy and even breezy conditions on colder days resulted on more than one occasion in lower water temperatures than desired. In contrast, hot and still days supported higher water temperatures and on one occasion resulted in a slightly higher water temperature than the set goal. Later experiments mitigated some temperature control issues with use of a wooden “lid” that offset weather conditions to some extent. The result was that consistent temperatures within 1-2° of the desired temperature were typically achieved, but these inconsistent temperature days need to be taken into consideration, particularly when assessing the influence of water temperature on the process and results of silk-reeling.

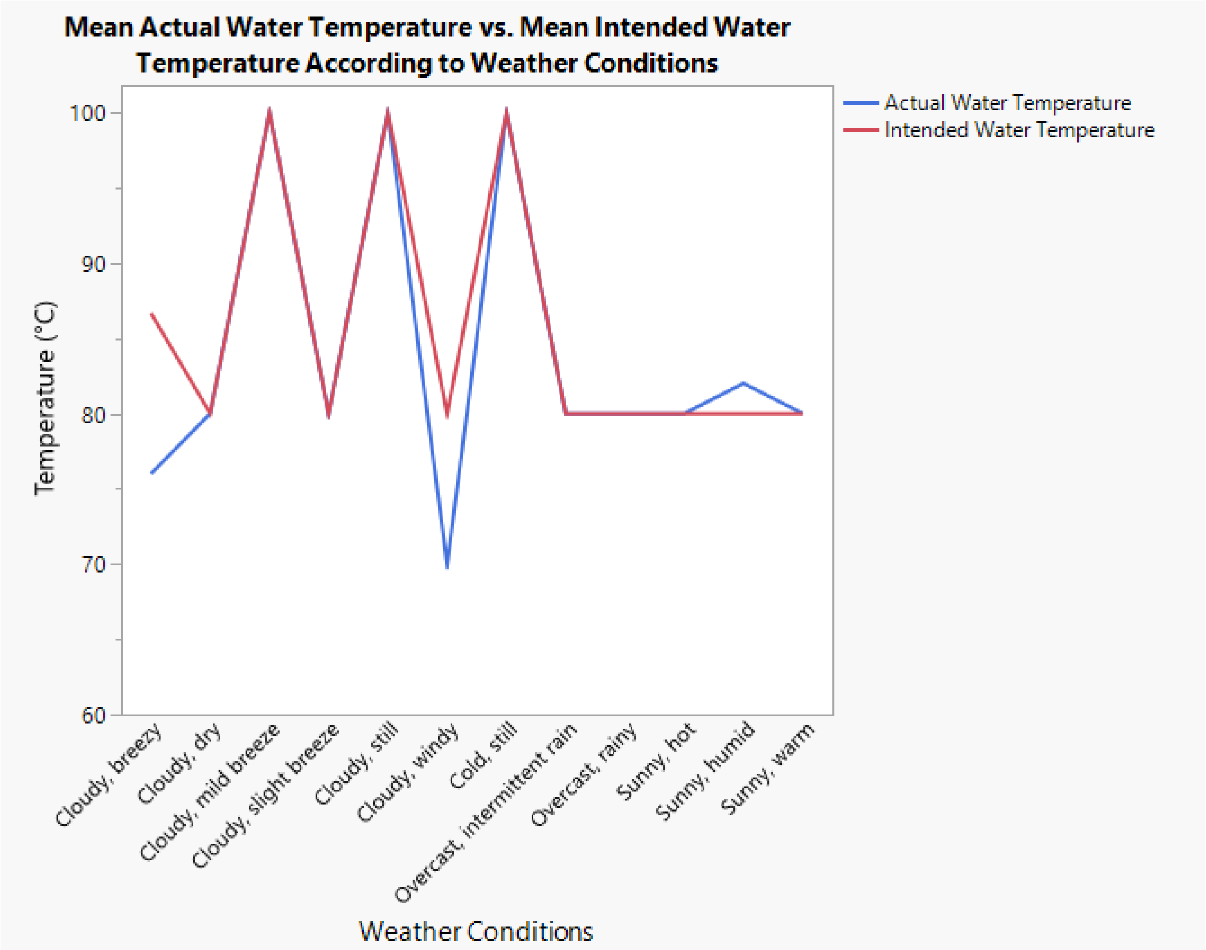


Figure 5.2:The average actual water temperatures achieved in contrast to the intended water temperatures in relation to weather conditions

During the experiments, the temperature of the water was observed to have an influence on the number of cocoons from which fibres were successfully reeled during a given experiment. A noticeable trend was observed, in which water temperatures sitting consistently below 80°C increased the likelihood of a lower number of cocoons than intended being reeled. In contrast, boiling water temperatures brought the number of cocoons picked up in the reeling process above the desired number (Figure 5.3).

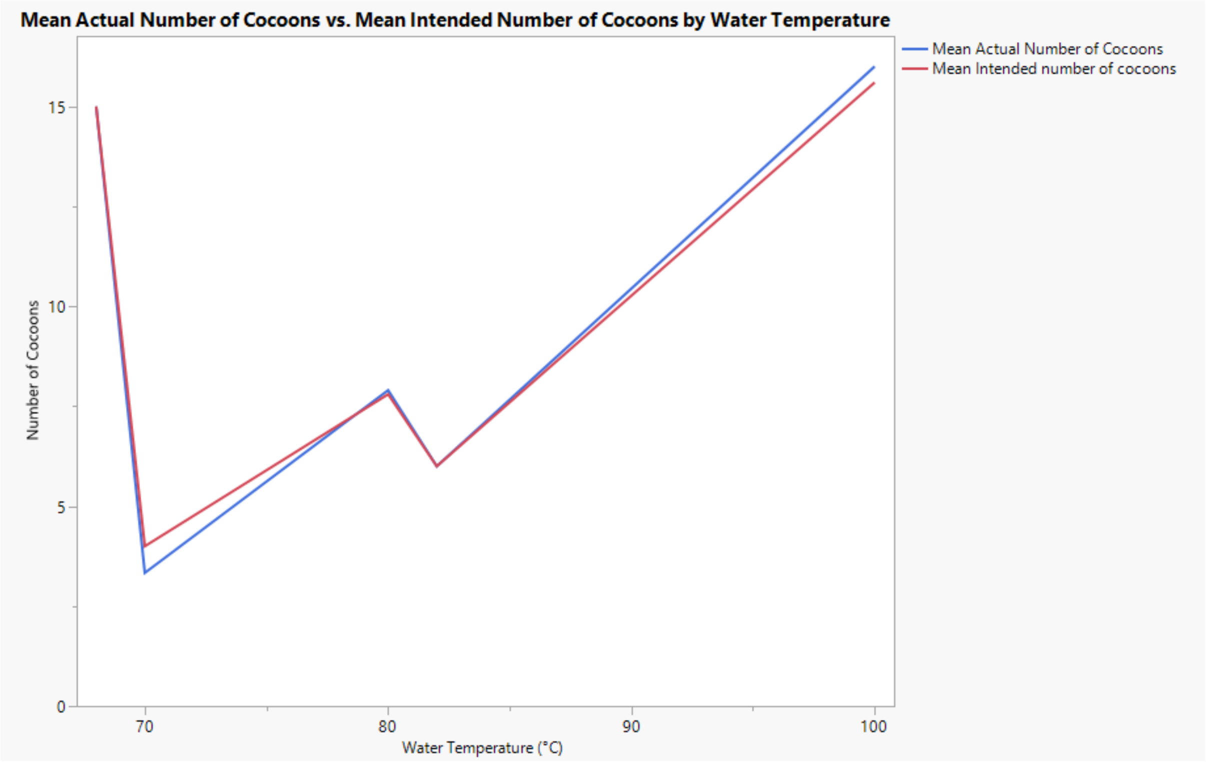


Figure 5.3:Actual numbers of cocoons reeled vs intended number of cocoons in relation to temperature of the water during reeling

Higher water temperatures were also observed to improve the efficiency of the reeling process by allowing for the ends of the silk cocoons to be gathered more easily and quickly, and generally leading to a smoother reeling process overall. Related to a question broached in chapter 2.2.1.3, high water temperatures were not observed to automatically result in the cocoons rotating in the pan. This confirms that cocoon rotation is a manual process that must be initiated by the operator.

5.4.3 Efficacy of crossing methods

The crossing methods trialled showed varying levels of efficacy and efficiency. As discussed in Chapter 4, the “Complete” winding method as theorised by Kuhn was the least successful of the methods tested and may merit further exploration with modified equipment. The single winding method used in combination with the treadled reeling was efficient, and did not significantly increase friction on the reeled filament. The double winding method marginally decreased the efficiency of the reeling process due to a slight increase in friction, which resulted in a slightly higher risk of broken filaments.

The self-crossing method combined with the soundless-roller was successful but did slightly reduce the efficiency of the reeling process, particularly when introducing new cocoons. This became a more pronounced problem due to its combination with the smaller reel, as the slowed reeling process gave the silk more opportunity to shrink on the reel, resulting in an unusable skein of silk. This should primarily be attributed to user error and could be improved a upon with a different reel design, but the fact remains that use of the soundless-roller did slow the process in contrast to reeling with no crossing method.

The most interesting observation during these experiments was the efficiency of the Piedmont crossing method in combination with the treadled reel. The experiments found that the Piedmont crossing method was carried out with little difficulty and no notable reduced efficiency after initial set-up. In fact, this method did not substantially increase the friction on the reeled filaments, which meant fewer instances of stopping to repair filaments occurred in comparison to the double winding method. This contradicts Kuhn’s argument that the piedmont crossing method was slow and difficult, and marks the method as an important innovation in the silk-reeling process, particularly if it can be demonstrated to improve the quality of the silk being reeled.

5.4.4 Visual Cues

The reeling experiments highlighted several important visual cues integral to the reeling process. This included monitoring parts of the reel such as the ramping-board to ensure that it was moving correctly.

Another important visual cue was the motion of the silk cocoons in the water basin. Silk cocoons bob and turn as they are unravelling; therefore, any still cocoons are not being unravelled to form the filament, and need to be reincorporated. The motion of the cocoons is a more reliable visual cue than attempting to count the number of incredibly fine fibres being incorporated into a filament.

Prior to the innovation of thermometers, visual cues would have been a crucial aspect of monitoring water temperature. An important visual cue mentioned in Chapter 2.2.1.2, describes bubbles resembling the eye of a crab as an indication of optimal reeling temperature. This historical description was partially confirmed by observations from the reeling experiments during which “crab eye” bubbles formed on the round-bottomed water pan when the temperature was around 80°C. Notably, these bubbles did not form on the flat-bottomed pan used for most of the experiments. This may have important implications for how water temperature control was approached regionally, as illustrations of silk-reeling from as early as the Song dynasty clearly indicate use of a water pan with a round bottom (See reeling equipment catalogue in Appendix A), which supports the use of this visual cue. While early-medieval images of silk-reeling cannot be found, late-medieval and renaissance European depictions almost universally show flat-bottomed water basins, which would provide less visual indication of the c. 80°C temperature target described by authors specialising in Chinese silk production. The question remains whether the reelers using these basins were more likely to reel at a lower temperature than 80°C, which has been demonstrated to result in less-cohesive filaments, or whether the reelers were more likely to boil the water, to be sure of adequate heat. It is also possible, of course, that preferred water temperature varied regionally, but it can be argued that any water temperatures lower than boiling will have been harder to judge visually when using a flat-bottomed pan.

5.4.5 Silk reeling as a tactile process

The experiments highlighted the importance of haptic experience to the silk-reeling process. When working with such fine fibres, visual cues alone could not be relied upon to ensure that reeling was operating smoothly, as the fine filaments were nearly invisible, particularly in the lower light conditions of overcast days. Without being able to feel the filament passing from the water basin, it would be very easy to continue rotating the reel without noticing that no new silk was being wound. In many instances, complications such as filament breaks were avoided because changes in tension were felt rather than seen and could be quickly corrected. In instances where broken filaments could not be avoided, they were at least detected instantly because the loss of tension was felt. This observation reflects a statement made by Bunn (2022, 70), that "…one aspect of technological expertise is to be able to feel the potential within the material through one's hands and through tools"

Both making and using material culture is described by Dobres as a sensuous physical experience, which marks both producers and consumers (Dobres 2000, 128). In the case of these experiments the physicality of silk-reeling included some unconscious postures and movements. The social process of communicating with volunteers during the experiments resulted in the recognition of these gestures, such as a particular twirl of the wrist while gathering the loose ends of cocoons, or the pinching of silk reeled on the simple reel within the first knuckle of the forefinger while guiding the filament from basin to reel (Figure 5.4), which allowed for control of the filament without the application of too much tension (which could break the silk). These physical gestures were developed through practice and repetition, and it is reasonable to suppose that other unconscious gestures and movements may have developed across different reeling traditions, all of which could have a subtle impact on the quality of reeled silk.

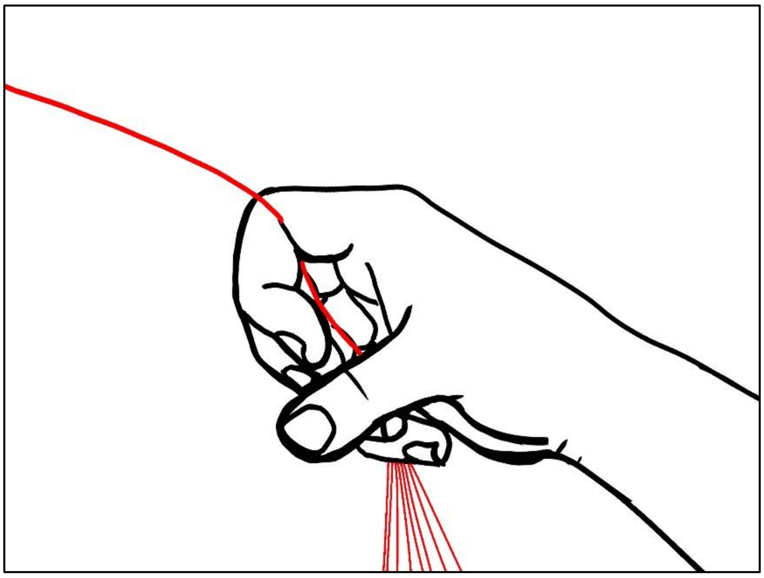


Figure 5.4: Diagram of silk filament being guided with the reel operator's knuckle (Source: the author)

Although these experiments were not designed as a study of knowledge acquisition, the process of working and conversing with volunteers provided the opportunity to reflect on the role of haptic experience in different forms of apprenticeship. Both verbal and non-verbal communication were an important part of this cooperative reeling process, and when assisting with certain actions, several volunteers took on specific gestures when handling silk without specific direction from me. This unintentionally enacted a passive form of apprenticeship, one that fits an informal learning model rather than a more formalised, master-apprentice relationship (Wendrich 2016, 11).

The non-verbal transmission of gestures fits with the phenomenon of technique transmitted through the trappings of tradition as discussed by Lemonnier (2004, 3), ie. an apprentice doing things the way their teacher did because “that’s the way it’s done”. Furthermore, many of these often-unconscious gestures may be considered reflective of an experienced silk-reeler’s tacit knowledge. On this topic, Lise Bender Jorgensen (2016, 242-45) argues that “the language of craftsmanship and professional knowledge is far from tacit”, rather that there is a lack of clearly defined vocabularies appropriate to communicating this knowledge. This issue was borne out through a lack of terminology for some of the subtle gestures described. This disconnect between language and haptic experience relates to a recognised tension between 2 different ways of understanding craft processes as described by archaeologist and carpenter Harald Bentz Høgseth as "knowing how" and "knowing what". Høgseth (Høgseth 2012, 67) links "knowing how" to the physical knowledge of the craftsperson as they carry out their work. Tacit knowledge of these intuitive movements is acquired through social processes whether through formal or informal apprenticeship . "Knowing what", in contrast, is linked to the ability to reflect upon and describe the techniques used (Høgseth 2012, 64). In this case "knowing what" can be achieved by any analyst studying archaeological textiles, but without the "knowing how" achieved through practical engagement with relevant material processes, many technical features of a textile may be subject to unsubstantiated speculation or remain a mystery altogether.

Underlining the importance of tacit knowledge developed through practice to the success of a craft process, are the failed experimental attempts: particularly the attempt to trial the "complete winding" method described by Kuhn. Kuhn highlights the complexity of this process, stating that, "'Complete winding' was bound to "fail" in the context of becoming the prevalent method during the Northern Song (960-1127 CE), while explaining that "the method could only work out when the operative had already gained some experience with this type of reeling and had in addition a well-developed flair for balancing the tensions". He goes on to suggest that styles of roller frame from the 19th century onwards were more suitably balanced with an appropriate application of trigonometric ratios, which apparently improved the ease with which the complete winding method could be carried out (Kuhn 1988, 389). This suggests that the complete winding method was unlikely to be frequently applied to silk-reeling during the Song dynasty, while also underscoring the importance of both hands-on experience and an understanding of correct tension when reeling silk. This example from Kuhn's writing underscores the interrelationship between a tactile understanding of the silk-reeling process and the type of equipment used.

5.5 Throwing

5.5.1 The Thrown Silk

A key observation of the thrown silk was that its “springy” nature when in a raw state resulted in the silk untwisting more easily. It was also observed that the twisted silk did not acquire as much twist as was expected from any of the techniques tested. This was obvious even without angle of twist measurements being taken (Figure 5.5) and it was concluded early on that a comparison of twist angle between the experimental silk and archaeological silk textiles would not produce useful results. This does however highlight throwing methods as a particularly interesting topic for future focussed experimental study.

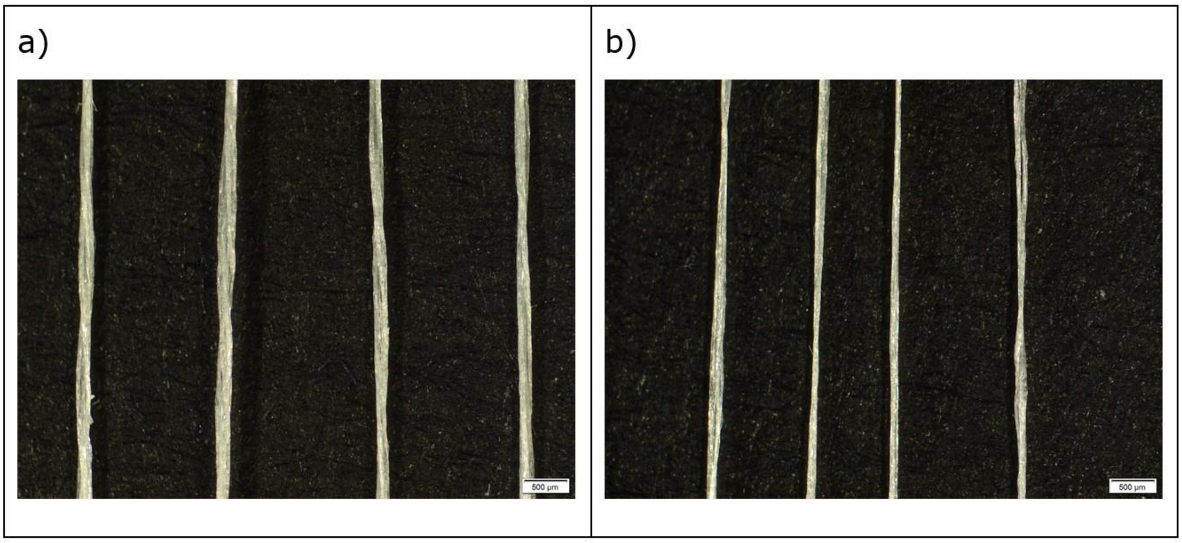


Figure 5.5:Reflected light micrograph of experimental silk sample Sr_T_035 (a), and Sr_T_039 (b), viewed at 20x magnification

5.5.2 The Process

The silk-throwing experiments highlighted how time-consuming the process of adding twist to fine silk is. While these experiments were not timed precisely, it was observed early on that the amount of silk reeled in one experimental session could not be twisted into a suitable yarn in the equivalent time. In fact, it would have been impossible to add twist to all of the silk from one reeling session in a single-day throwing session, as even the selected sampling approach to throwing experiments required multiple full-day sessions to process only portions of the silk reeled. It was also observed that, even when using the spindle-wheel, producing yarn with higher twist (relative to the range of twist produced during these experiments) increased the required processing time.

The throwing process also presented another opportunity to remove uneven sections of silk filament, by cutting them out and rejoining the ends with an overhand knot, which is less noticeable in the overall finished thread than a particularly coarse section of filament. This level of "quality control" does add to the time taken during the throwing process, which is already significantly greater than the time it takes to reel silk if twist is being introduced.

Overall, a key takeaway from the throwing experiments is just how time-consuming the process of twisting silk is. The time-consuming nature of silk twisting is frequently alluded to but is typically framed within the context of technological innovations. For example, Kuhn's discussion of the development of the spindle-wheel frames it as a more efficient twisting device than a spindle (Kuhn 1988, 156). Similarly, the multiple twisting frame, established in places like Bologna, is praised for its efficiency (Bartolomei and Ippolito 2016, 35), in particular because of the number of spindles operated simultaneously, but degree of twist is not explicitly discussed. Other writing discusses the technical steps of twisting (Farmer 2014, 387–388), or mentions the "ease" of producing silk without twist (Desrosiers 2019, para.18), but typically focusses on technological differences in production rather than differences in time expended. This overall pattern emphasises the role of technology in improving the efficiency of silk twisting and operates on the premise that silk twisting is a bottleneck, but little attention has been paid to the time investment of producing silk with higher degrees of twist. The experiments have confirmed the throwing stage as a bottleneck in silk production. Furthermore, it can be safely concluded that any silk yarn with a moderate to high degree of twist will have taken a significantly longer time to produce than any silk yarn with low or no twist.

5.6 Degumming

5.6.1 The Degummed Silk

The degumming experiments yielded different results regarding the amount of sericin stripped from the silk. Prior to microscopic analysis, this was primarily felt when the samples were wound onto sample cards after drying at the end of the degumming process. The early experiments – which based the quantity of degumming agent on weight of silk – resulted in silk that was still stiff, and even if it was not to be described as raw, it was evident from texture alone that there was still a high level of sericin preservation in the samples produced. This was more pronounced with samples degummed at a lower temperature than in the samples simmered in 80°C water, and increased degumming time did appear to yield results that were slightly less stiff, particularly when citric acid was used as a rinsing additive.

In contrast, the silk samples that were degummed using a method that prioritised raising the pH of the water were noticeably softer and shinier following the degumming process. These tactile and visual differences in the samples demonstrate the functional effects of the degumming process as they would be perceived by someone working with or purchasing silk. The effects of degumming observed on a microscopic level will be discussed in Chapters 7.5.1 and 8.3.1.2 .

5.6.2 The Process

Complications during the degumming process were primarily a result of weather affecting water temperature during the first experiment, and an uncertainty around the quantity of degumming agent to be used, emerging from gaps in information from primary sources. The overall process had relatively few other complications. That said, it was noted that samples with extremely low twist or no twist were more prone to tangling following degumming, and in one case, the sample needed to be cut after forming a knot that was too tight to be undone.

5.7 Saving silk, saving time

The efficiency of silk-reeling processes has been an important discussion point in Kuhn’s writing, and is often the explanation provided for the enduring popularity of simpler reeling methods that use uncomplicated equipment (Kuhn 1988, 389). When considering the economy of silk production, there were 2 things throughout the experiments that could be saved: time and the silk itself. The process of reeling silk inevitably produces waste. This occurs in the form of loose silk floss pulled from the cocoons prior to the beginning of reeling (Figure 5.6): the apparently large masses of waste silk that accumulate while finding the continuous end of each cocoon. Smaller instances of waste also occur in the form of sections of uneven silk cut or broken from the skein during the throwing process (a knot is less disruptive than thick, uneven sections of filament).

Figure 5.6: Waste silk being pulled from the cocoons prior to reeling (Source: the author)

Attempts to reduce silk waste by commencing reeling before the cocoons are properly unravelling were found to result in sections of thick, uneven silk. The temptation to save this waste silk may come from inexperience; I remember explaining to each volunteer who worked with me that the masses of silk being deposited by the basin were not as great as they seemed, relative to the hundreds of metres of silk we would be producing. It is also important to recognise that in other contexts, particularly in regions that relied on cocoon import, that the desire to use every centimetre of silk possible might trump the desire for perfectly fine, smooth silk. This is without factoring in the many ways that waste silk can be processed outside of reeling, as this is not a focus of the experimental research herein.

Uneven patches of silk may also occur when a new cocoon is added, especially if it is added too quickly, but an eye or loop can stop the fresh cocoon from getting tangled in the fine silk. This means that reeling directly from basin to reel can easily result in uneven silk, if care is not taken by the reeler.

Uneven reeled silk can therefore be an indication of equipment used, time saved through rushed reeling, or attempts to save waste silk (particularly at the start of the reeling process). Essentially, the presence of uneven reeled silk *could* be evidence of a lack of skill ("know-how") on the part of the reeler, which is a common interpretation, however, it could equally provide evidence of an economical consideration regarding silk waste or time. Bearing in mind that the intentions of medieval silk reelers cannot be known, it is worth considering the multiple possible interpretations for these characteristics.

5.8 Summary

The observations recorded during the silk-processing experiments demonstrate that different variables in the process do impact both ease of working and efficiency. Weather was identified as an important factor during the reeling process: particularly the relationship between weather conditions and control of water temperature. Water temperature itself was identified as an important variable, related to both the efficiency of the silk-reeling process and to the ease with which fibres could be gathered from the cocoons.

Like the previously mentioned "sea of theory", the current substantial body of research regarding medieval silk production and trade forms an ocean of its own that can also easily submerge a keen researcher in an overwhelming wave of historical detail. Indeed, it can be difficult to see the silk for the narrative. The experimental process has highlighted frequently overlooked visual and tactile aspects of silk production. A clear difference in the visual and tactile properties of the silk manufactured using different methods was also observed. This may have implications when viewed in relation to the results of further macro-and micro- textile analysis and may also be worth taking into consideration in relation to historical descriptions of silk quality.

6 Developing a Protocol for the Analysis of Silk Fibres, Yarn, and Tabby Cloth

6.1 Introduction

The methods of textile and fibre analysis used in this research were designed to maximise the range of potentially useful qualitative and quantitative data that could be gathered from 2 key sources:

1. The reference collection of silk produced using experimental archaeological methods;
2. Woven silk textile sample sets from archaeological contexts.

The overall aim of taking this broad approach to data collection was to identify the most useful data points for understanding silk production methods, and in so doing refine the questions that could be answered with this data.

This chapter will introduce the types of material analysed during this stage of research, the formats of the data collected, and the textile recording methods used as applicable to each sample set. Following this, the different methods trialled in connection to sample preparation will be described along with their respective benefits and pitfalls. Finally, the approaches taken in collecting quantitative data, and defining and organising qualitative data will be discussed. The chapter will close with a summary of the data collected for processing and analysis.

6.2 The Textiles Selected for Analysis

6.2.1 Experimental Silk Reference Collection

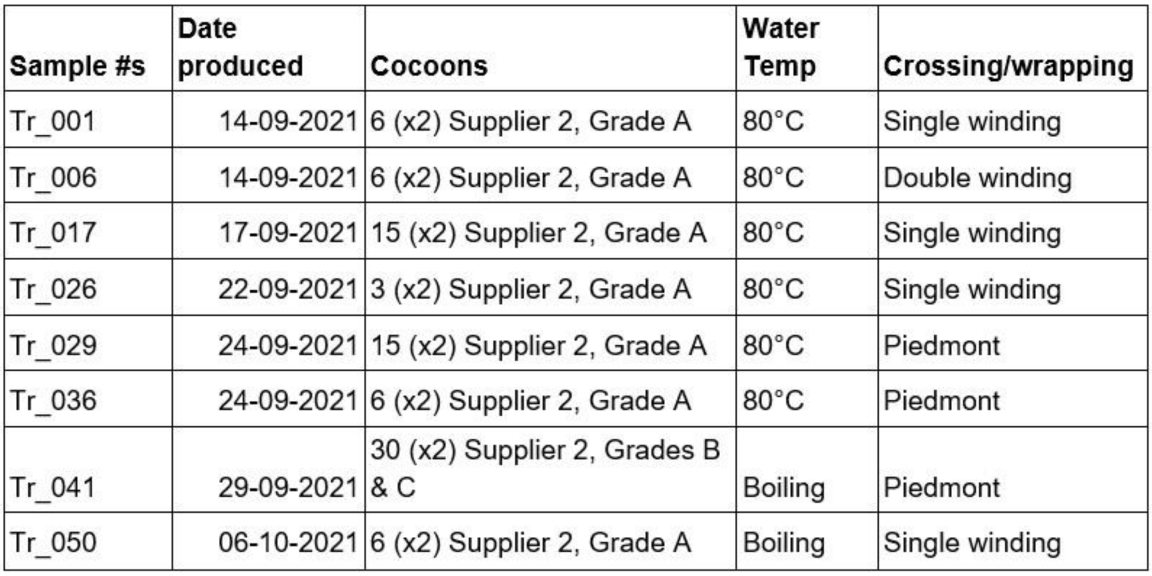
The reference collection of experimentally produced silks comprises 3 types of material:

1)Raw reeled silk filaments;

2)Raw silk yarn (2 or more filaments combined with or without twist);

3)Degummed silk yarn.

As discussed in chapter 5, the total number of samples in this reference collection exceeds 130. A selection of samples representing each of the equipment and method variations were selected for whole-mount fibre analysis, with the understanding that the remaining samples could be revisited for further analysis in future. A narrowed selection of samples was particularly necessary regarding the raw reeled filaments produced with the treadled reel (Table 6.1), as the number of samples produced with this equipment exceeded 50. In this case, samples from the middle of the reeling process were prioritised for recording.



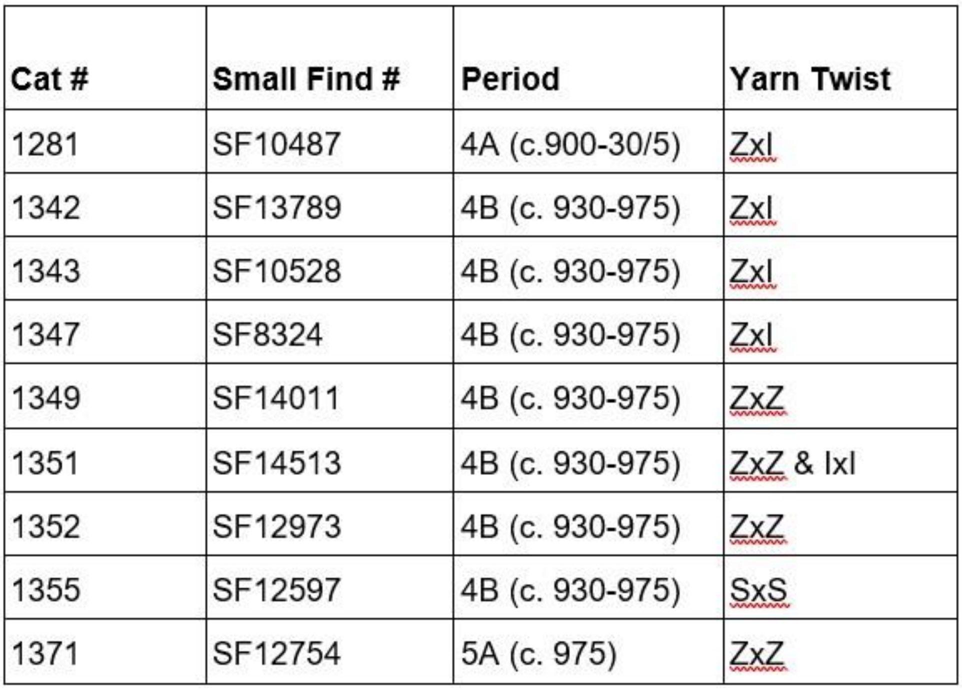
Sample #s	Date produced	Cocoons	Water Temp	Crossing/wrapping
Tr_001	14-09-2021	6 (x2) Supplier 2, Grade A	80°C	Single winding
Tr_006	14-09-2021	6 (x2) Supplier 2, Grade A	80°C	Double winding
Tr_017	17-09-2021	15 (x2) Supplier 2, Grade A	80°C	Single winding
Tr_026	22-09-2021	3 (x2) Supplier 2, Grade A	80°C	Single winding
Tr_029	24-09-2021	15 (x2) Supplier 2, Grade A	80°C	Piedmont
Tr_036	24-09-2021	6 (x2) Supplier 2, Grade A	80°C	Piedmont
Tr_041	29-09-2021	30 (x2) Supplier 2, Grades B & C	Boiling	Piedmont
Tr_050	06-10-2021	6 (x2) Supplier 2, Grade A	Boiling	Single winding

Table 6.1:The treadled reel silk samples selected for fibre microscopy

6.2.2 The Archaeological Silk Textiles

6.2.2.1 16-22 Coppergate

Access to a selection of 10th-century silk textiles from the Coppergate excavations was provided by York Archaeology (YA). A total of 9 textiles (Table 6.2) were selected for analysis based on size and preservation of fragment, variation in yarn combinations, and availability. Where possible, textiles from different phases of the Coppergate excavation were also selected. The 9 textiles were loaned in 2 separate batches, to be studied in the Palaeohub microscopy and imaging lab at the University of York. Of these 9 textiles, 2 comprise two smaller textile fragments stitched together. Textile 1351 was previously identified as comprising 2 distinct textiles, given that the fragments were woven from yarn with distinctly different directions of twist, while Textile 1355 was described as comprising “two similar pieces stitched together” (Walton 1989, 369). Consequently, the 2 pieces of this textile were treated as distinct samples for the purposes of analysis. This means that while access was provided to 9 items, a total of 11 textile fragments were analysed.



Cat #	Small Find #	Period	Yarn Twist
1281	SF10487	4A (c.900-30/5)	ZxI
1342	SF13789	4B (c. 930-975)	ZxI
1343	SF10528	4B (c. 930-975)	ZxI
1347	SF8324	4B (c. 930-975)	ZxI
1349	SF14011	4B (c. 930-975)	ZxZ
1351	SF14513	4B (c. 930-975)	ZxZ & IxI
1352	SF12973	4B (c. 930-975)	ZxZ
1355	SF12597	4B (c. 930-975)	SxS
1371	SF12754	5A (c. 975)	ZxZ

Table 6.2: Silk textiles from 16-22 Coppergate excavations selected for yarn and fibre analysis (Data from Walton 1989)

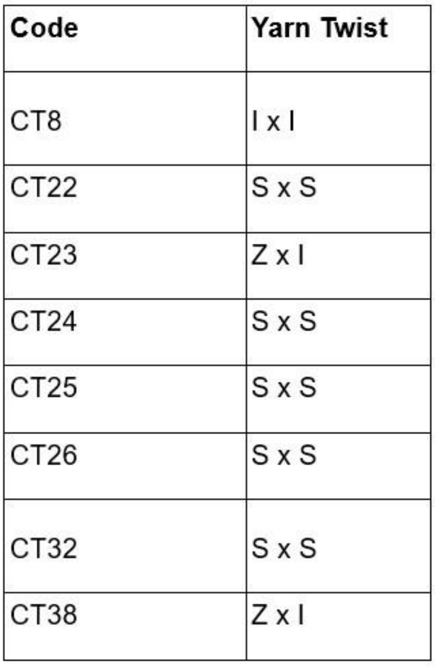
Fibre sample extraction was carried out in the Palaeohub imaging lab at the University of York. Two short (3-5mm) fibre samples for whole-mount and cross-section analysis were extracted from both systems of each textile during the macro-imaging process. The 2 samples were stored separately, one in a gelatine capsule, and one in a chemist-folded piece of acid-free paper, which were then stored in a labelled sample bag. Both methods were effective in the safe storage of the fibre samples, but the gelatine capsules were determined to be more space efficient. The initial arrangement with YA agreed that SEM imaging of further fibre samples from the textiles would be discussed pending successful SEM trials. During the initial fibre extraction phase, the surprisingly good preservation of several of the Coppergate silk textiles resulted in the extraction of some fibre samples that were somewhat longer than the desired 3-5mm. Therefore, following the successful completion of SEM imaging trials, the select number of longer fibre samples were split between cross-sectioning and SEM imaging, which allowed for a more efficient imaging workflow prior to the collection of the remaining requirement of fibre samples.

6.2.2.2 Winchester

Access to a group of silk textiles tentatively dated from the 7th to 12th centuries (Swire 2024) from Winchester Cathedral was arranged by Penelope Walton Rogers of the Anglo-Saxon Laboratory (ASLab). A key condition of access to these textiles was that they could not be removed from ASLab premises. Bearing this limitation in mind, the following access requests were submitted:

1. The opportunity to study the textiles in person to take notes on yarn structure in relation to the whole textile. This would serve as an important reference point during microanalysis;
2. Scans of the textile samples with a scale, allowing yarn measurements to be taken digitally;
3. Fibre samples from both the warp and weft system of each sample, to be viewed in whole-mount and cross-section using a transmitted-light optical microscope, and a Scanning Electron Microscope. The total quantity of each fibre sample required would comprise 3 discrete bunches of fibre c. 3-5mm in length; 2 to be mounted on slides (one whole-mount, one cross-section) and one to be mounted on a stub for SEM imaging.

Permission to study the textiles as proposed was granted by Winchester Cathedral. A total of 8 of the Winchester textiles (Table 6.3), all silk tabbies, were selected for analysis and scale-referenced scans of the 8 textiles were provided by ASLab. These samples were also selected based on size, preservation, and variety of yarn types. Fibre samples were collected and deposited in gelatine capsules, which allowed for safe transport and storage prior to microscopic analysis.



Code	Yarn Twist
CT8	I x I
CT22	S x S
CT23	Z x I
CT24	S x S
CT25	S x S
CT26	S x S
CT32	S x S
CT38	Z x I

Table 6.3:Winchester textiles selected for fibre analysis (Data provided by Penelope Walton Rogers)

6.2.2.3 Assigning System labels and interpreting the warp direction

Textiles with preserved selvedges allow for the unambiguous identification of the warp and weft systems. For all remaining textiles, the labels system A and system B were applied, rather than assigning presumed warp and weft directions when there was room for error. For ease of data formatting, identified warp systems were labelled as system A, and identified weft systems were labelled as system B.

While only textiles with surviving selvedges were concluded to have an identifiable warp and weft, the designation of Systems A and B in textiles without a selvedge was for the most part not arbitrary; In all ZxI textiles the Z-twisted system was labelled as system A, and the system without twist as system B. This was based on the textiles in this category with at least one surviving selvedge, all of which have a Z-twisted warp. Textiles with the same direction of twist in each system and no surviving selvedges were assigned system labels more arbitrarily, although an effort was made to designate any system with a distinctive quality, such as a difference in colour or a higher thread count as system A. Ultimately the subset of 6 textiles with no surviving selvedge or difference in twist comprised 2 ZxZ, 3 SxS, and 1 IxI textile. This subset was not included in comparisons of quantitative measures by system.

6.3 Textile Recording Methods

A variety of visual recording methods were employed in the analysis of all silk textiles in question. Recording images of the archaeological textiles at each stage of analysis had the added benefit of producing images that could be referred to throughout the textile analysis process. Scale-referenced images of all textile types were used to capture accurate measurements even after the initial recording stage was complete. As access to each textile group was provided under different conditions, a varied approach to digital recording was taken, tailored to each group. The benefit of this multi-approach model is that it has allowed for a survey of recording techniques that can be adapted to textile collections with varied access conditions.

6.3.1 Scale Referenced Scanning of the Winchester Silk Textiles

Because the Winchester textiles could not be removed from ASLab, it was not possible to take the same macro-recording approach as was taken with the silk textiles from Coppergate. Fortunately, Penelope Walton Rogers had developed a digital recording method using a flat-bed scanner to capture a high-resolution digital image of a textile fragment. The scanned images provided by ASLab were a useful visual reference for qualitative analysis, and allowed for the recording of measurements thanks to the inclusion of a ruled scale reference.

The images were confirmed to be ideal for measuring thread counts and yarn diameter, although the capture of details such as direction of twist was somewhat hit-and-miss, as a scanner cannot be adjusted to magnify an image in the same way that a microscope can. That said, it was still possible to identify the direction of twist in all images. It was determined that scanned images of the textiles at 1200 dpi and saved in JPEG format still provided sufficient detail for analysis while saving significantly on digital transfer speeds and storage space, therefore images of the remaining textiles in that format were transferred for analysis.

6.3.2 Digital Photography of the Coppergate Silk Textiles

Macro-image capture of the silk textiles from Coppergate was carried out at 2 levels. The first approach aimed to record the overall shape and texture of the textiles (Figure 6.1).

Figure 6.1: DSLR camera mounted on copy stand in advance of photographing the silk textiles from Coppergate (Source: the author)

To mitigate risk of light damage, only ambient lighting was used when photographing the textiles, which did result in slightly lower-resolution images than was ideal. The images, while useful in characterising the textiles, captured significantly less detail than the high-resolution scanning method used to record the Winchester Textiles. This issue could be resolved under different lighting conditions, but in this case the use of digital photographs rather than a flatbed scanner emphasised the importance of magnified image capture, particularly for the purpose of recording measurements.

6.3.3 Low-Powered Reflected Light Microscopy

Reflected microscopy via an Olympus SZ61 Stereo Microscope (Figure 6.2) in combination with an Olympus LC30 camera was used during the macro analysis of both the Coppergate silk textiles and the experimentally-produced silk yarn samples.

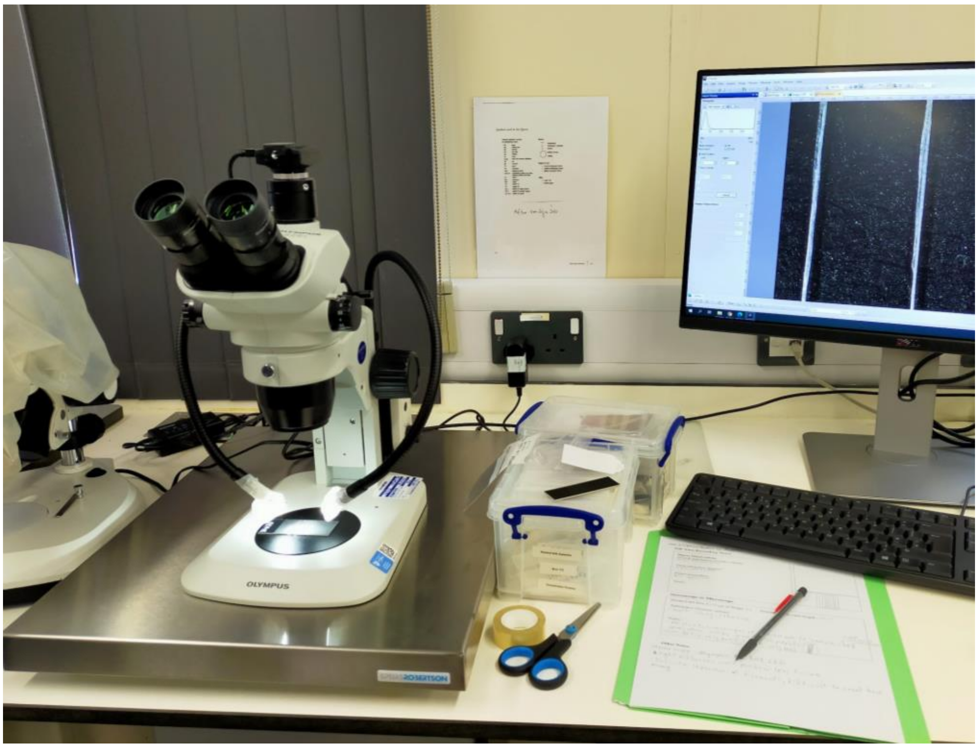


Figure 6.2:Olympus SZ61 Stereo Microscope set up to record an experimental silk yarn sample (Source: the author)

Scale-calibrated micrographs were captured with a magnification range of 6.7x-45x. The stereomicroscope was fitted with a KL300 double gooseneck light modified with diffusers made from lens-cleaning tissue (Figure 6.3). This diffusion reduced the amount of glare from light reflected by the silk fibres.

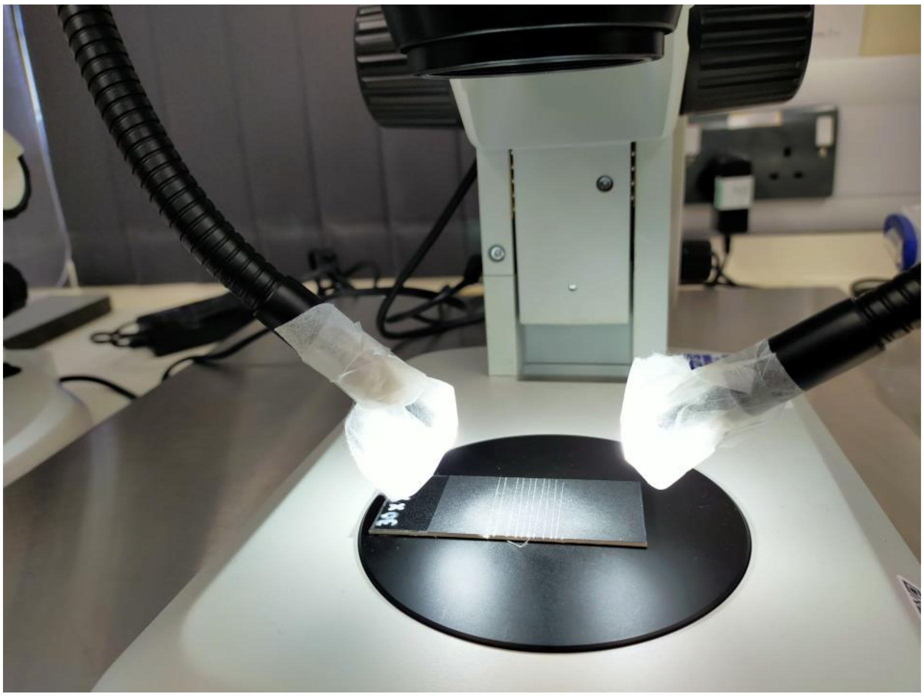


Figure 6.3:Close-up of lens-tissue diffusers on KL300 LED light unit being used to light an experimental silk yarn sample for image capture (Source: the author)

Visual analysis of the Coppergate textiles was carried out using an 8x-45x magnification range, and notes on the overall characteristics of each textile were taken in a custom-formatted textile recording sheet (Appendix H). During image capture, specific levels of magnification were determined to be better suited for recording different measurements (Table 6.4). A minimum of 4 images were captured at each of the indicated magnification levels to allow for enough measurements to be taken.

Measurement type	Magnification	If selvedge is present
Threads/cm	6.7x	Additional counts of paired warps/cm at selvedge
Yarn diameters	10x	Separate warp measurements at selvedge
Yarn angle of twist (if applicable)	20x and 40x	Separate warp measurements at selvedge

Table 6.4: Types of measurement taken at each level of magnification

The experimental silk samples required an additional stage of preparation prior to analysis and recording. Each sample was mounted on a card with known dimensions (Figure 6.4). The number of times the yarn was wrapped and the height of the card were noted, to calculate how many discontinuous cm of yarn were being analysed. For example: 10 wraps on a 30mm card = 30 discontinuous cm of yarn as only the front of the card was analysed. Micrographs were captured at multiple levels of magnification ranging from 6.7-45x.

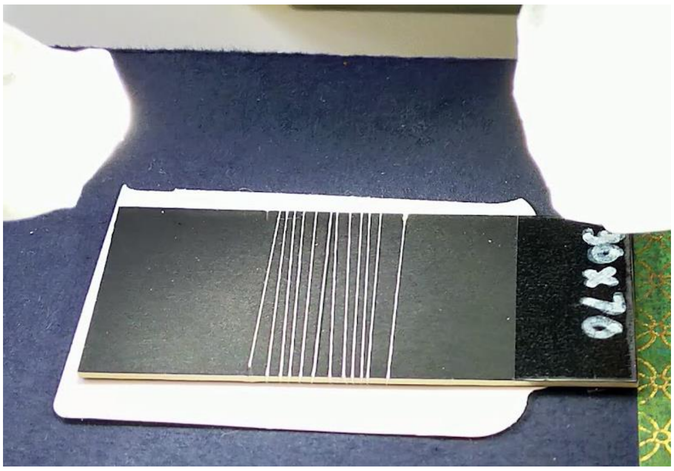


Figure 6.4:Experimental silk wrapped around a 30mmx70mm card (Source: the author)

Reflected light microscopy was determined to be primarily useful in the analysis of experimental yarn samples, and was therefore not used as extensively as fibre-microscopy methods in the analysis of the experimental silks.

6.3.4 Experimental Silk Fibre Microscopy

The protocol for the microscopic analysis of fibres prepared in whole-mount (fibres laid transversely across the slide) and cross-section (Fibres that have been sliced at 90° to the axis of the fibre) was developed following fibre microscopy training provided by Penelope Walton Rogers at ASLab.

A minimum of 4 c. 10mm long segments of the experimental sample to be analysed were mounted on a slide with 1-2 drops of mounting medium, and secured with a coverslip. Methodological modifications were made over the course of analysis; these were noted throughout the process, and included a switch from bottled water to deionised water as a mounting medium, and experimentation with placing the fibres on the slide prior to the addition of the mounting medium to reduce trapped bubbles. The latter tests proved ineffective, and the concern regarding trapped air bubbles was primarily addressed by refining the coverslip-lowering technique. It should also be noted that any experimental silks recorded after the archaeological fibre samples were analysed were mounted in a glycerol/water mounting medium. The reasons for this change in mounting medium are detailed, along with the permanent mount trials, in section 6.4.

Once mounted, the experimental silk samples were analysed using an Olympus BX53M metallurgical microscope with a transmitted light base attachment and both brightfield and polarised light imaging capabilities (Figure 6.5). The micrographs were captured using Olympus Stream software at 12.5x, 50x, 100x, and 400x magnification. Each micrograph was duplicated and saved with a scale reference.

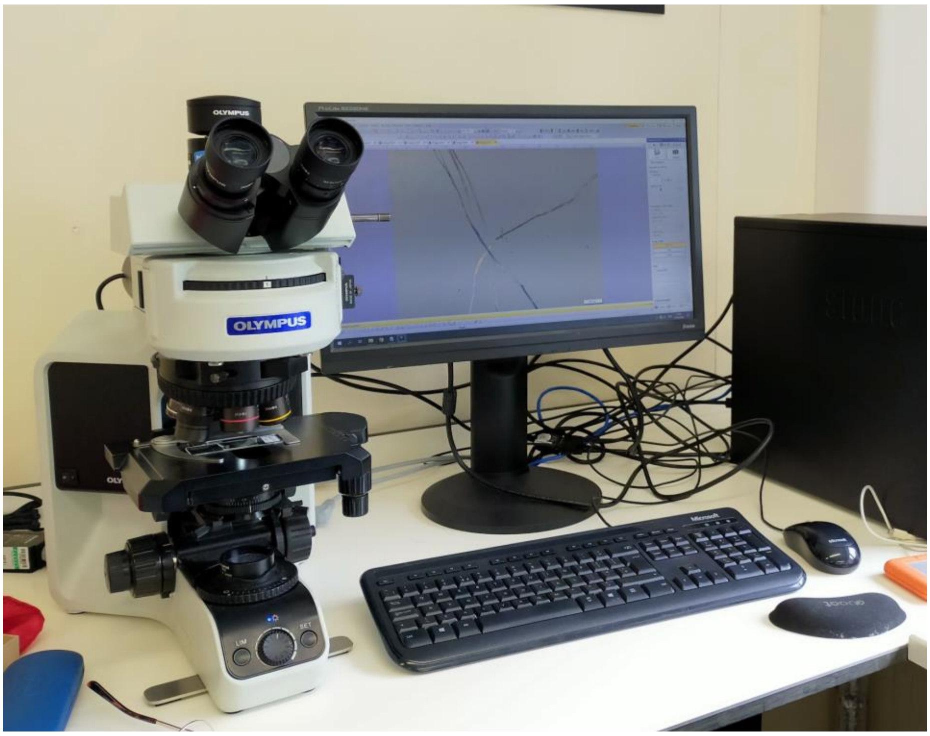


Figure 6.5:Olympus BX53M microscope in use (Source: the author)

Two image processing features were also used as part of the image capture process. The first was Manual Stitched Image Acquisition (MIA), which allowed for the generation of a stitched-together image of a broad area of the slide (Figure 6.6). This facilitated recording of the overall spread and morphology of the raw silk filaments. The other process, Extended Focal Imaging (EFI) allowed for the capture of a modified image with an extended depth of focus, effectively extending the focal range of micrographs taken at higher levels of magnification. The efficacy of this method did become more limited at these levels, and the capture of EFI images was slower than standard micrograph capture, so this technique was used sparingly, as needed.

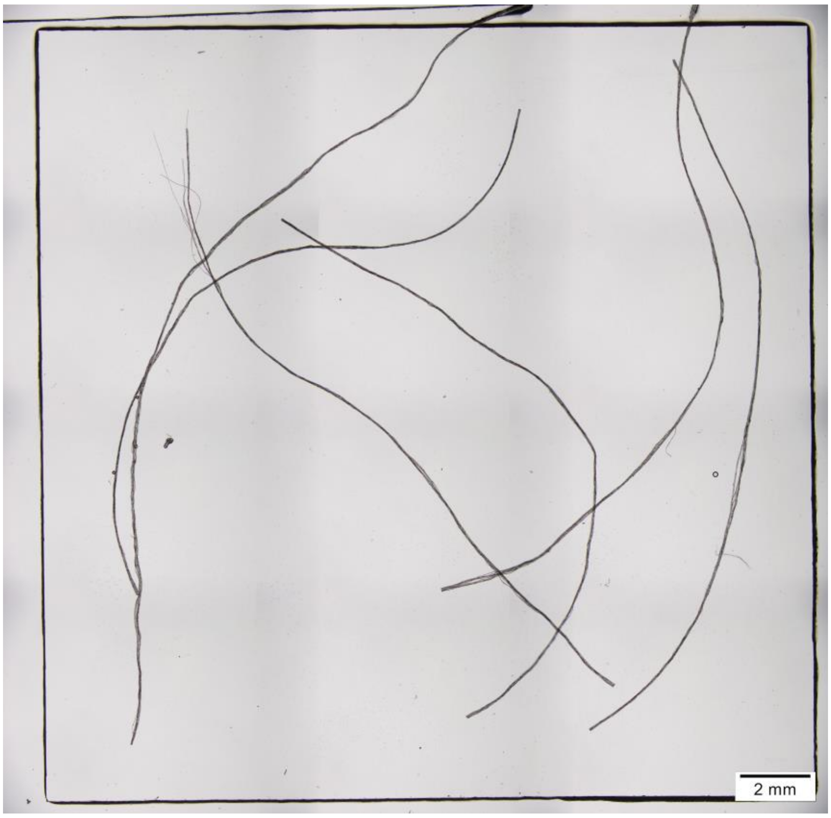
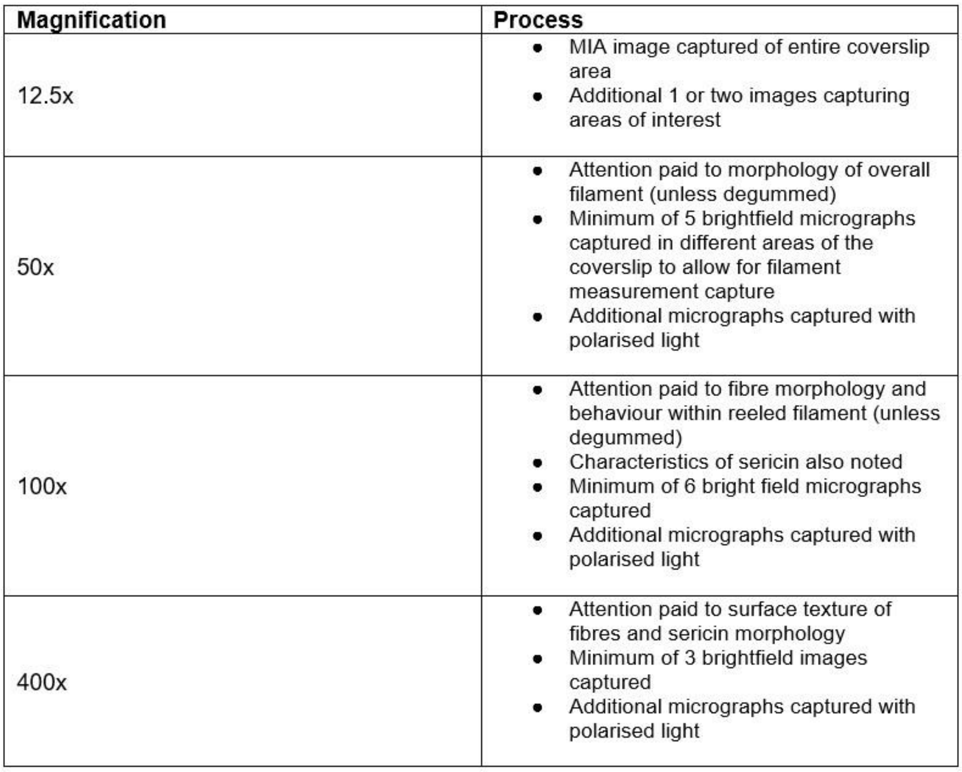


Figure 6.6:Composite image of experimental silk sample Sr_022 captured using Manual Stitched Image Acquisition at 12.5x magnification

To establish an efficient and consistent analysis workflow, the same levels of magnification were used to record details, as the image-capture process cycled through the levels of magnification (Table 6.5).



Magnification	Process
12.5x	• MIA image captured of entire coverslip area • Additional 1 or two images capturing areas of interest
50x	• Attention paid to morphology of overall filament (unless degummed) • Minimum of 5 brightfield micrographs captured in different areas of the coverslip to allow for filament measurement capture • Additional micrographs captured with polarised light
100x	• Attention paid to fibre morphology and behaviour within reeled filament (unless degummed) • Characteristics of sericin also noted • Minimum of 6 bright field micrographs captured • Additional micrographs captured with polarised light
400x	• Attention paid to surface texture of fibres and sericin morphology • Minimum of 3 brightfield images captured • Additional micrographs captured with polarised light

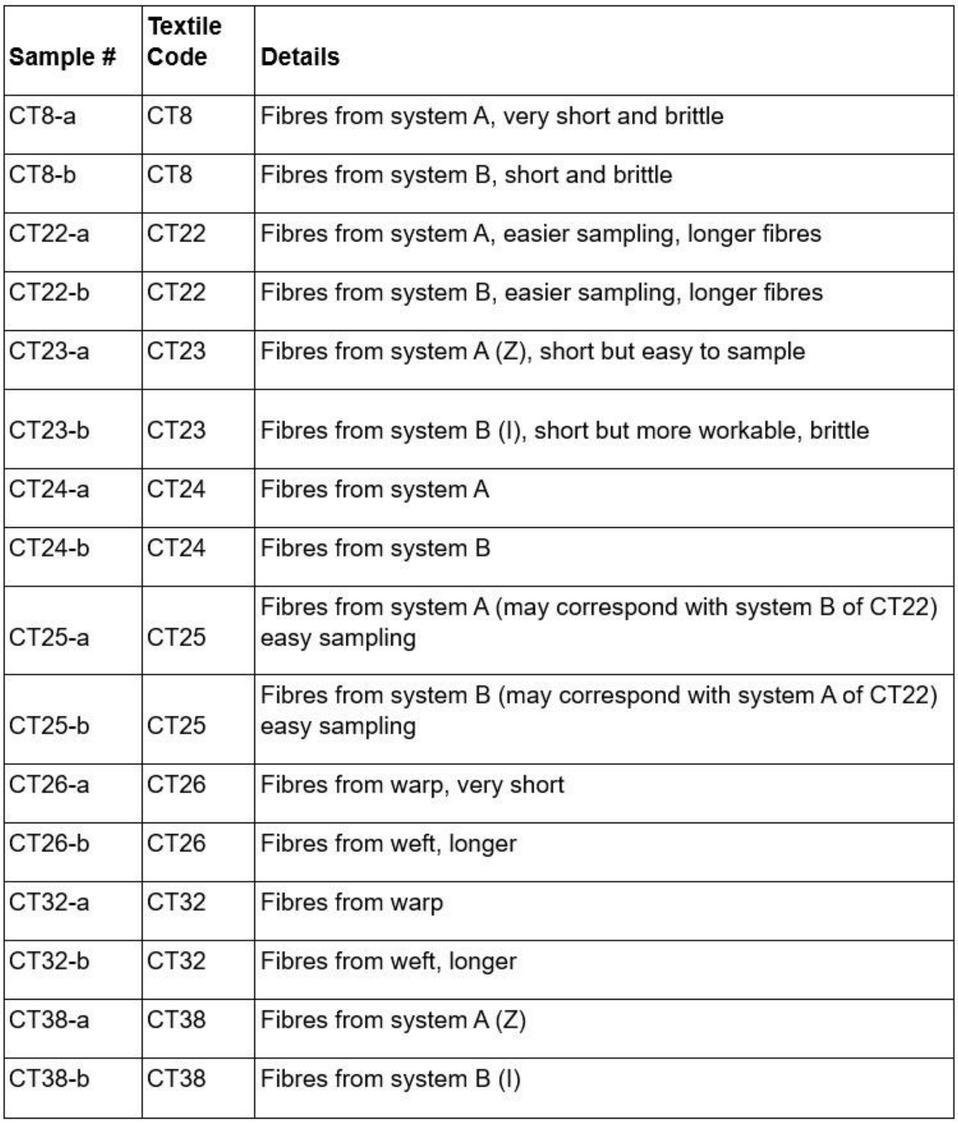
Table 6.5: Processes of image capture and analysis of experimental silk fibres at each level of magnification

The use of polarised light during transmitted light microscopy allowed for clear distinction between sericin and fibroin (silk fibres), and set an important framework for the identification of preserved sericin in the archaeological textile fibres.

A method for producing reliable fibre-cross sections was established following an extensive series of trials (Detailed in Section 6.4.4.2.2). Micrographs of the prepared cross-section slides were captured at 100x and 400x magnification, as the fibre cross-sections were too small to be clearly visible at lower levels of magnification.

6.3.5 Archaeological Silk Fibre Microscopy

Fibre samples from both systems of each archaeological textile were collected for whole-mount and cross-sectional microscopic analysis. Additional fibre samples were also collected from the thicker warp and weft threads of Coppergate 1347. Samples were labelled according to their textile of origin and the system from which they were extracted (For example see Table 6.6)



Sample #	Textile Code	Details
CT8-a	CT8	Fibres from system A, very short and brittle
CT8-b	CT8	Fibres from system B, short and brittle
CT22-a	CT22	Fibres from system A, easier sampling, longer fibres
CT22-b	CT22	Fibres from system B, easier sampling, longer fibres
CT23-a	CT23	Fibres from system A (Z), short but easy to sample
CT23-b	CT23	Fibres from system B (I), short but more workable, brittle
CT24-a	CT24	Fibres from system A
CT24-b	CT24	Fibres from system B
CT25-a	CT25	Fibres from system A (may correspond with system B of CT22) easy sampling
CT25-b	CT25	Fibres from system B (may correspond with system A of CT22) easy sampling
CT26-a	CT26	Fibres from warp, very short
CT26-b	CT26	Fibres from weft, longer
CT32-a	CT32	Fibres from warp
CT32-b	CT32	Fibres from weft, longer
CT38-a	CT38	Fibres from system A (Z)
CT38-b	CT38	Fibres from system B (I)

Table 6.6:List of Winchester fibre samples collected for analysis with notes on thread systems

The process of slide preparation, observation and image capture for cross-sectional analysis of the archaeological silk fibres was identical to the methods established using the experimental silk fibres. In contrast, the slide-preparation process when preparing the archaeological fibres for whole-mount analysis was modified slightly with a shift towards the use of a mixture of glycerol and deionised water as a mounting medium for the majority of the archaeological fibre samples, in order to extend the life of the mounting medium, and allow more time for thorough recording.

The whole-mount fibre-analysis and image-capture process applied to the archaeological silk fibres was similar to the protocol established during microscopy of the experimental silk fibres, with the exception that the MIA process was not used to capture the overall spread of fibres, and instead one or 2 micrographs were captured at 12.5x magnification. This decision was made because the samples were typically small enough that their entire fibre spread could be captured within a single micrograph at the lowest level of magnification (Figure 6.7).

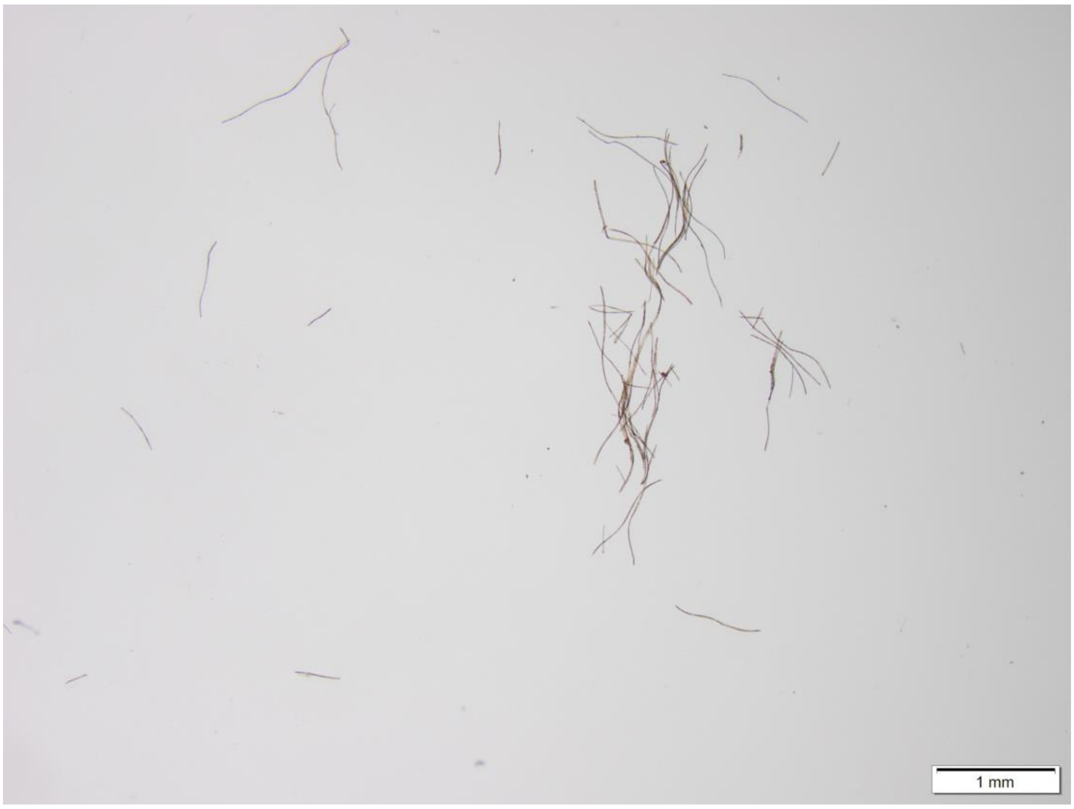
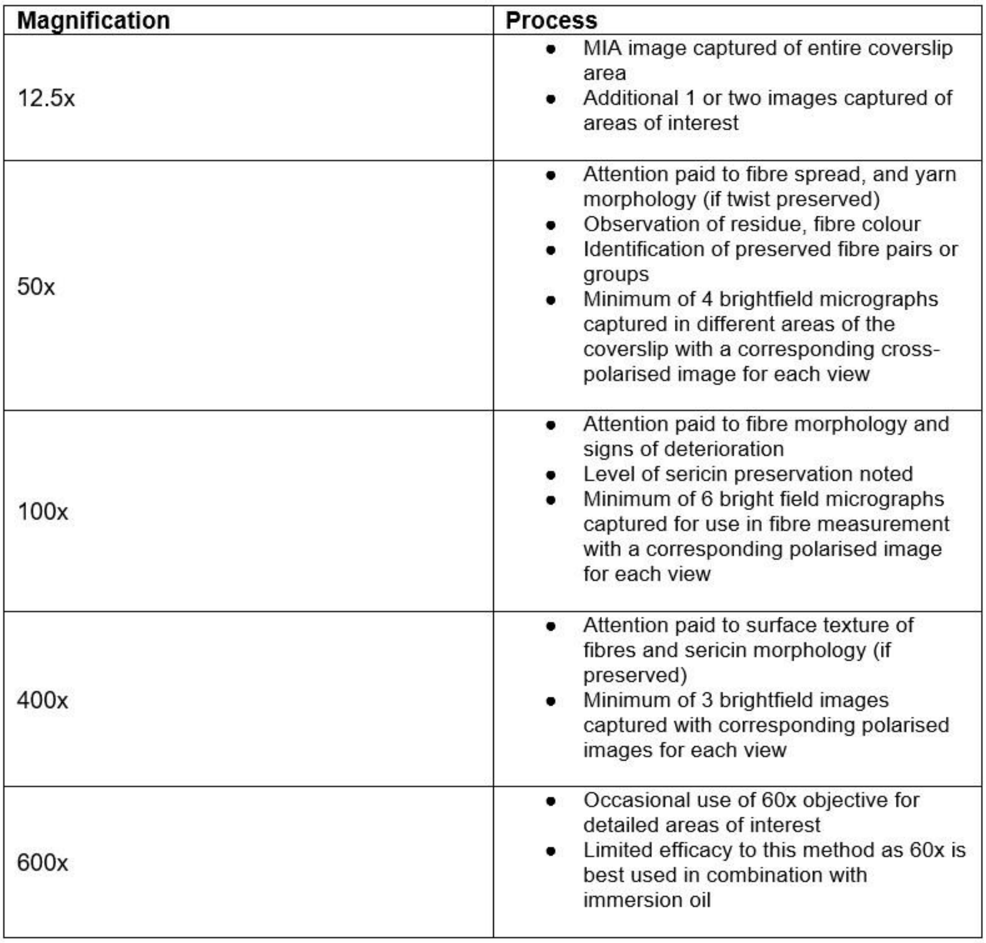


Figure 6.7:Transmitted light micrograph of silk fibres from Winchester fibre sample CT23-a viewed at 12.5x magnification

A slight modification was made to the micrograph-recording process during this time, following additional microscopy training. This improved the overall efficiency of the analysis workflow. A modified recording process was carried out for each level of magnification (Table 6.7).



Magnification	Process
12.5x	• MIA image captured of entire coverslip area • Additional 1 or two images captured of areas of interest
50x	• Attention paid to fibre spread, and yarn morphology (if twist preserved) • Observation of residue, fibre colour • Identification of preserved fibre pairs or groups • Minimum of 4 brightfield micrographs captured in different areas of the coverslip with a corresponding cross-polarised image for each view
100x	• Attention paid to fibre morphology and signs of deterioration • Level of sericin preservation noted • Minimum of 6 bright field micrographs captured for use in fibre measurement with a corresponding polarised image for each view
400x	• Attention paid to surface texture of fibres and sericin morphology (if preserved) • Minimum of 3 brightfield images captured with corresponding polarised images for each view
600x	• Occasional use of 60x objective for detailed areas of interest • Limited efficacy to this method as 60x is best used in combination with immersion oil

Table 6.7: Modified image capture and analysis protocol applied to Archaeological silk fibres at different levels of magnification

As may be noted from the described workflow, priority was given to capturing micrographs at 100x magnification, as filament measurement was not possible with these samples; nonetheless, fibre diameters were of interest.

6.3.6 Scanning Electron Microscopy

A narrowed selection of experimental fibre samples was established for Scanning Electron Microscope (SEM) analysis, informed by preliminary transmitted light microscopy. This selection included samples from both the simple reel and treadled reel, and covered a spread of different numbers of cocoons, water temperatures, and filament crossing/wrapping methods (Table 6.8) so that differences in morphology potentially associated with these techniques could be observed.

Sample #	Date Produced	Cocoons	Water Temp	Crossing/ Wrapping	Area(s) of interest
Sr_008	06-09-2021	6	80°C	None	Sericin texture, filament shape
Sr_014	08-09-2021	6	80°C	Soundless Roller	Sericin texture, filament shape
Sr_022	13-10-2021	8	Boiling	None	Sericin texture, filament shape
Sr_T_D_004	05-01-2022	N/A	68°C	N/A	Sericin condition post degumming
Sr_T_D_005	10-01-2022	N/A	80°C	N/A	Sericin condition post degumming
Sr_T_D_006	10-01-2022	N/A	80°C	N/A	Sericin condition post degumming
Sr_T_D_007	10-01-2022	N/A	80°C	N/A	Sericin condition post degumming
Sr_T_D_008	10-01-2022	N/A	80°C	N/A	Sericin condition post degumming
Sr_T_D_009	21-10-2022	N/A	80°C	N/A	Sericin condition post degumming
Tr_003	14-09-2021	6	80°C	Single	Sericin texture, filament shape
Tr_011	16-09-2021	6	80°C	Double	Sericin texture, filament shape
Tr_032	24-09-2021	15	80°C	Piedmont	Sericin texture, filament shape
Tr_035	24-09-2021	6	80°C	Piedmont	Sericin texture, filament shape
Tr_041	29-09-2021	c. 30	Boiling	Piedmont	Sericin texture, filament shape
Tr_047	06-10-2021	6	Boiling	Single	Sericin texture, filament shape
Tr_T_D_003	08-01-2023	N/A	80°C	N/A	Sericin condition post degumming

Table 6.8: Experimental silk samples selected for SEM analysis

Samples from System A and System B of each archaeological textile, and the previously noted thicker warp and weft threads from Coppergate 1347 were also collected and prepared for SEM analysis.

All samples were mounted on Hitachi threaded stubs with carbon tabs (Figure 6.8) and were coated prior to imaging. The samples were coated with gold/palladium (Au/Pd) to approx. 5 nanometre thickness using a Polaron sputter coater (Figure 6.9). The coating was carried out by Clare Steele-King at the Imaging and Cytometry Technical Facility at the University of York.

Figure 6.8:A group of archaeological and experimental fibre samples mounted on Hitachi threaded SEM stubs with carbon tabs (Source: the author)

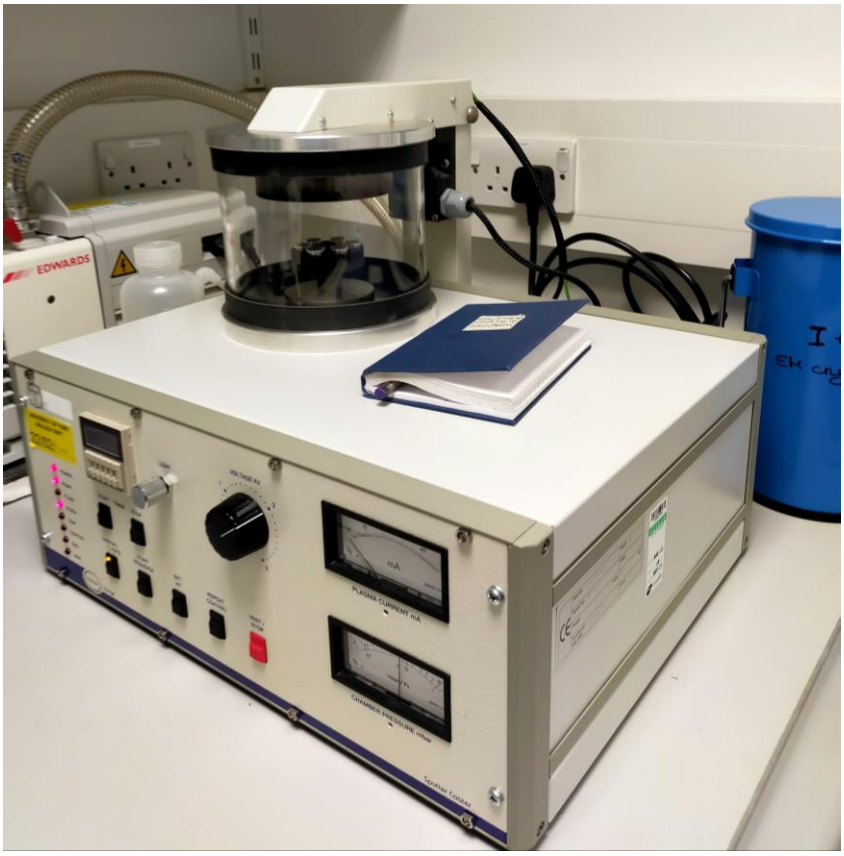


Figure 6.9:Archaeological fibres samples in the sputter coater (Source: the author)

SEM Analysis was performed using a Hitachi TM4000Plus II tabletop environmental SEM (Figure 6.10). Each sample was viewed and captured at a magnification range between 40x-2000x, the lowest magnification being particularly useful for characterising fibres still maintaining the original twist of the yarn or in situ in raw filaments, and the highest allowing for detailed study of fibre surface texture and deterioration. That said, most micrographs captured were in a magnification range of 400x-800x, which allowed for the recording of the overall texture and morphology of the silk fibres with a greater depth of focus than can be achieved at similar levels of magnification with a transmitted light microscope. While the Hitachi SEM interface offers automatic brightness, contrast, and focus adjustment, better results were obtained using manual adjustments for each setting. During each SEM session, handwritten notes were taken, recording general observations and notable characteristics of the fibres.

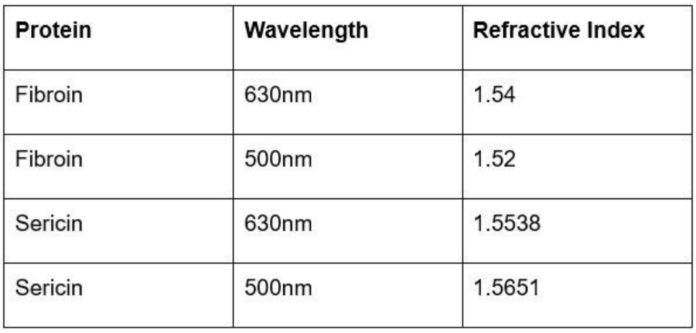
Figure 6.10:Hitachi TM4000Plus II tabletop environmental Scanning Electron Microscope (Source: the author)

6.4 Sample Preparation Trials

The above image-capture protocols were established following extensive trial and error. While there are many well-established approaches to textile analysis and the types of data typically recorded, there is significant variation in how these approaches may be taken when using different types of equipment. Additionally, certain methods –particularly regarding sample preparation – needed to be trialled and tailored to each textile sample being analysed. As each fibre and textile type presents a unique set of challenges, effective sample preparation approaches that are suitable for wool or plant fibres may not be suitable for silk fibres, and vice versa. The following trials did not in themselves produce final data but were essential in developing the methods used to obtain both the final qualitative and quantitative data.

6.4.1 Permanent Slide Mount Trials

As has been described above, microscopy of the experimental samples was carried out using distilled or deionised water as a mounting medium. One clear advantage of using water as a mounting medium is that its Refractive Index (RI) of 1.33 is different enough from both silk fibroin and silk sericin (Table 6.9) to allow for both components of silk fibres to be easily observed without the need for staining. Using water as a mounting medium is an inexpensive and efficient method of sample preparation, albeit an impermanent one. This was not of particular concern with the experimental fibres that can be re-sampled as necessary, though was a concern for the analysis of archaeological silk fibres, where there would not be an opportunity for re-sampling in the event of water-evaporation.



Protein	Wavelength	Refractive Index
Fibroin	630nm	1.54
Fibroin	500nm	1.52
Sericin	630nm	1.5538
Sericin	500nm	1.5651

Table 6.9:Refractive indices of silk sericin and fibroin (From Bucciarelli et al. 2018, 3-15). It should be noted that these are based on silk proteins reconstituted as thin films.

Several trials in preparing experimental silk samples with permanent mounting media were carried out with the aim of identifying a suitable medium for mounting archaeological fibre samples. The desired criteria of such a medium were that: it would be permanent in nature, low in toxicity, readily available, and quick to mount and cure. UV-cured mounting media were of interest due to their relatively quick curing time and successful use in other microscopy applications (See Noetinger et al. 2017). Images included in this section were not colour- or contrast-corrected, in order to demonstrate the differences between media.

Three potential permanent mounting media were tested:

1. Clear nail varnish (Nitrocellulose in solution with Butyl Acetate and Ethyl Acetate)
2. UV-curable resin
3. Norland #61 Optical glue

All 3 potential mounting media showed benefits and drawbacks. The nail varnish method was the quickest of the 3 but, even though no bubbles were visible within the first few hours after mounting, within a day the shrinking of the nail varnish had resulted in large air bubbles under the coverslip (Figure 6.11). The fibres could be viewed with clarity under the microscope, with a slight increase in difficulty of bringing sericin into focus. Overall, the image quality was acceptable, but the large voids caused by the nail varnish shrinking while drying rendered it an unsuitable permanent mounting medium. Varnish formulas vary by brand, and it is possible that further experimentation would yield a particular brand of nail varnish that would serve as a suitable mounting medium, but this was not pursued due to time constraints.

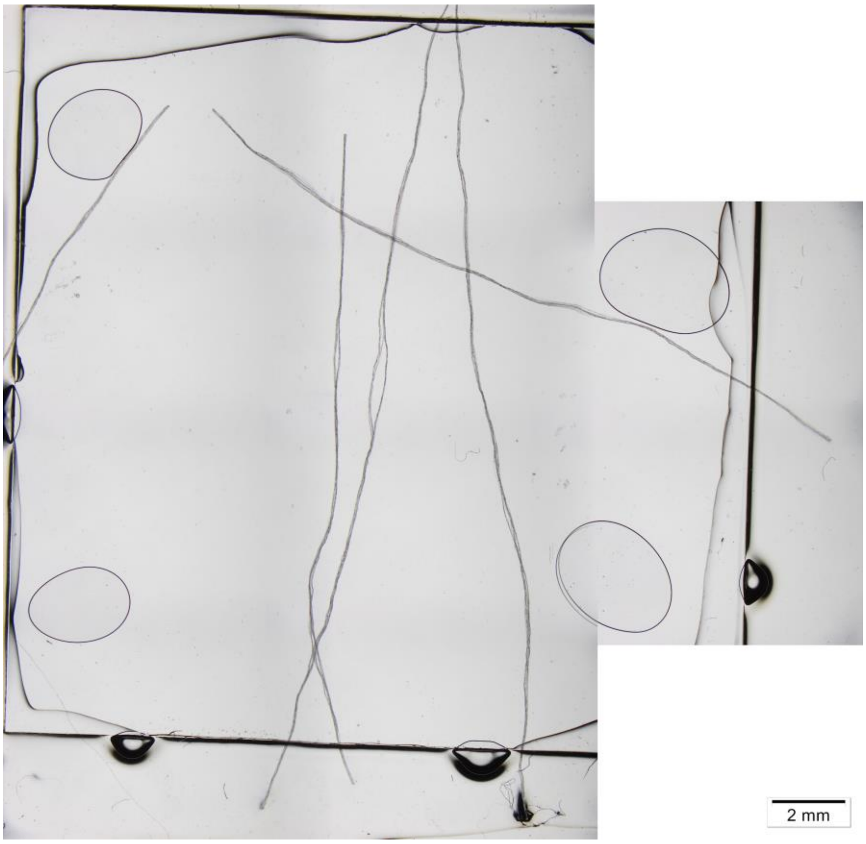


Figure 6.11:Composite micrograph of raw silk mounted in clear nail varnish. Viewed at 12.5x magnification showing large voids resulting from the mounting medium shrinking while drying.

Norland #61 optical glue cured with a UV light resulted in comparatively low contrast images of the fibres, which could not be fully compensated for through adjustment of the microscope’s field diaphragm. Even with the use of polarised light, it was more difficult to observe the sericin in Sr_022 in comparison to the same sample viewed in a water-mounted slide. There were also several small air bubbles, which created dark spots along the filaments. Further tests were conducted to attempt to eliminate these air bubbles including leaving the sample to sit for a minimum of 10 minutes prior to affixing the coverslip (Figure 6.12), which did not reduce air bubbles, and treatment in a vacuum chamber prior to curing, which appeared to draw some of the air bubbles away from the fibres, resulting in a high volume of bubbles in the mounting medium (Figure 6.13).

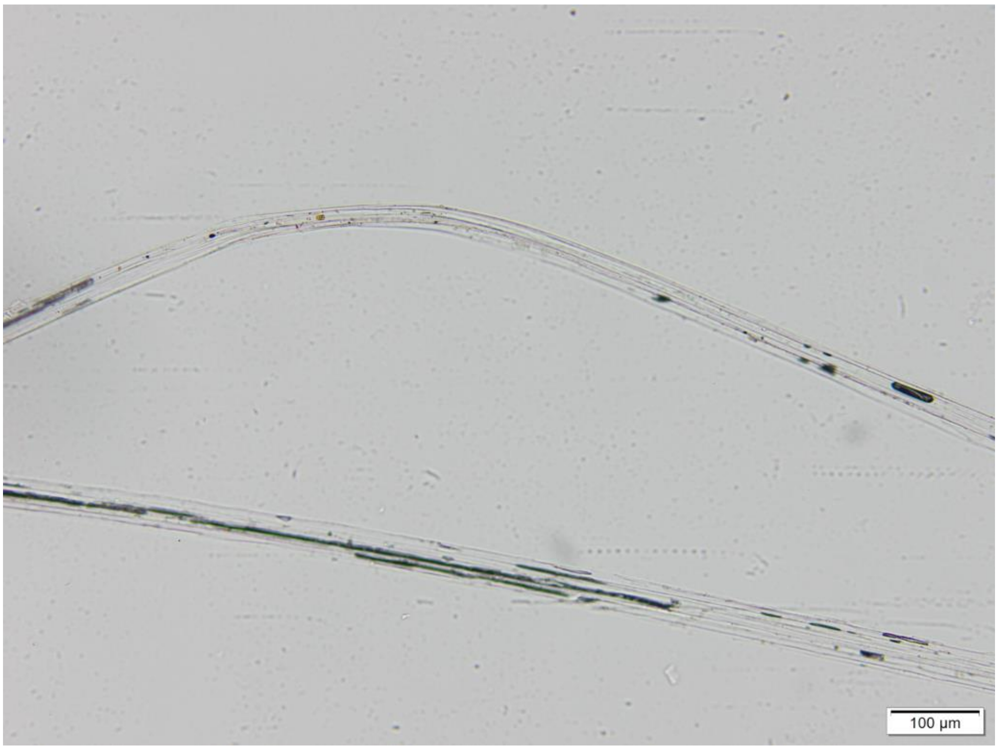


Figure 6.12:Sr_017 mounted in Norland #61 optical glue showing air bubbles along the silk fibres.

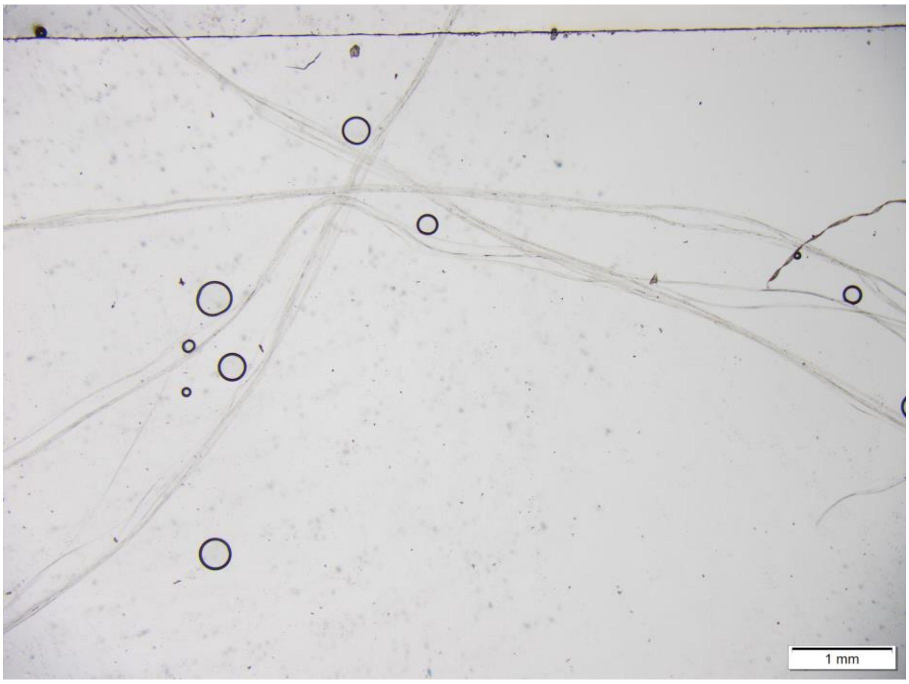


Figure 6.13:Sr_T_D_001 mounted in Norland #61 optical glue and treated in vacuum chamber prior to curing, viewed at 12.5x magnification showing visible bubbles in mounting medium

The reduced contrast in comparison to water mounted samples (Figure 6.14) and difficulty with air bubbles, likely due to the low viscosity of the mounting medium led to the conclusion that Norland #61 optical glue was also an unsuitable permanent mounting medium.

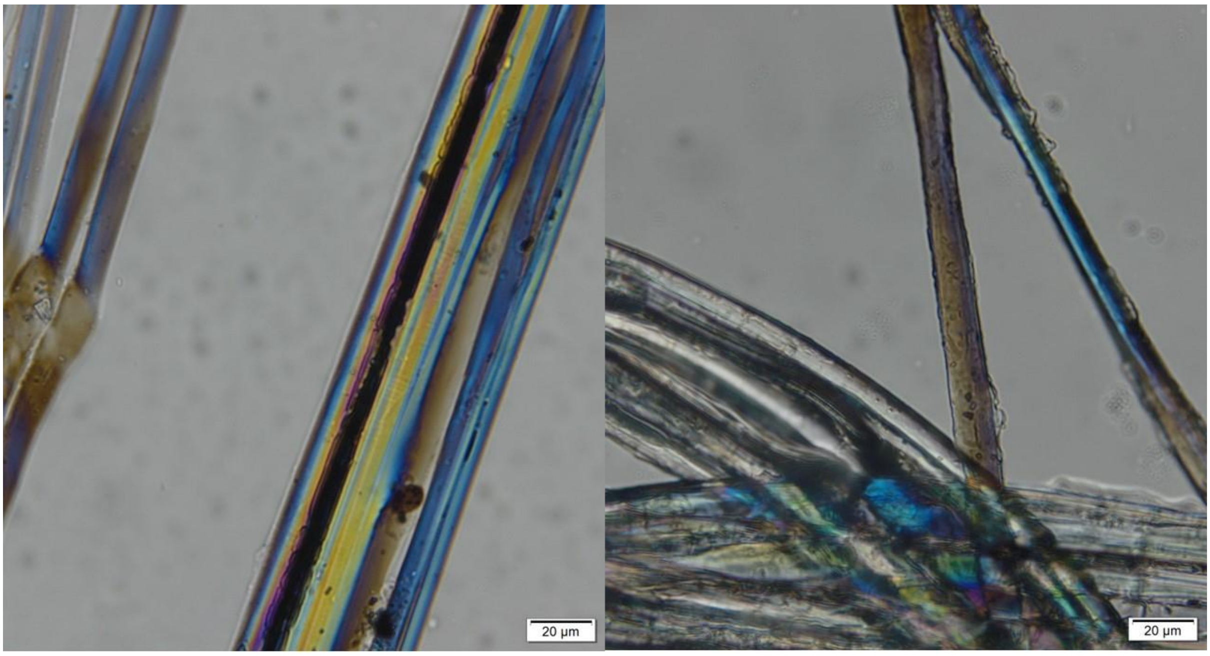


Figure 6.14:Sample Sr_017 mounted in Norland #61 Optical glue (left) showing barely visible halo of sericin around fibres and mounted in water (right) showing much clearer ripples of sericin around fibres. Both samples are shown under polarised light, viewed at 400x magnification

Similar problems with air bubbles and focus of fibres were observed in the samples mounted with Jdiction UV resin (Figure 6.15) with a moderate contrast improvement in comparison to Norland optical glue. Given the complications listed, it was concluded that this UV resin was not an ideal permanent mounting medium for silk fibres.

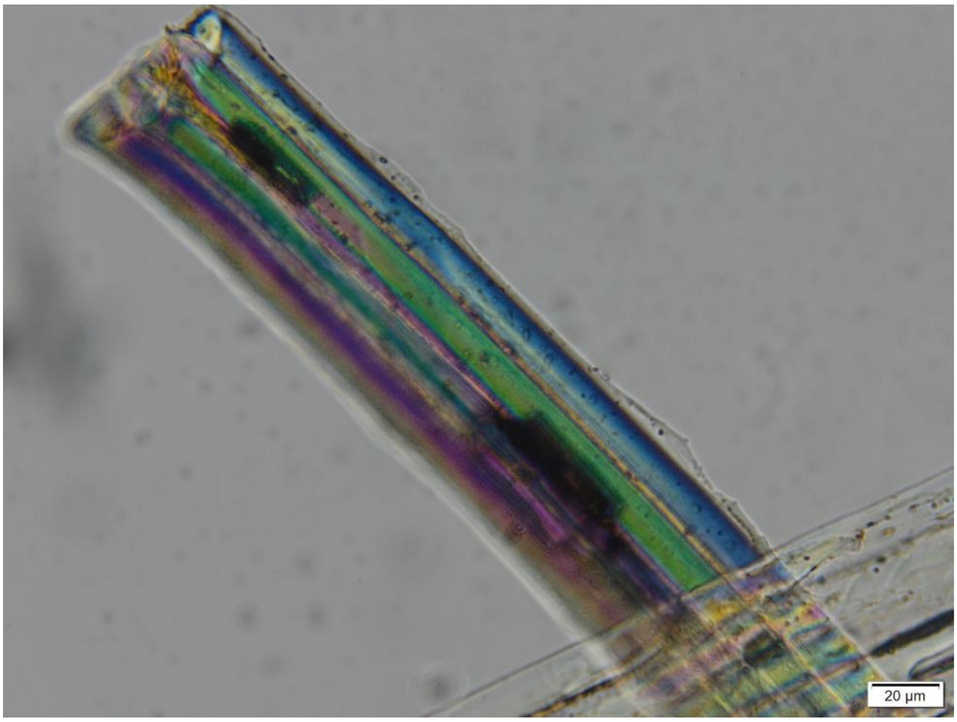


Figure 6.15:Sample Sr_002 mounded in Jdiction UV resin, shown under polarised light viewed at 400x magnification.

6.4.2 Continued Use of Water as a Mounting Medium

Following the permanent mount trials, it was determined that sericin texture and coverage was more clearly observable with a temporary water mount. Therefore, a decision was made to prepare the archaeological fibre samples using water as a mounting medium. To compensate for the limited time given for observation due to water evaporation, care was taken to capture enough micrographs at each level of magnification to allow for any necessary revisitation of the micrographs. As an extra precaution against sample contamination, deionized water was used for the archaeological fibre samples. The majority of the Coppergate fibres were mounted in deionized water without complication, but a series of heatwaves in July/August 2022 sped the evaporation of the mounting medium to the point that imaging was briefly paused to find a solution that would not compromise image quality or risk damage to the fibres.

6.4.3 Extended-life Mounting-medium: Glycerol/Water Mixture

Tests with a semi-permanent mounting medium were conducted to resolve the problem of water-mount evaporation in high temperatures. Glycerine jelly, also called Glycerol, is a common ingredient in slide-mounting media and is typically described as a semi-permanent mounting medium when used pure (Zander 1997, 380). Because Glycerol is hygroscopic it can be mixed with water to extend the use-time of a temporary slide mount. This proved to be an ideal solution to the water evaporation problem following tests conducted to ensure that the use of glycerol would not negatively impact the clarity of the micrographs.

Concentrations of both 100% glycerol and 50% glycerol/50% deionized water were tested. Micrographs of the samples mounted in 100% glycerol showed the fibres and sericin clearly, but with some formation of bubbles along areas of the fibre, likely due to the low viscosity of the glycerol (Figure 6.16).

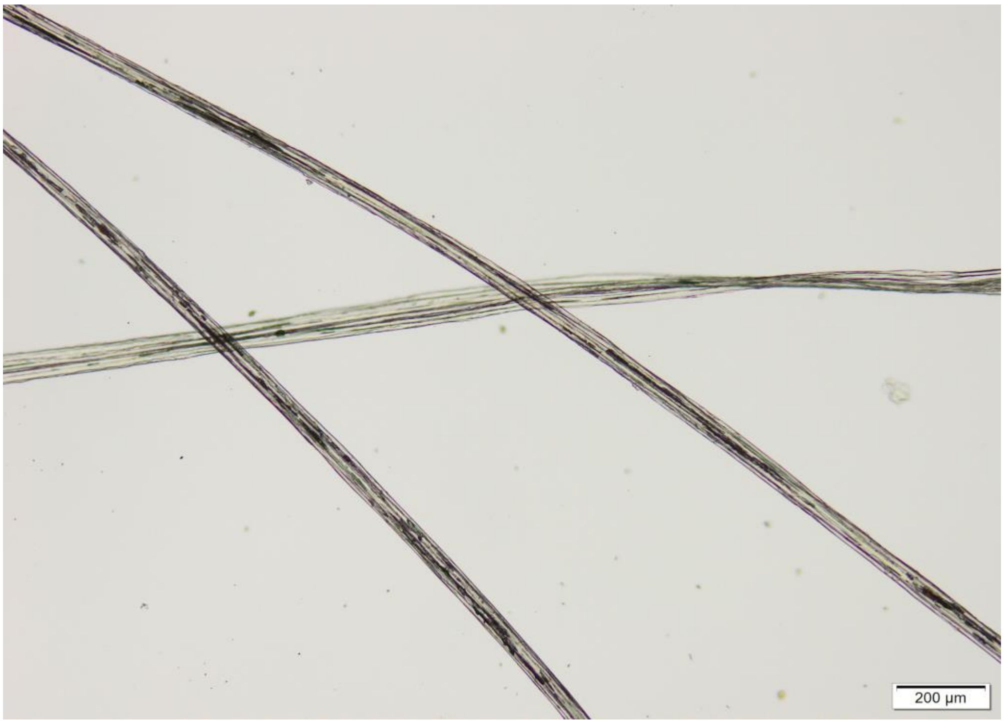


Figure 6.16:Sample Sr_014 mounted in 100% glycerol, showing minute air bubbles along the length of the reeled filaments. Sample viewed at 50x magnification.

The images produced of the sample mounted in the 50% glycerol/50% deionized water mounting medium appeared to have a higher degree of clarity than slides mounted with water alone (Figure 6.17), clearly showing both the sericin and fibroin. The mixture with water lowered the viscosity of the glycerol, eliminating issues with bubbling, while the addition of the glycerol extended the life of the water, meaning that after 1 hour of analysis no evaporation had occurred.

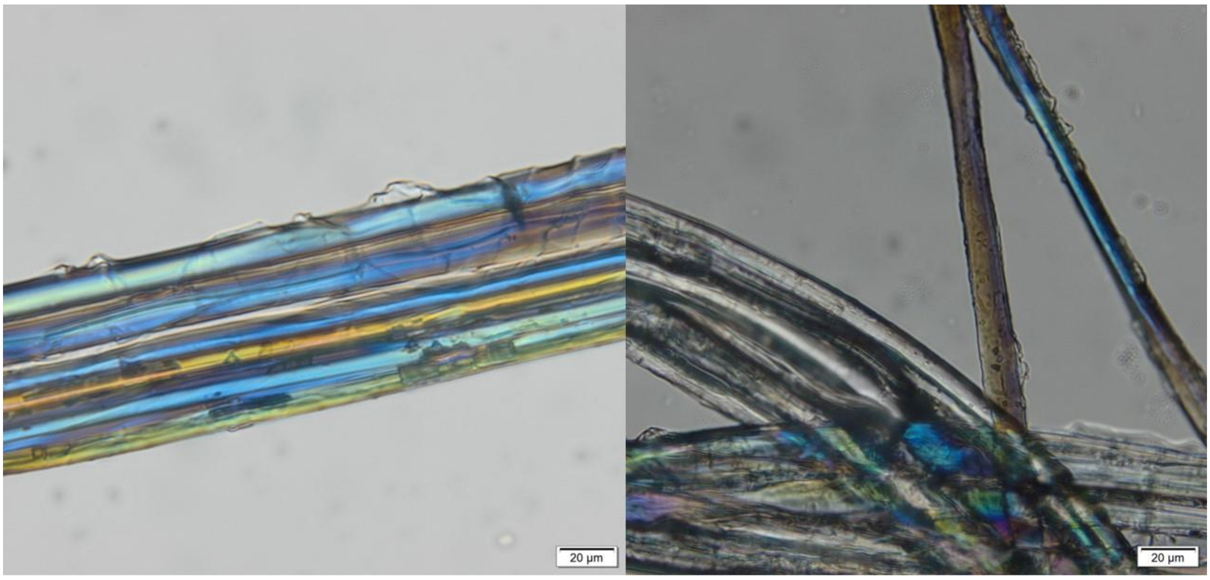


Figure 6.17:Sample Sr_017 mounted in 50% glycerol, 50% water mixture (left) and mounted in water (right). Both samples are shown under polarised light, viewed at 400x magnification.

Following these tests it was concluded that a mixture of 50% glycerol and 50% water was the ideal mounting medium for all fibre mounts moving forward.

6.4.4 Fibre Cross-section Trials

While the analysis of fibre cross-sections is standard practice for textile fibre analysis, there is no single standardised method for producing fibre cross-sections. This may be a result of limited access to specialist equipment and differences in the intended use of fibre cross-sections by different analysts. Still, there is an abundance of cross-sectioning methods that may be applied to silk fibres, each with their own benefits and drawbacks. To determine the most suitable approach for cross-sectioning silk prior to producing cross-sections of the archaeological silk fibres, a series of tests were conducted using the experimentally reeled silk. What follows is a summary of the methods tested and corresponding observations.

6.4.4.1 Methods for hand-cut sections

6.4.4.1.1 Plate Method

Cutting cross-sections manually by mounting them in small holes drilled in a thin metal plate is a straightforward and economical approach to creating cross-sections. This method was attempted with training from Penelope Walton Rogers at ASLab. Silk fibres were pulled through a hole in the plate with the aid of polyester thread. Clear nail varnish was used to fix the fibres in place and an attempt was made to cut thin sections of the fibres with a razor blade. Other approaches to the plate method trim the fibres and leave them in situ in the plate for analysis (Ford and Simmens 1959, 151) resulting in a relatively thick section, which can be less reliable for the characterisation of fine silk fibres. The modified method employed at ASLab effectively uses the plate as a miniature hand microtome to procure thin sections that can be transferred to a slide. This method is overall less accessible as it requires the use of specialist plates that are difficult to procure. Additionally, the thin sections produced were less reliable than those resulting from other methods trialled, therefore this method was ruled out for the purposes of this research.

6.4.4.1.2 Gelatine Capsule Method

A method of embedding fibres using epoxy adhesive was trialled with guidance at ASLab, though was only partially successful, due to only partial filling of the capsule (Figure 6.18). This is another method that posed difficulty in yielding satisfactory results, partially due to the degree of hardness to which the adhesive dried prior to slicing.

Figure 6.18:Hand-sliced cross-section of Tussah silk fibres, experimentally embedded in nail epoxy in a Gelatine capsule mould. Image taken at ASLab, viewed at 400x magnification.

6.4.4.1.3 Silk Embedded Horizontally in 2-part Epoxy Without Support

Another method was developed based on the partial success of the gelatine capsule trial. The aim was to mount the fibres in a thinner section of epoxy adhesive and establish an easier method for aligning the fibres. To achieve this, a thin layer of 2-part epoxy adhesive was spread over a smooth plastic surface. Test fibres were then laid over top of the epoxy, covered with another thin layer of adhesive and left to cure. Once cured, one end of the embedded fibres was trimmed flat and thin sections were cut manually with a single-sided razor blade. This thin layer of epoxy still offered some extra resistance but was overall easier to cut, and produced visible cross-sections that were still somewhat cloudy and uneven when viewed under the microscope (Figure 6.19).

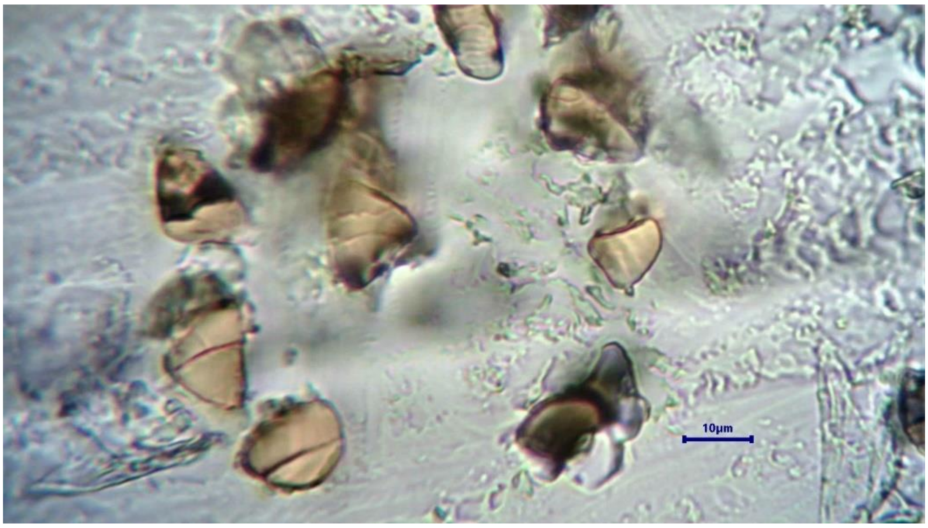


Figure 6.19: Epoxy-embedded cross-sections of historical silk fibres recorded at 400x magnification

6.4.4.1.4 Silk Embedded Horizontally in UV Resin with Shallow Guide

To improve upon the method of embedding fibres horizontally in 2-part epoxy, a variation of this approach was developed, using an edged support made from layers of office tape built up over a short length of 2cm x 2cm timber. This support allowed the fibres to be held in tension during embedding with the aid of additional pieces of tape. A further substitution of UV-cured clear resin instead of epoxy adhesive achieved a better cross-section. The UV resin had the benefit of curing completely within 2-4 minutes exposure under a UV lamp and curing to a slightly more pliable consistency than the Epoxy adhesive, which made the process of cutting sections manually easier. This method produced clearly discernible cross-sections, but the process of manually cutting sections resulted in a slightly uneven surface that prevented all the fibres in the section from being brought into focus at once (Figure 6.20). This method is effective for basic fibre identification and has the benefit of being relatively inexpensive and efficient, but the frequent angle offset resulting from manually cutting the sections meant that this could not be relied upon for producing fibre cross-sections that could be used to take reliable diameter measurements.

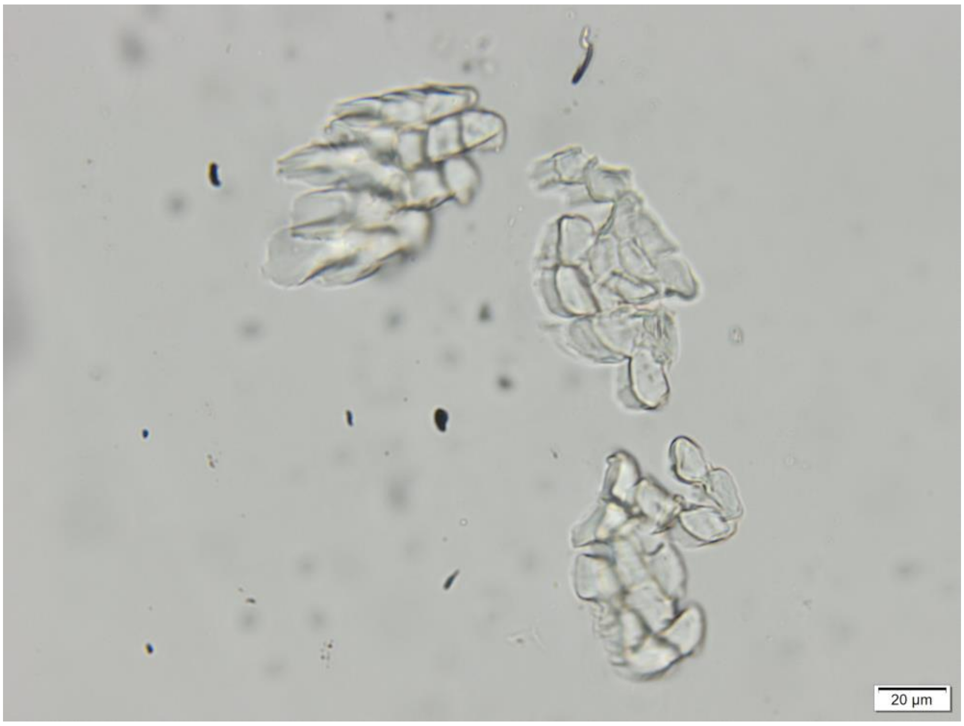


Figure 6.20:Sample of Raw silk, embedded in thin layer of UV resin and hand cut, viewed at 400x magnification

6.4.4.1.5 Pipette Method

The method of using a polythene transfer pipette to prepare fibre cross-sections is explained in a blog post from the website of the Field Museum in Chicago, Illinois, U.S. (Brown 2011) and is also demonstrated in a video on the Hooke College of Applied Sciences' YouTube channel (Hooke College of Applied Sciences 2020). This approach uses heat to embed fibres in the pipette and once cooled, thin sections are cut manually using a single-sided razor blade. This approach is cost-effective and has the benefit of eliminating the need for adhesives or other fume-producing chemicals. The melted pipette is also the softest of the embedding media used for manual section cutting that provided ergonomic benefits, and theoretically should support the cutting of a more even section. One consequence of the pipette being a softer material is that cutting striations were more pronounced in the sections and the resulting uneven surface produced a section that was difficult to bring into focus (Figure 6.21). Furthermore, the pliability of the pipette when clusters of fibres were embedded, resulted in the plastic shifting during cutting, which led to some fibres falling out of place. This is another method that is efficient and cost-effective for fibre identification, but less reliable if measurements are to be taken.

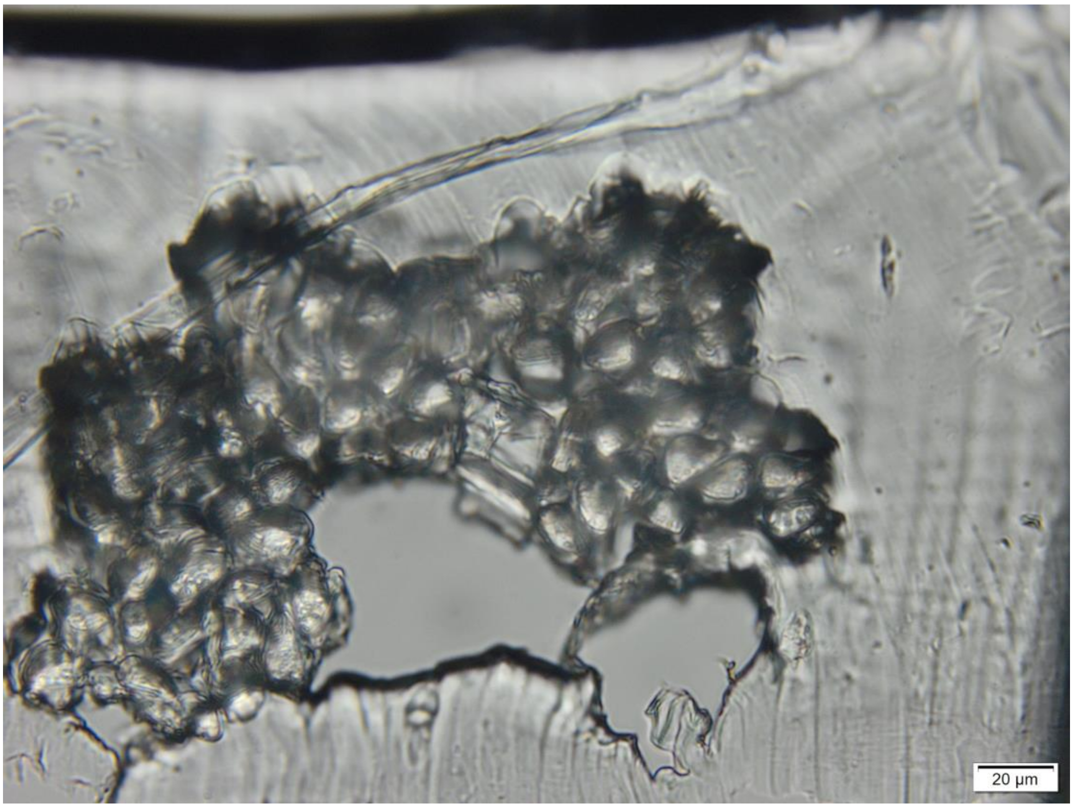


Figure 6.21: Cross-section of Sr_014 produced with Pipette method, viewed at 400x magnification. Voids where fibres have separated from the melted plastic can be seen.

6.4.4.2 Machine-assisted cross-sectioning

6.4.4.2.1 Diamond saw Method

This method was developed using facilities at the University of York but may parallel methods used by other researchers (Lukesova and Holst 2021, 220). A series of specialist cylindrical moulds were used to embed the test fibres in Epothin 2-part epoxy resin.

The cured resin cylinders were ground flat at one end using 400 carborundum grit and a flat glass slab. Each cylinder was then mounted on a manually frosted slide using Norland #61 Optical Glue and left to cure for 3-4 hours on a UV light. Once cured the samples were sliced thin using a diamond blade saw. The samples were then further ground flat using 800 grit carborundum, and micrographs were captured at thicknesses of 378 μm (Figure 6.22a), 247μm (Figure 6.22b), 121μm (Figure 6.22c), and 45μm (Figure 6.22d).

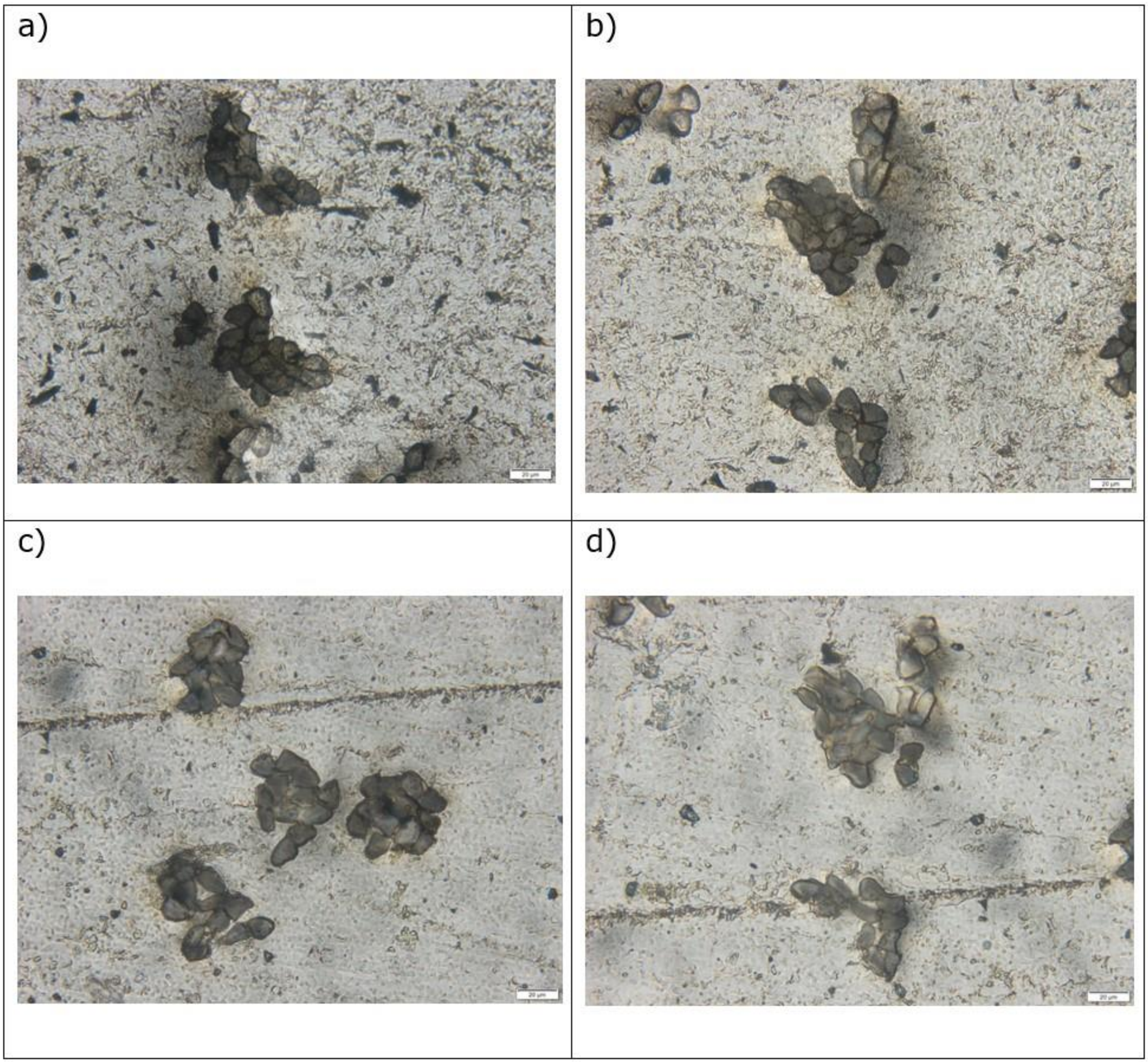


Figure 6.22:Resin-embedded Cross-sections of Sr_014 at 378μm (a), 247 μm (b), 121μm (c), and 45μm (d) thicknesses

Cover slips were applied to the samples using Norland optical adhesive, and micrographs were captured again once the adhesive had cured (Figure 6.23).

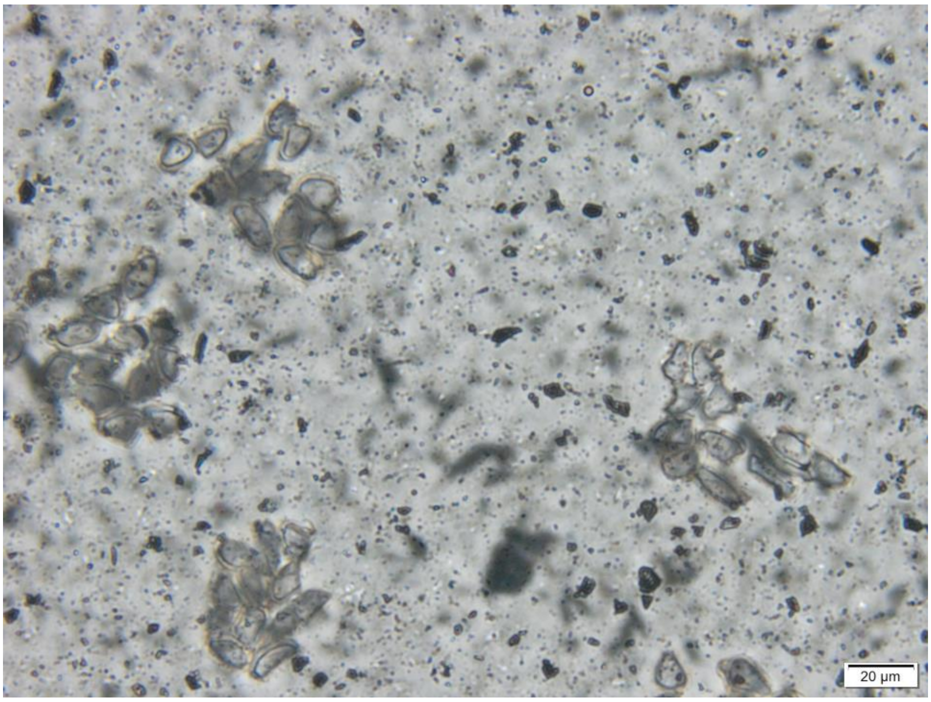


Figure 6.23:Resin-embedded Cross-section of Sr_014, 45 µm thickness, permanent mount with coverslip

This method was effective for producing flat cross-sections, with some clarity hindered due to the frosted glass of the microscope slide. The cross-sections at 247µm appeared to have the best clarity, while the boundaries between fibres became more difficult to distinguish in thinner sections. Overall, this test was considered successful but the distracting texture of the ground surface and the process of embedding the samples requiring a minimum of 24 hours cure time were deterrents.

6.4.4.2.2 Wax Microtome and Cryostat Methods

Cross-sectioning of fibre samples embedded in paraffin wax and cut with a rotary microtome were trialled, but when viewed with the transmitted light microscope, the fibres were found to blend in somewhat with the texture of the wax (Figure 6.24). This was not particularly improved with the use of polarising light, which did little more than create a new pattern of colour in the wax. It also became clear that of the samples embedded, only Sr_005 was correctly oriented, meaning the other slides were not useful for analysis. Additionally, some fibre sections separated from the wax embedding medium, leaving voids behind.

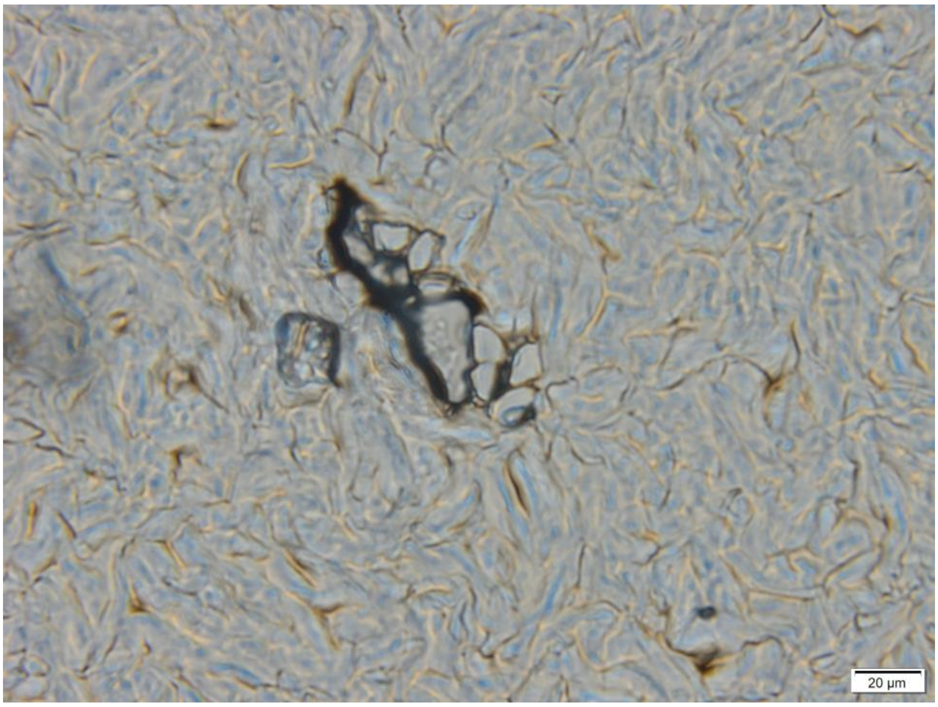


Figure 6.24: Wax-embedded cross-section of Sr_005, 10µm thickness viewed at 400x magnification. The central void resulted from a bundle of fibres falling out of the section.

To trial the cryostat, experimental samples Tr_003, Tr_005, Sr_005, and Sr_023 were mounted in a gel medium using a plastic cartridge mould. The first was mounted vertically as was done with the wax embedding process, but the higher viscosity of the gel medium resulted in the fibre falling out of place. The rest of the fibre samples – including a second cutting of Sr_023 – were mounted horizontally and the fibre orientation was marked on the mould before they were placed in the cryostat to freeze. Once the samples were frozen, an additional line indicating fibre orientation was marked across the frozen gel medium with a felt tip pen, and each sample was transferred from the mould and mounted onto a metal chuck with more gel medium. The samples were once again left to freeze. From each sample, 2-3 section long ribbons 10µm thick were cut and mounted on a slide, the process was then repeated, producing 2 slides per sample with 2-3 sections per slide. After mounting, each slide was left to dry at which point the sample was stable. Each slide was labelled.

The horizontal orientation of fibres prior to freezing was made possible because the frozen samples could be re-oriented prior to mounting in the cryostat, something that was not possible with the wax embedding process. This meant that the cryostat supported a more reliable embedding process with an efficient freezing time (c. 20 minutes). Additionally, once the sections were mounted on the slide and given time to dry, they were stable at room temperature without the need for additional processing.

When viewed with the transmitted light microscope (Figure 6.25) the fibres were observed to be more clearly visible against the cryostat medium. The fibre edges were observed to be less crisp in appearance than with the resin-embedded samples at 247 µm thickness but were of higher quality than the resin samples at 45µm thickness.

Figure 6.25:Cross-section of Sr_005 produced using a Cryostat, 10 µm thickness, viewed at 400x magnification

Mounting a coverslip over the section with pure glycerol somewhat improved the crispness of the cross-section edges (Figure 6.26). Interestingly, the Cryostat samples appear to render the sericin surrounding the fibres more visible, something that is not seen clearly in the other cross-sections.

Figure 6.26:Cross-section of Sr_005 produced using a Cryostat, 10 µm thickness, with glycerol-mounted coverslip, viewed at 400x magnification.

In terms of efficiency, ease of embedding, and quality of cross-sections, the Cryostat was determined to be the most suitable method for completing the cross-sections of both experimental and archaeological silk fibres. One further test session on the cryostat trialled slicing the samples at thicknesses of 15µm, 30µm, 7µm, 6 µm, and 5µm, and established that a 6µm-thick cross section struck the ideal balance in depth of focus during image capture, while still being relatively easy to mount on slides, as cross-sections with a thickness of less than 6µm had higher tendency to tear and fold when mounted on a slide.

6.4.5 SEM trials

To minimise risk of damage to the archaeological fibre samples, preliminary trials using the Hitachi TM4000Plus II Tabletop Scanning Electron Microscope were conducted using experimentally produced silk samples. Rast-Eicher (2016, 70) states that best practice is to coat organic samples with carbon or another conductive substance such as platinum prior to imaging with an SEM. This helps to avoid the build-up of charging, which can cause burn damage to the samples. Charged areas appear white in an SEM micrograph, creating the effect of an overexposed image.

The Hitachi TM4000Plus II specifies that its low vacuum secondary electron (SE) detector is capable of imaging both conductive, and non-conductive samples without the need for coating (Hitachi High-Tech Corporation 2022). It therefore seemed sensible to test the possibilities for imaging uncoated fibre samples which, if successful, would eliminate both the need for additional equipment access and the added time and cost of sample coating.

Several experimentally produced silk samples were imaged using the SEM and underwent EDS chemical analysis using varied settings. Despite the low vacuum, the silk fibres were prone to charging, compromising the quality of the SEM micrographs (Figure 6.27). This is partly because the areas where silk fibres crossed over one another and were not in direct contact with the carbon tab were most prone to charge build-up. Changes in setting reduced charging but at the expense of image resolution (Figure 6.28).

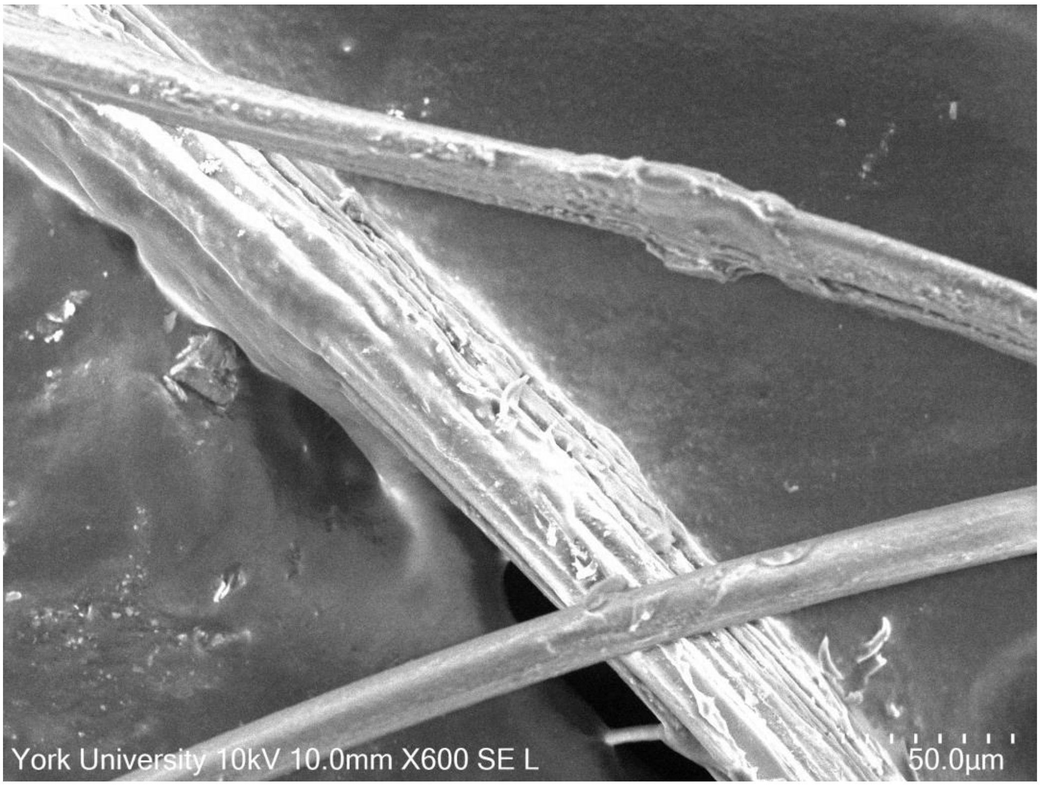


Figure 6.27: SEM image of Sample Sr_002 at 600x magnification. The bright white areas are a result of charge buildup, a consequence of imaging an uncoated sample at 10kV (mode 3)

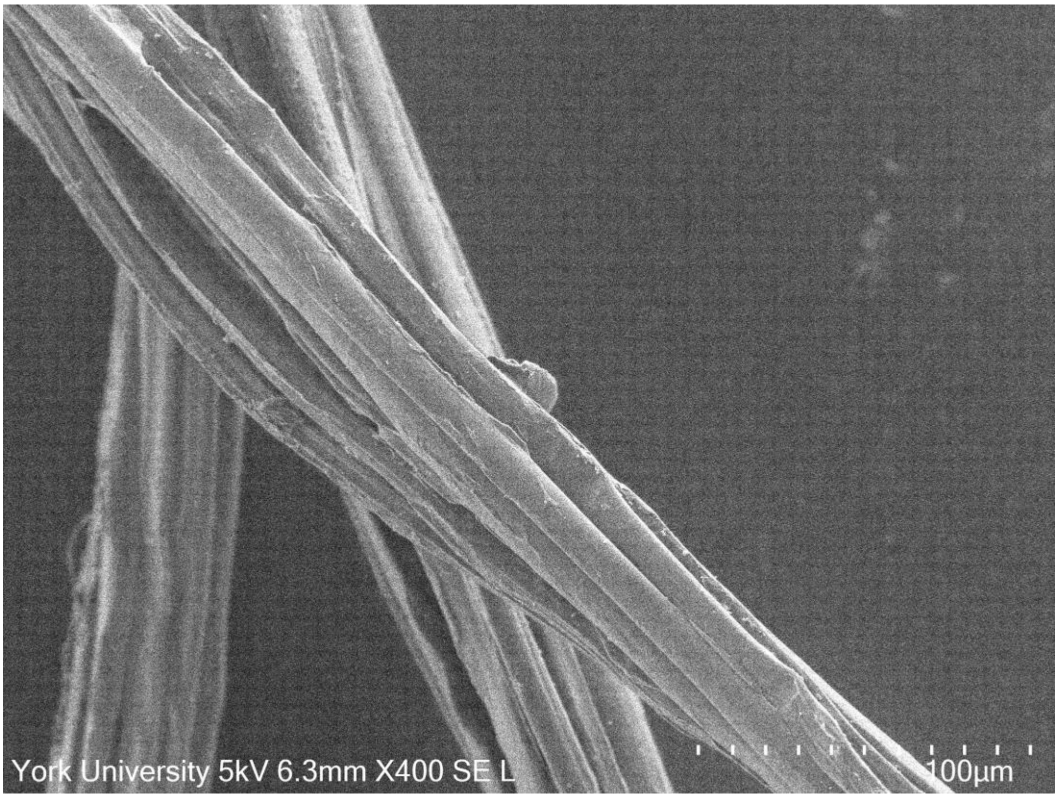


Figure 6.28:SEM image of sample Sr_022 at 400x magnification showing reduced resolution and significant reduction of charging resulting from imaging at 5kV (mode 1)

The Gold/Palladium-coating method applied following these initial trials resolved the problem of static charging, and allowed for the capture of significantly better-quality images at 10kV, which displayed fibre morphology and surface texture in sufficient detail (Figure 6.29).

Figure 6.29: SEM image of a gold/palladium coated sample of Sr_022 at 800x magnification

6.5 Quantitative Data Collection

Following established textile analysis protocol (see Chapter 2.3) fibre diameter, thread count, yarn diameter and angle of twist measurements were recorded from the experimental silk samples and archaeological textiles as applicable. In the case of the experimental silks, thread counts were not gathered as the samples did not include woven textiles and relatively few yarn diameter and twist measurements were collected. Additionally, due to the large number of raw silk samples in the experimental reference collection, an additional measurement of filament diameter was also recorded.

It was determined that while thread counts, yarn, and fibre diameters of the silk textiles from Coppergate have been recorded and published previously (Walton 1989), re-recording these measurements as part of a re-examination of the selected Coppergate silk textiles was important to maintaining consistency in the measurement collection approach. Obtaining this raw data allowed for more transparency during statistical analysis following data collection.

6.5.1 Measurement Capture with Olympus LC Micro and Stream Software

A range of measurements were taken of the experimental silks and the Coppergate textiles using 2 different yet compatible image capture and processing programs. *LC micro* and *Stream* are both proprietary Olympus software compatible with Olympus microscope cameras. The software has the benefit of being cross-compatible while offering slightly different image processing capabilities, so the use of each program was tailored to the type of measurement being recorded.

6.5.1.1 Yarn diameters in Stream

Using Olympus Stream software, a minimum of 20 yarn diameter measurements were captured using the Arbitrary line tool (Figure 6.30). The measurements, in µm, were exported as an excel spreadsheet with minimum, maximum, mean, and standard deviation summaries. The same measurement protocol was used for both the experimental yarn samples and the Coppergate silk textiles, with the exception that at least 2 sets of measurements (one for each system, and another for the warp threads in a preserved selvedge) were taken for each woven textile. The exported spreadsheets were labelled and once this step was complete, duplicate images with the measurement overlays were saved as a visual record of the measurements taken.

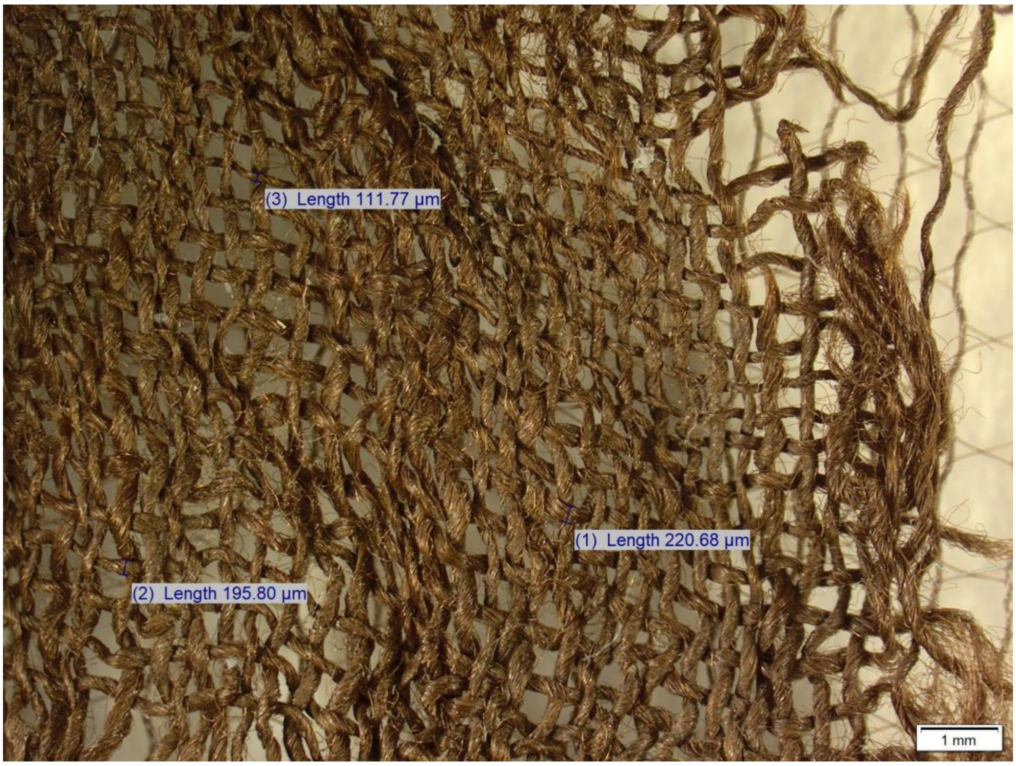
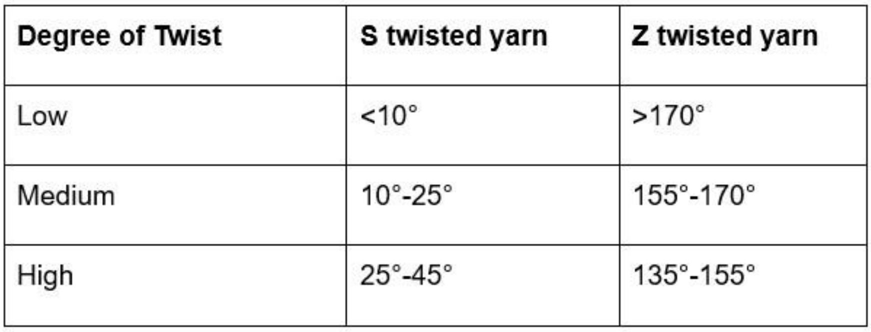


Figure 6.30: Micrograph of Coppergate textile 1371 captured at 10x magnification with system B measurements marked using the arbitrary line tool

6.5.1.2 Silk Yarn Angle of Twist in Stream

Methods of measuring and classifying twist angles were adapted from Ozkaya at al. (2010) and Malcom-Davies et al. (2018). The approach established in Ozkaya et al. using a range of 10°-80° for S twist, and 100°-170° for Z twist was favoured for angle measurement, as it reflected direction of twist without the need for additional notation. The relationship between twist angle and degree of twist established by Emery and used by Malcolm Davies et al., was also adapted to reflect Ozkaya's use of a (nearly) full 180° range (Table 6.10). These categories were used as a point of comparison during analysis but were not used to assign descriptors of degree of twist during visual analysis.



Degree of Twist	S twisted yarn	Z twisted yarn
Low	<10°	>170°
Medium	10°-25°	155°-170°
High	25°-45°	135°-155°

Table 6.10: Categories of twist corresponding to angle measurements adapted from Malcolm-Davies et al (2018) and Ozkaya (2010)

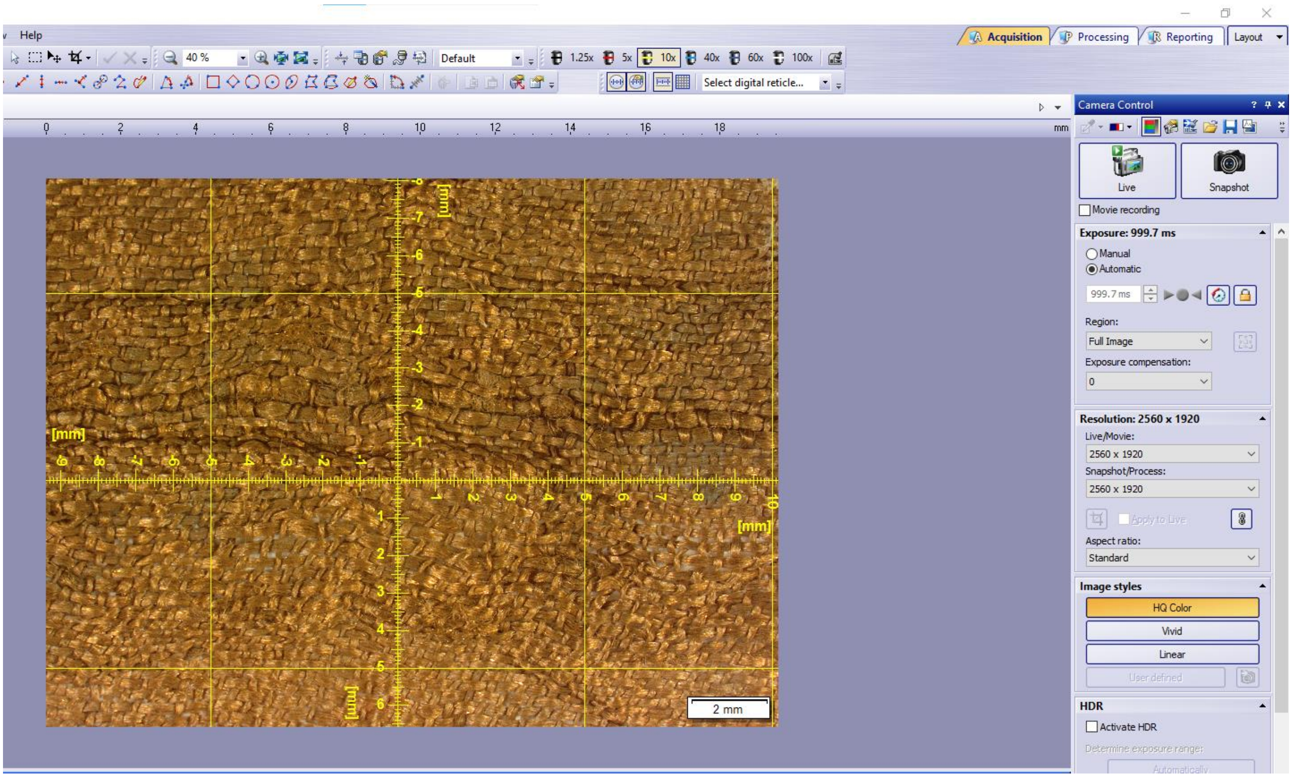
The angle measurement tool in Stream was used to record a set of 20 angle-of-twist measurements from a selection of experimental silk textiles and all systems of the Coppergate textiles that exhibited twist. These twist measurements were then exported as spreadsheets and labelled accordingly, as was done with the recorded yarn diameters. Yarn that had previously been categorised as I (without twist) was assessed for angle measurement. While the fibres did appear at subtle angles to the overall direction of yarn, the angles themselves did not follow a consistent direction that would be reflective of twist. This meant that it was not possible to capture meaningful angle measurements and confirmed the established yarn identification.

6.5.1.3 Coppergate Thread Counts in LC Micro and Stream

Two approaches were taken when recording the thread counts of the Coppergate textiles:

1. In LC Micro an arbitrary line was drawn as close to 10000 µm as possible perpendicular to the system being counted (Figure 6.31)
    a. The number of threads of interest along length of this line were counted and recorded in spreadsheet
2. A digital reticle overlay was used in Stream with 5mm increments marked (Figure 6.32)
    a. Threads of interest within a 1cm area were counted and recorded in a spreadsheet

Figure 6.31: Coppergate textile 1347 with arbitrary line measure guide c. 1cm long in LC Micro



☐ Movie recording

Exposure: 999.7 ms

○ Manual

● Automatic

999.7 ms

Region: Full Image

Exposure compensation: 0

Resolution: 2560 x 1920

Live/Movie: 2560 x 1920

Snapshot/Process: 2560 x 1920

Aspect ratio: Standard

☐ Activate HDR

Figure 6.32: Coppergate textile 1347 viewed with digital reticle in Stream

A comparison of counts produced by each method confirmed that there was no appreciable difference between the 2 approaches. However, the reticle provided a concrete 5mm increment guide and was more efficient to set up and use, so this method was used moving forward. Care was taken to align warp and weft threads parallel to reticle during image capture for greater accuracy. The number of threads in the area of interest were then counted and a minimum of 15 thread counts for each thread system across different areas of the textile were input to a spreadsheet set up with formulas that also calculated the measurement count, minimum, maximum, mean, median, mode, and standard deviation (based on sample). In some cases, a textile fragment was too small to obtain the minimum number of thread counts in multiple 10mm areas. In this case, thread counts were taken in 5 mm areas, and doubled after they had been recorded. In one case this process was carried out counting threads across 2.5mm increments, which were then multiplied by 4. In all cases a point was made of conducting as many thread counts as possible in a 10mm area prior to taking counts for an area less than 10mm.

6.5.1.4 Experimental Reeled Silk Diameters

Diameter measurements of both reeled filaments (Figure 6.33) and individual fibres (Figure 6.34) were captured manually in Stream using the arbitrary line measurement tool. Filament measurements were taken from micrographs captured at 50x magnification as this provided the necessary balance of a high enough level of magnification without sacrificing the depth of focus required to accurately mark the edges of the filaments. When taking measurements of the silk fibres, micrographs captured at 100x magnification were used, as this improved accuracy when marking the edges of the fibres.

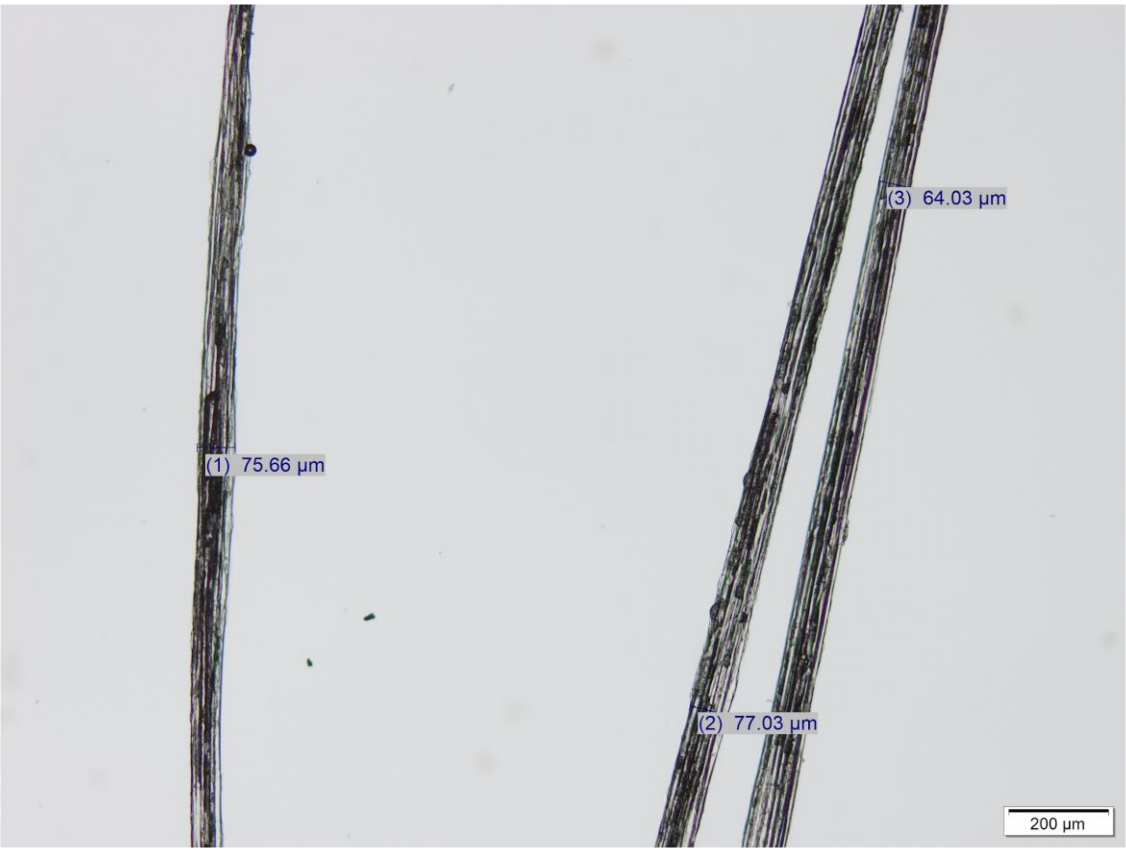


Figure 6.33: Micrograph of experimental sample Tr_006 viewed at 50x magnification showing filament measurements marked with the arbitrary line tool

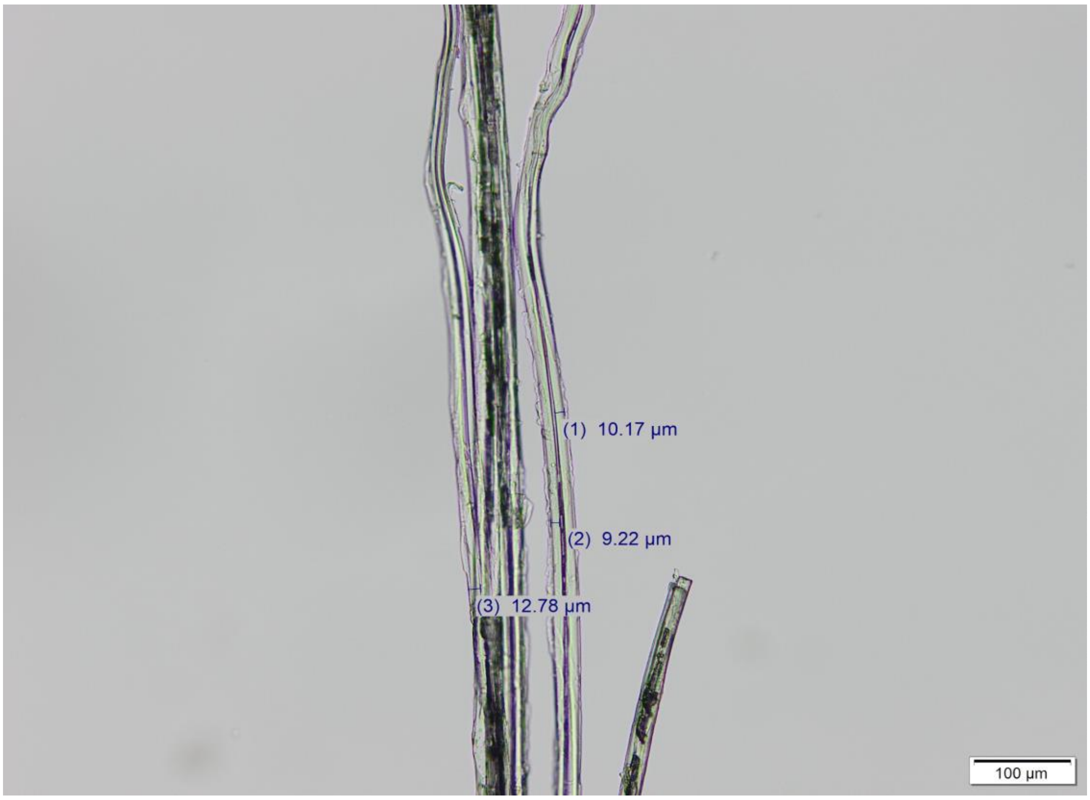


Figure 6.34: Micrograph of experimental sample Tr_006 viewed at 100x magnification showing fibre measurements marked with the arbitrary line tool

Where possible a minimum of 15 measurements of the reeled filament diameters and 20 measurements of individual fibre diameters were captured for each sample. When measuring the diameter of raw silk fibres, the sericin coating the fibre was not included in the measurement but the sericin thickness was included in the overall diameter of the filaments. Individual spreadsheets were saved for each sample's measurement set and the measurement count, minimum, maximum, mean, and Standard deviation were compiled for further analysis. Duplicate copies of the micrographs with burned-in measurements were also saved.

6.5.1.5 Archaeological Fibre Diameters

The diameters of archaeological silk fibres were captured following the same approach that was taken in measuring experimental silk fibres. The key difference was that the archaeological fibres were typically not grouped into filaments. In cases where groups of fibres suggestive of preserved raw silk filaments were observed, these were generally so fragmented that the requisite minimum of 15 measurements could not be captured, and there was some uncertainty as to whether these fibres groups were reflective of a whole reeled filament or whether they represented a fragmented section. Therefore, only fibre diameters were captured following the same procedure used for experimental silk fibre measurement.

6.5.1.6 Diameter Measurements of Fibre Cross-Sections

Diameter measurements of a selection of cryostat cross-sections of fibres from the experimental reference collection, and the 2 archaeological silk collections were taken manually using the arbitrary line measurement tool. Sets of 20 measurements were collected from 2 of the prepared slides for each sample measured, which allowed for comparisons of differences in different sets of diameters captured from the same samples.

As the cross-sections of silk fibres generally resemble isosceles triangles skewing close to equilateral, the measurements taken cannot technically be described as diameters. To establish a consistent metric the measurements taken spanned from base to apex of the triangle, to record the longest distance across the cross-section of the fibre (Figure 6.35). The measurements captured using this method would therefore theoretically be more consistent than the fibre diameters captured transversally from silk fibres imaged in whole-mount as transverse diameter measurements could skew to shorter lengths depending on the rotation of the fibre measured. Care was taken during measurement capture to only measure cross-sections that appeared to be true cross sections, as there was some evidence of tilted fibres that had not been sliced at a true 90° angle to the fibre axis. This was particularly true of fibres in the archaeological textiles, most of which had been twisted for c. 1000 years and did not lie perfectly parallel to each other.

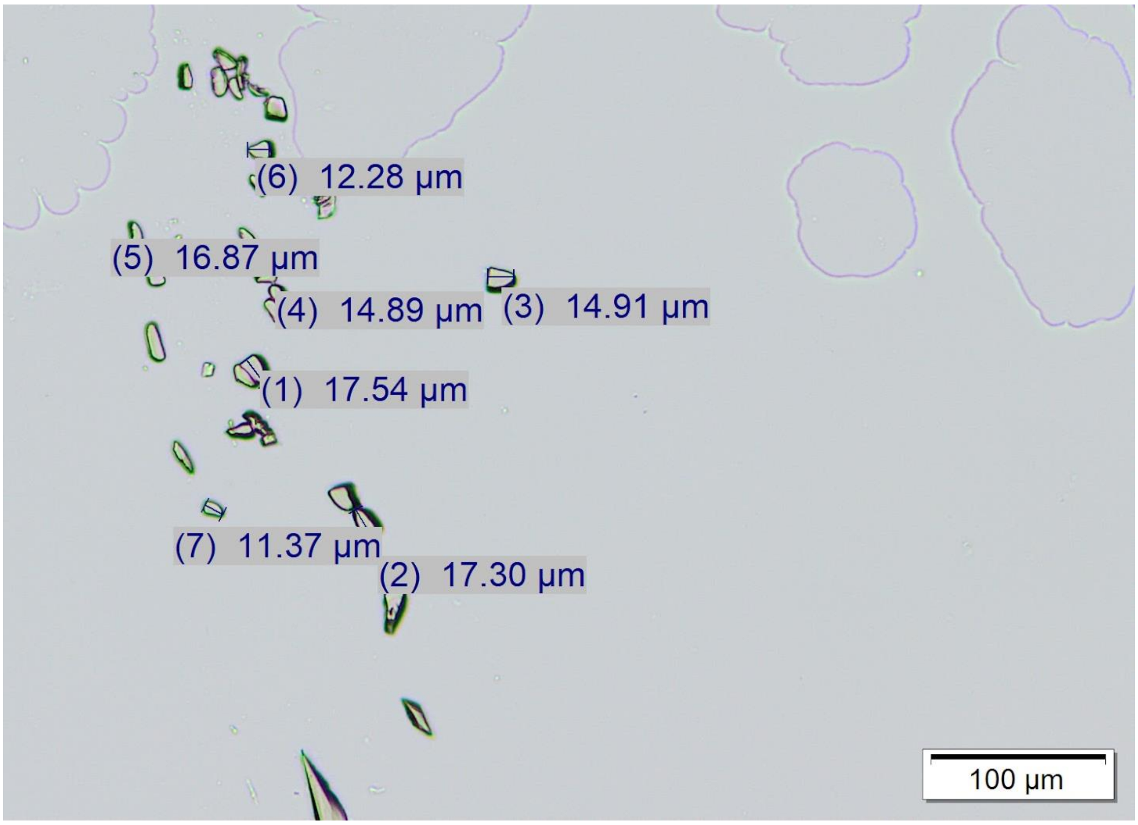
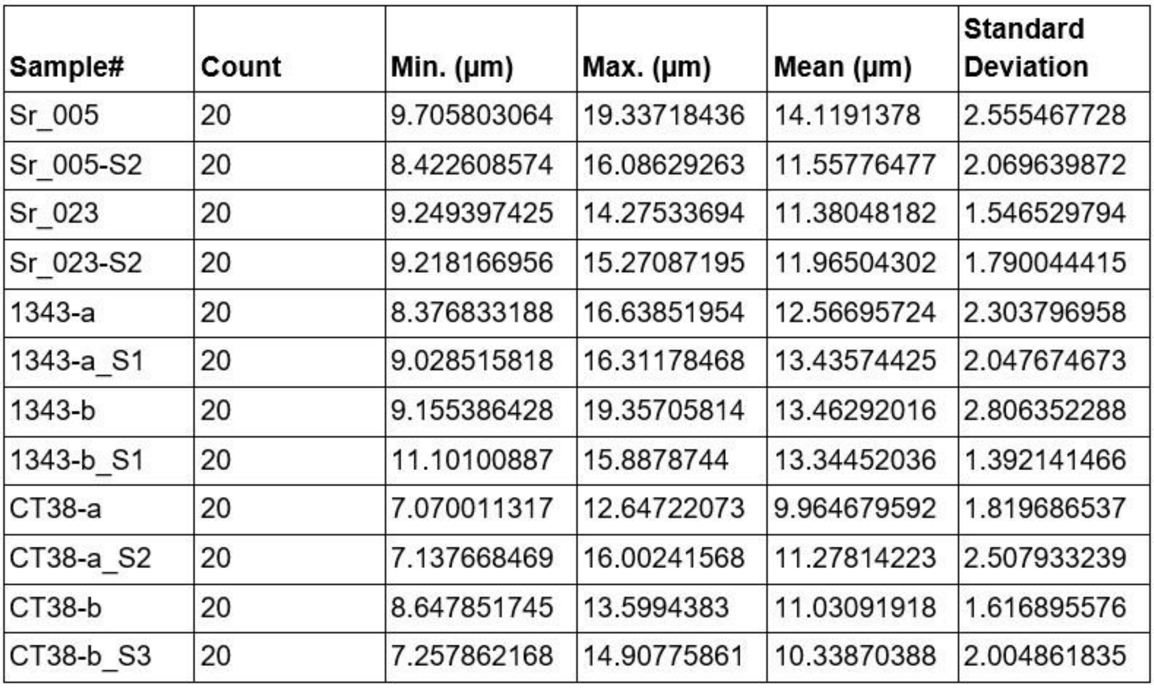


Figure 6.35: Micrograph of fibres cross-sections from Coppergate sample 1347-a (fibres from the warp system) viewed at 100x magnification and measured in Stream with the arbitrary line tool

6.5.1.7 Comparison of Cross-Section and Whole-mount Diameters

Given the time-consuming nature of fibre cross-section preparation, measurements taken via cross-section from each of the selected samples were gathered for comparison to measurements taken transversally from whole-mount slides of the same samples (Table 6.11). The aim was to determine whether there was an appreciable difference between the measurements taken with each method.



Sample#	Count	Min. (µm)	Max. (µm)	Mean (µm)	Standard Deviation
Sr_005	20	9.705803064	19.33718436	14.1191378	2.555467728
Sr_005-S2	20	8.422608574	16.08629263	11.55776477	2.069639872
Sr_023	20	9.249397425	14.27533694	11.38048182	1.546529794
Sr_023-S2	20	9.218166956	15.27087195	11.96504302	1.790044415
1343-a	20	8.376833188	16.63851954	12.56695724	2.303796958
1343-a_S1	20	9.028515818	16.31178468	13.43574425	2.047674673
1343-b	20	9.155386428	19.35705814	13.46292016	2.806352288
1343-b_S1	20	11.10100887	15.8878744	13.34452036	1.392141466
CT38-a	20	7.070011317	12.64722073	9.964679592	1.819686537
CT38-a_S2	20	7.137668469	16.00241568	11.27814223	2.507933239
CT38-b	20	8.647851745	13.5994383	11.03091918	1.616895576
CT38-b_S3	20	7.257862168	14.90775861	10.33870388	2.004861835

Table 6.11: Summary of fibre diameter measurements from cross-section and whole-mount samples

The measurement minimums, maximums, means, and standard deviation of each were compared and the mean of each data set, while differing slightly were each determined to fall within the range of standard deviation established in the sets of measurements, meaning that the difference in diameter means derived from the 2 distinct sample preparation and measurement approaches was not statistically significant. This initial conclusion was further supported by a one-way Analysis of Variance (ANOVA) of fibre diameter measurements from 2 prepared cross-section slides and one whole-mount slide of the Coppergate fibre sample 1343-a, which returned a P value higher than the selected significance level of 0.05, meaning that a null hypothesis could not be rejected (Table 6.12), although this test did, unsurprisingly demonstrate a higher similarity in the means of the 2 cross-section slides in contrast to the mean of the whole-mount slide (Figure 6.36).

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Slide Mount	2	9.80300	4.90150	0.9449	0.3947
Error	57	295.66869	5.18717		
C. Total	59	305.47170			

Table 6.12: Results of One-way Anova of Cross-section and whole-mount derived fibre diameter measurements for Coppergate 1343-a

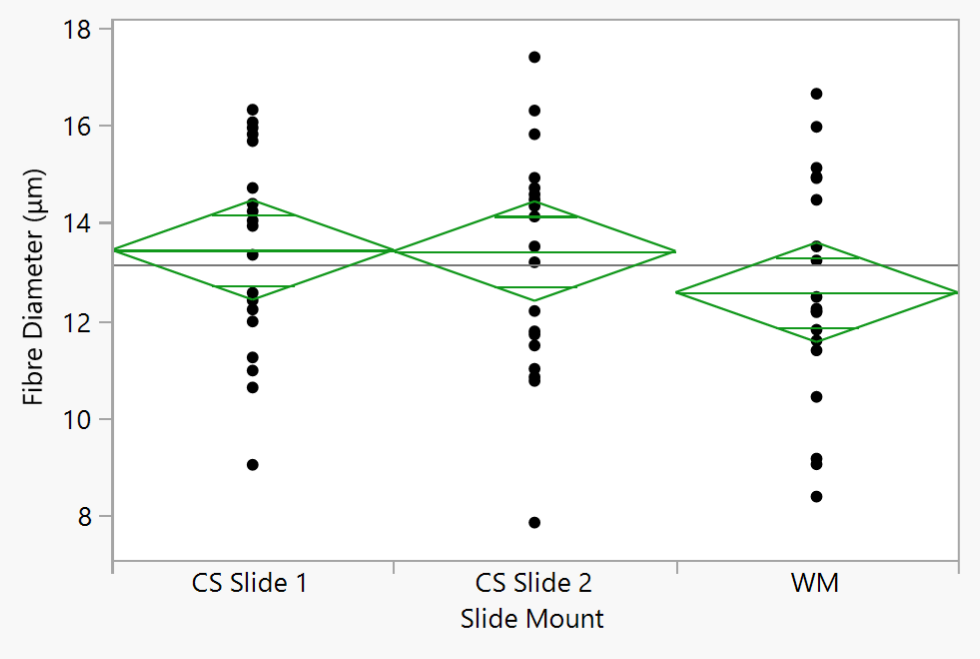


Figure 6.36: Visualisation of One-Way Anova of Cross-section and whole-mount derived fibre diameter measurements for Coppergate 1343-a showing slight difference in means

Having concluded that the difference between the means of fibre diameters measured by cross-section and whole-mount was statistically insignificant, it was determined that measurements collected from whole-mount samples would be sufficient for this research. The diameter measurements taken transversally from whole-mount fibre slides can be collected more efficiently and with fewer steps to sample preparation, in comparison to cross sectional measurements. The diameters collected from whole-mount slides were determined to be better suited to the aims of this research. This has the added benefit of being a more accessible approach for other researchers who may wish to replicate these methods. While the subtle differences in diameter measurements across different methods may merit further exploration, particularly in combination with other variables such as fibre cross-sectional area and shape, this type of statistical work falls beyond the scope of this thesis.

6.5.2 Measurement Capture Using Fiji (ImageJ)

Fiji, a packaged version of the open-source software ImageJ (Schindelin et al 2012) was used to calibrate and take measurements from the scanned Winchester images. This was because, while the micrographs captured of the Coppergate textiles using *LC micro* produced images with embedded scale calibration metadata, the same was not the case for the scanned images of the Winchester textiles, so measurements could not be recorded using Olympus' proprietary software.

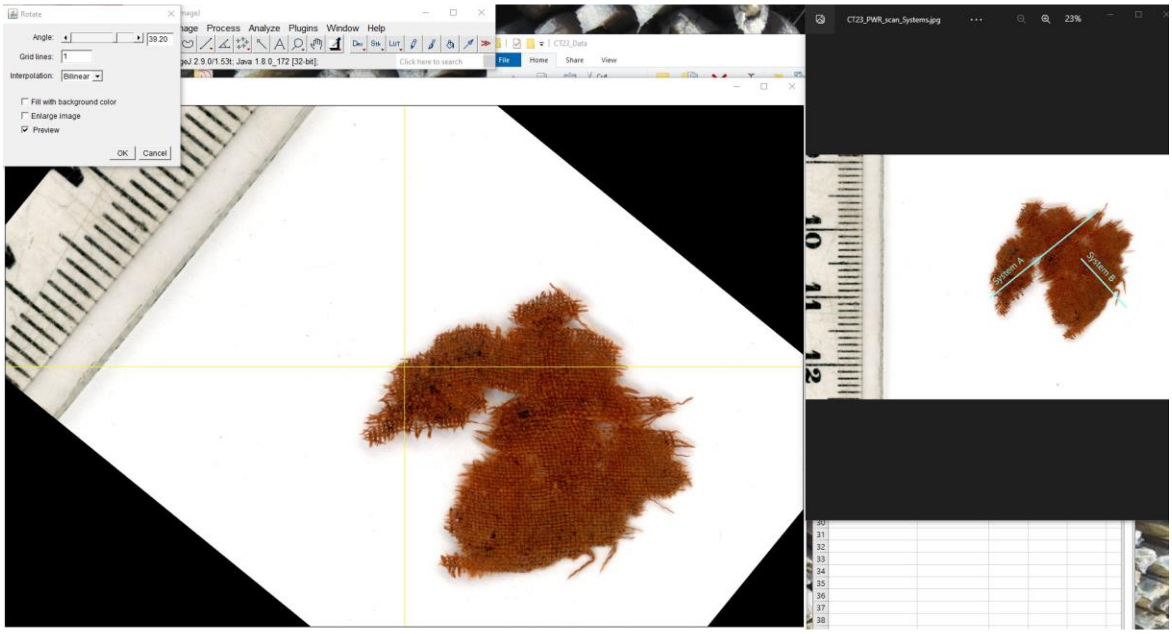
6.5.2.1 Image Calibration

Prior to procuring any measurements, each scanned image needed to be calibrated in Fiji. This was done by adjusting the magnification of the image to 100%. The Draw Line tool was then used to draw a line spanning 10mm on the ruled scale included in the image. Using the Set Scale setting, the length of the line drawn, was input as 10, and the unit specified as mm. This process aligns the given real-world measurements to the number of pixels spanned by the line drawn, calibrating the entire image. Because there is some room for error with this type of manual calibration, a test measurement was taken each time. If the generated measurement was within 0.3mm of the measurement indicated on the scale, the calibration was considered valid.

6.5.2.2 Winchester Thread Counts

As was the case with taking thread counts for the Coppergate textiles, 2 initial approaches to conducting thread counts were tested using Fiji. Prior to conducting both methods, the image was rotated in the software

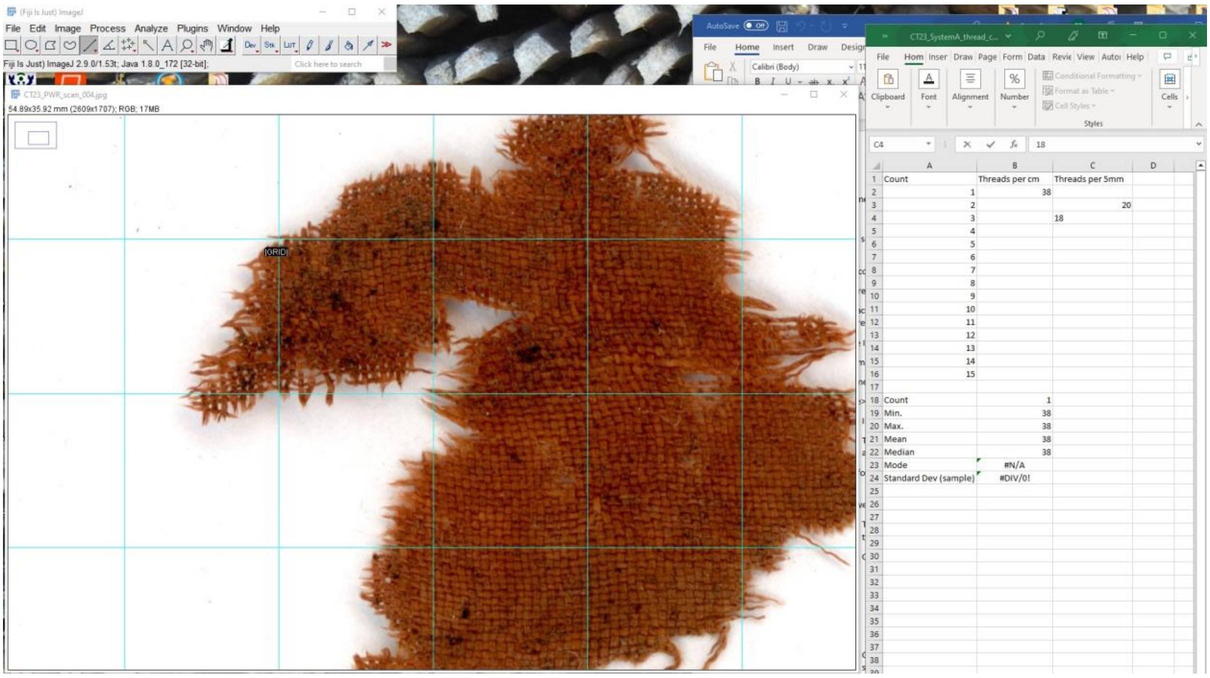
(Figure 6.37) so that the thread systems would be parallel to a square grid within the image area.



Angle: 39.20
Grid lines: 1
Interpolation: Bilinear
☐ Fill with background color
☐ Enlarge image
☑ Preview

Figure 6.37: Screenshot of the scanned image of CT23 being rotated prior to conducting thread counts

The first thread count method inserted a scale bar with a set length of 10mm as an overlay. The second approach had a similar effect to the digital reticle used in stream. A grid overlay with a set square area of 100mm² (producing lines that intersected every 10mm) was inserted over the image, which allowed for efficient thread counting in both system A and B (Figure 6.38). As was the case with some of the Coppergate textiles, a minority of the Winchester textiles required the use of smaller increments than 10mm, in this case, once the maximum number of thread counts per 10mm were taken from the textile in question, the grid was updated to contain squares with an area of 25mm² to acquire the remaining thread counts. The compiling of the thread counts then followed the same approach taken with the Coppergate textiles, and a minimum of 15 thread counts for each thread system across different areas of the textile were input to a spreadsheet set up with formulae that also calculated the measurement count, minimum, maximum, mean, median, mode, and Standard deviation.



	A	B	C	D
1	Count	Threads per cm	Threads per 5mm	
2	1	38		
3	2		20	
4	3		18	
5	4			
6	5			
7	6			
8	7			
9	8			
10	9			
11	10			
12	11			
13	12			
14	13			
15	14			
16	15			
17				
18	Count	1		
19	Min.	38		
20	Max.	38		
21	Mean	38		
22	Median	38		
23	Mode	#N/A		
24	Standard Dev (sample)	#DIV/0!		

Figure 6.38: Screenshot of the scanned image of CT23 set up with a grid for taking system A & B thread counts

6.5.2.3 Winchester Yarn Diameters

Prior to taking yarn diameter measurements, the image calibration was adjusted to µm. Measurements were taken manually using the Draw a line tool to indicate the length of measurement. A minimum of 20 diameters were taken for each system of every textile.

6.5.2.4 Winchester Yarn Twist

Angle of twist measurements were recorded for the Winchester textiles (Figure 6.39) using the Angle Measurement tool with the image set between %100-%150 zoom. Because the measured angle did not need to be tied to the physical dimensions of the textiles, it was not necessary to calibrate the images prior to taking angle measurements. A minimum of 20 measurements were taken for each system.

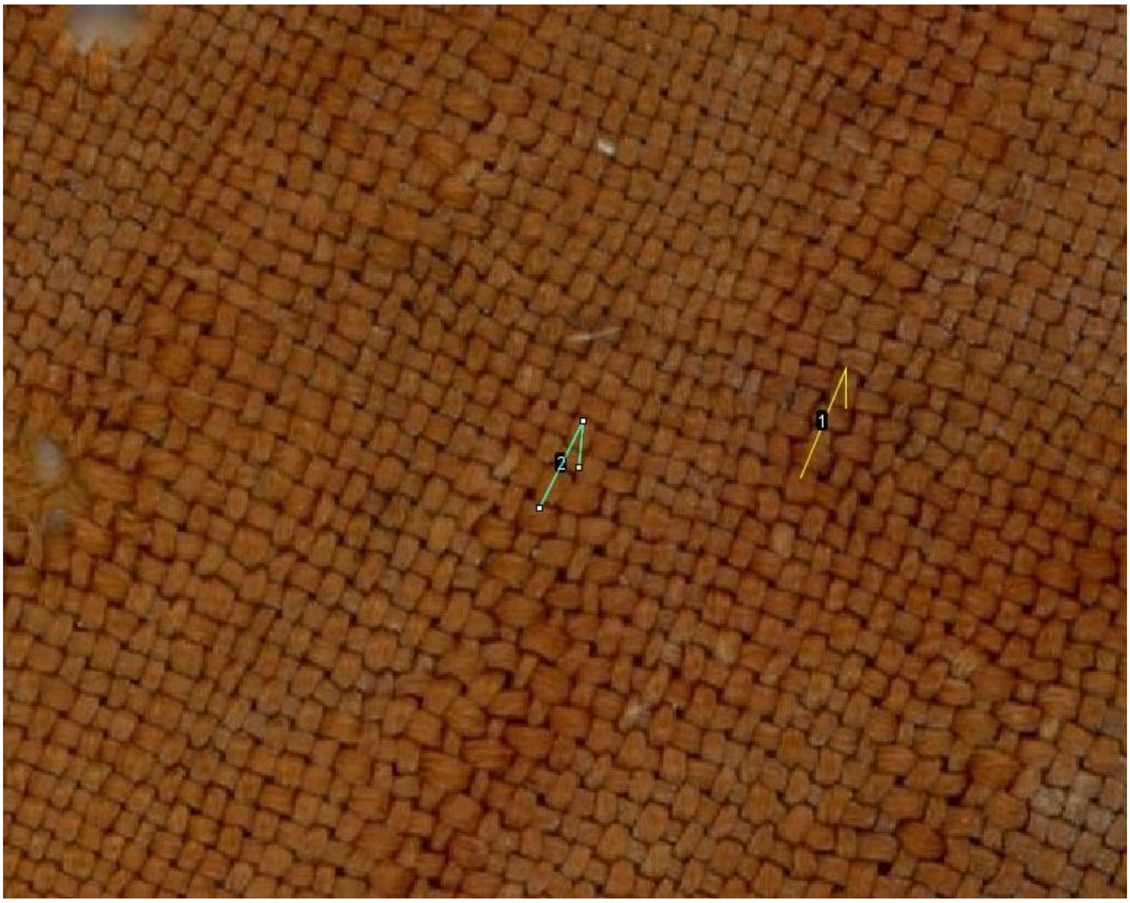


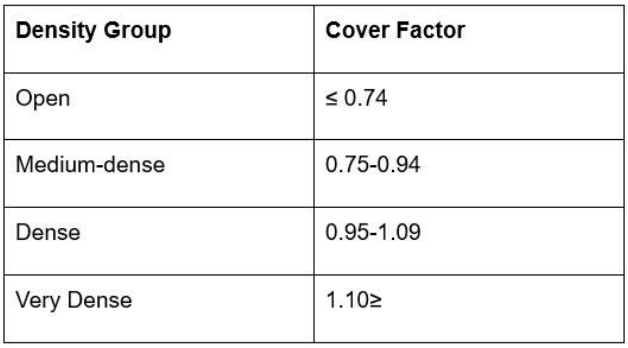
Figure 6.39: Detail of Fiji's angle measurement tool applied to System A of Winchester textile CT22 (Original scanned image courtesy of Penelope Walton Rogers)

6.6 Quantitative Data Analysis

The measurements collected from both the experimental and archaeological silk collections were processed and analysed using the statistical software JMP.

6.6.1 Calculating Cover Factor

The cover factor of each textile, apart from Coppergate 1352 was calculated using the thread counts and yarn diameters gathered. The categories of density established by Hammarlund (Table 6.13, also see chapter 2.3.4) were used as a reference point when contrasting the calculated cover factor with the perceived density of the Coppergate and Winchester silk tabby textiles.



Density Group	Cover Factor
Open	≤ 0.74
Medium-dense	0.75-0.94
Dense	0.95-1.09
Very Dense	1.10≥

Table 6.13: Cloth density groups and corresponding cover factor ranges adapted from Hammarlund (2005)

The method presented by Hammarlund is based on centimetre measurements, which is more difficult to approach with silk textiles given the extremely fine diameters of the silk yarn (most under 1mm). Further research was therefore undertaken to determine whether cover factor could accurately be calculated by the millimetre. Through this process several possible formulas for calculating cover factor were identified. Hammarlund's formula (see Chapter 2.3.4) calculates the cloth cover factor, using the Warp and Weft Cover factors (termed WA and WE). This method is also described in Kostajnšek & Dimitrovski (2021, 3), who applied an extended cover factor formula to thread count measurements based on a cm measure and yarn diameters given in μm.

6.6.1.1 Silk-Adapted Formulas

In further adapting the formula provided by Hammarlund, WA was replaced with CfA and WE was replaced with CfB (Cover factors of System A and B, respectively). The use of "System A" and "System B" rather than warp and weft in the terminology used is an important distinction as it allows the formulas to be applied even to textiles where warp and weft cannot be confidently identified.

Therefore, the formulas used to calculate cover factor were:

Cf= cfA+ cfB - (cfA x CfB)

Wherein Cf is the cloth cover factor. The cover factor of System A (CfA) was calculated with the following formula:

$$CfA = DA \times dA$$

and the cover factor of System B (CfB) was calculated with:

$$CfB = DB \times dB$$

In the above formulas DA and DB refer to the number of threads per given unit of measure in Systems A and B respectively. While dA and dB refer to the diameter of yarn in systems A and B.

6.7 Defining Qualitative Data Categories

The qualitative analysis of the experimental and archaeological silk textiles was conducted throughout the data collection process. Observations regarding the morphology and other visual characteristics of the silk samples were noted. It quickly became clear that a framework for describing the visual characteristics of the silk textiles was needed. The resulting framework, particularly as applied to woven textile samples was informed partially by a visual analysis approach initially developed by Lena Hammarlund (Hammarlund 2005b). Although this research works with a much smaller set of textiles, the potential for adapting Hammarlund's criteria to develop a framework of visual analyses for the archaeological silk textiles was immediately apparent and several categories of textile descriptors were established as relevant to the analysis of the 2 groups of silk tabby textiles (Table 6.14).

Selvedge Treatment	Density	Weave Balance	Yarn Movement	Surface Texture
Plain	Very Open	System A-faced	None	Flat
Paired Warp threads	Open	System A Dominant	Low	Crow's Feet
N/A	Balanced	Balanced	Moderate	Crepe
	Dense	System B Dominant	High	Ribbed
	Very dense	System B-faced	Very High	

Table 6.14: Established categories of textile characteristics with their respective descriptors

In addition to the above features, other categories of qualitative data (Table 6.15) were determined to be of interest, whether in relation to the overall preservation of the textiles, or as indicators of decisions made during the processes of textile production and use.

Selvedge Preserved	Weaving Flaws	Sewing Thread	Empty Stitch Holes	Yarn Deterioration
Yes	Yes	Yes	Yes	Low
No	No	No	No	Moderate
				High
				Very High

Table 6.15: Additional categories of qualitative data Established for archaeological textile analysis

Qualitative categories were also established for silk yarn (Table 6.16), either in situ or separate from a woven textile, and silk fibres (Table 6.17). These categories were based primarily on observations made during textile recording and analysis and were developed to be applicable to both the archaeological and experimentally produced silks.

Twist Direction	Ply	Degree of Twist	Yarn Cohesion	Texture	Rigidity	Residue	Diameter Variation
Z	Single (not plied)	none	Very Low	Smooth	Very Stiff	Yes	Low
S	2 elements	Low	Low	Slubby	Stiff	No	Moderate
I	>2 elements	Moderate	Moderate	Hairy	Pliable		High
		High	High		Very Pliable		Intermittent
		Overtwisted					

Table 6.16: Established categories of yarn characteristics with their respective descriptors

Filament Cohesion	Fibre Spread	Fibre Pairs	Fibre Groups	Sericin Integrity	Sericin Texture	Sericin Spread	Fibre Damage	Fibre Shape Variability
None	Compact	Yes	Yes	None	Mottled	Low	None	None
Low	Moderate	No	No	Low	Pitted	Moderate	Low	Low
Moderate	Wide			Moderate	Flakey	High	Moderate	Moderate
High				High	Pocked		High	High
					Smooth		Very High	

Table 6.17: Established categories of fibre characteristics with their respective descriptors

6.7.1 Textile grouping by System Twist

For ease of comparison, the tabby-textile twist categories established for the Coppergate textiles in Walton (1989) were used during analysis. The categories (ZZ, ZI, SS, II) provided a useful shorthand for one of the most obvious technical differences in the tabby silk textiles; the direction in which the yarn is twisted. One minor modification to the formatting of these categories was made, the addition of a lowercase x to more clearly visually distinguish between the 2 systems notated. Using this notation, ZxZ indicates a textile woven from Z-twisted yarn in both systems, ZxI indicates a textile with Z-twisted yarn in system A and yarn without twist (I) in system B, etc.

6.7.2 Identifying plied yarn

The identification of plied yarn that has been spun from discontinuous fibres is reasonably easy as the physical characteristics of this yarn are clearly observed (Figure 2.17). It would seem to be a reasonable assumption that this would also be the case for yarn constructed from reeled silk, but some incongruities in the yarn characteristics of Coppergate textile 1347 indicated that a more in-depth analysis was warranted.

A method of visual analysis was employed, aimed at developing a framework for describing the characteristics of plied silk yarns. The first stage of this approach employed the use of digital drawing software to trace the features of Coppergate 1347, and clarify yarn features that appeared to indicate the incorporation of at least some plied yarn (Figure 6.40).

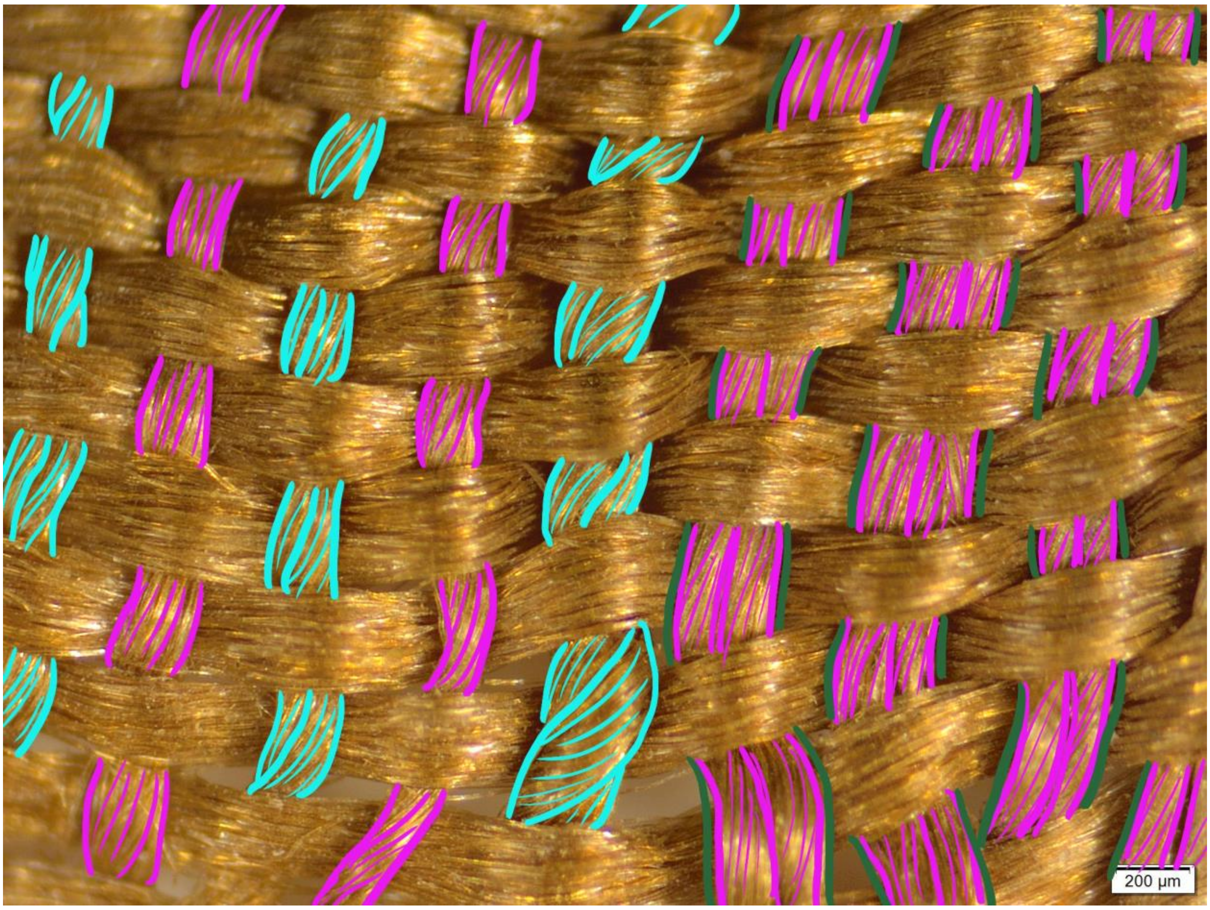
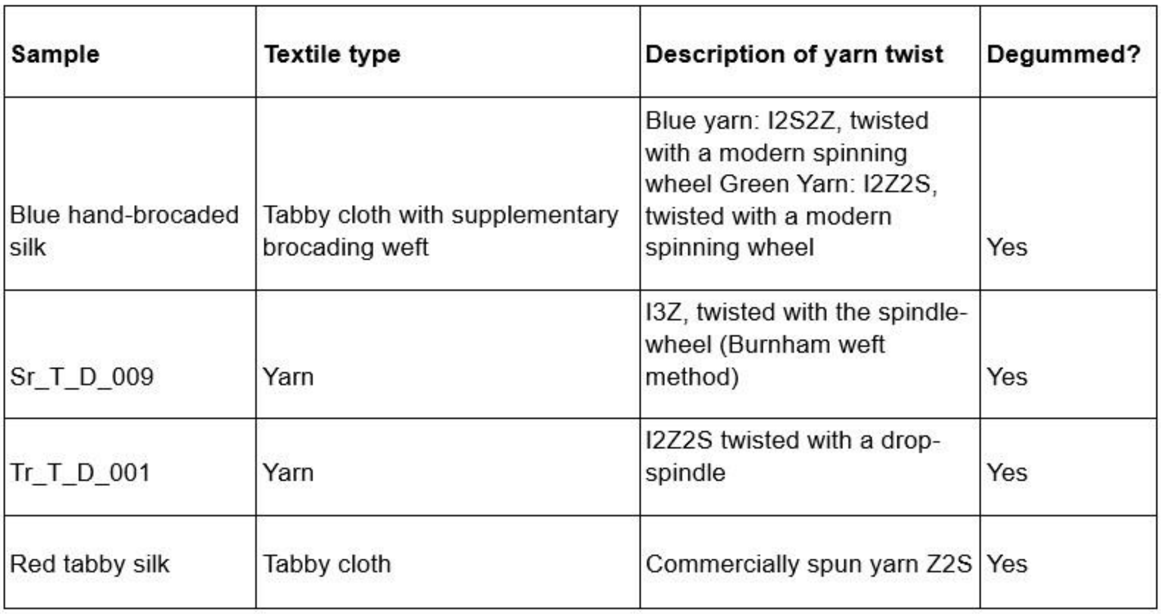


Figure 6.40: First tracing exercise over reflected light micrograph of Coppergate 1347. The cyan lines indicate suspected plied yarn and magenta lines indicate yarns tentatively defined as single, while the green outlines indicate paired single warp yarns in the selvedge

While this exercise aided in identifying visual features that could suggest plied yarn, it was clear that to establish a solid framework for plied yarn identification the approach needed to be applied to a selection of silk samples with known production stages (Table 6.18). An unexpectedly crucial sample for this study was a hand-brocaded silk sample that had been woven by the author from hand-reeled silk in 2013 and was used as a practice piece when developing the stereomicroscope image-capture protocol for the archaeological silk textiles. Because the exact stages of production for this piece of cloth were known, this textile sample provided an ideal reference point for the appearance of plied silk yarn within the structure of a tabby-woven cloth, while the supplementary brocading weft provided an additional reference for plied silk yarn. Also included in the selection of samples for visual analysis were plied (Tr_T_001) and twisted but not plied (St_T_D_009) experimental silks, and a sample handwoven from commercially spun silk, which was useful for contrasting the characteristics of spun and plied silk yarn and reeled and plied silk yarn.



Sample	Textile type	Description of yarn twist	Degummed?
Blue hand-brocaded silk	Tabby cloth with supplementary brocading weft	Blue yarn: I2S2Z, twisted with a modern spinning wheel Green Yarn: I2Z2S, twisted with a modern spinning wheel	Yes
Sr_T_D_009	Yarn	I3Z, twisted with the spindle-wheel (Burnham weft method)	Yes
Tr_T_D_001	Yarn	I2Z2S twisted with a drop-spindle	Yes
Red tabby silk	Tabby cloth	Commercially spun yarn Z2S	Yes

Table 6.18: The textiles samples chosen for ply analysis

The process of tracing the outlines of the sub-elements of plied yarns with different visual characteristics helped establish subtle visual cues that are more likely to indicate that a yarn is plied. At all stages of the tracing exercise, only features that were felt to be unambiguous were traced; any elements that were unclear were left uncovered. Following this process, notes on the observed characteristics and potential pitfalls in ply identification were taken, from which a list of plied-silk characteristics was generated. This list of ply characteristics was then converted into 2 flowcharts to aid in the analysis of other silk textiles: one flowchart was tailored to the characteristics of plied silk yarn in isolation (Figure 6.41), the other to the characteristics of plied silk yarn in situ in a woven textile (Figure 6.42).

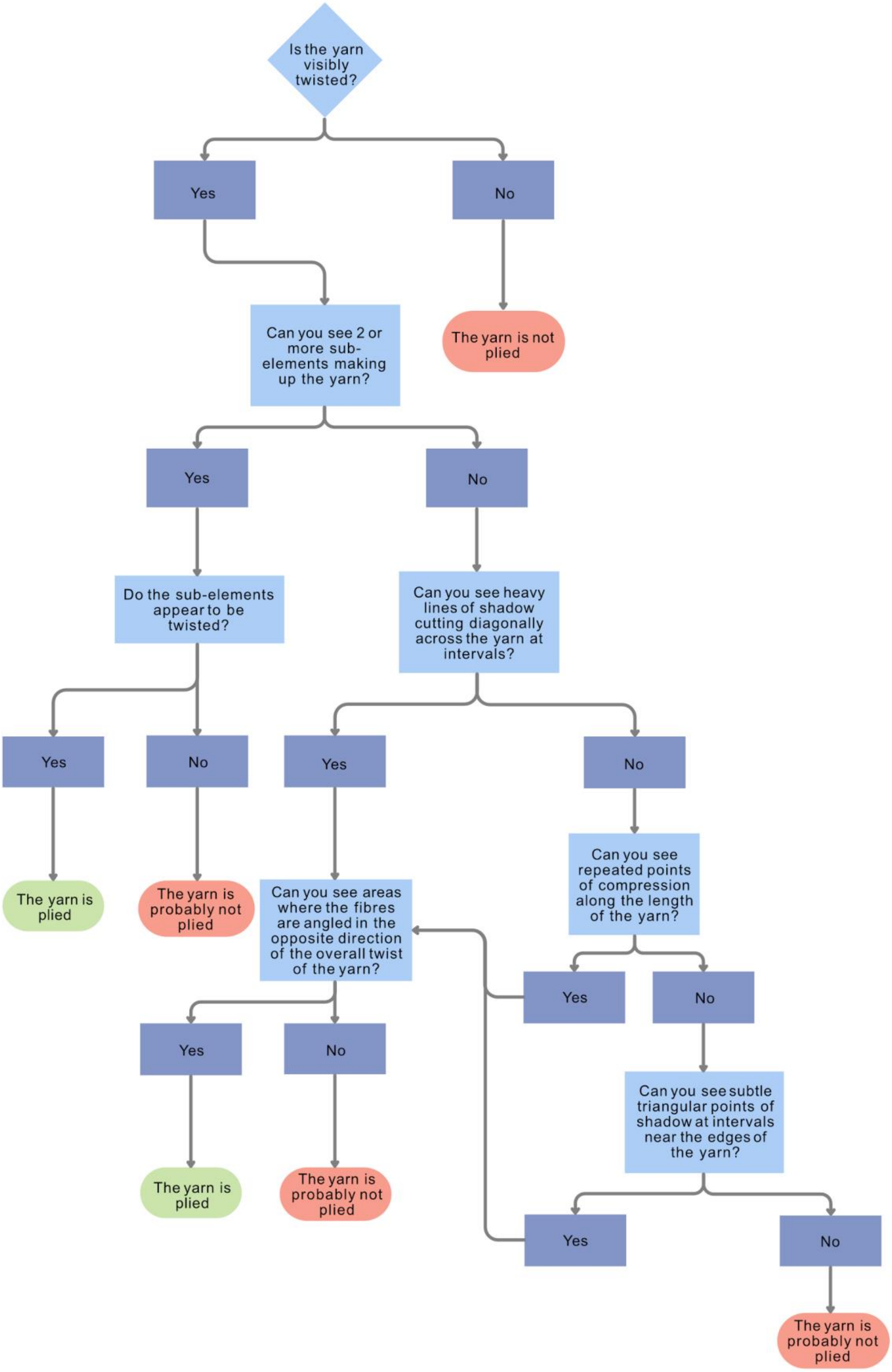


Figure 6.41: Flowchart for the identification of plied yarn (Source: the author)

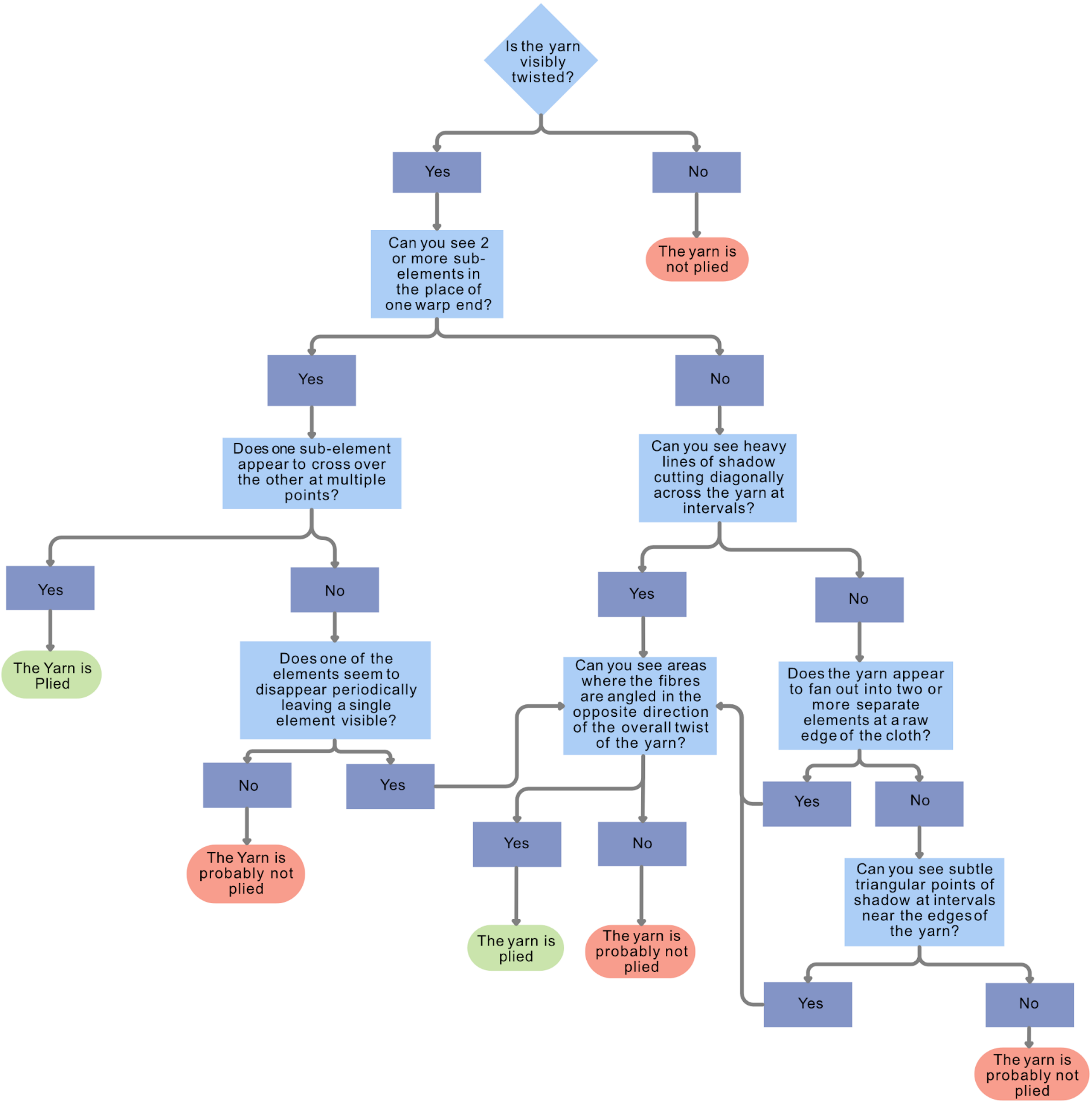


Figure 6.42: Flowchart for the identification of plied yarn in woven textiles (Source: the author)

With the aid of the flowcharts, it was possible to reexamine Coppergate 1347, reapplying the tracing exercise as a means of indicating confidently identified plied yarn within the woven structure. This framework was then applied to additional Coppergate textiles that had been noted as possibly incorporating plied yarn during macro analysis.

6.7.3 Weaving Flaws

During the measurement-capture process for the Winchester textiles, numerous flaws or weaving errors were noticed in several of the textiles.

The absence or presence of flaws in the woven structure of a textile was already established as a relevant category of qualitative data, but during the analysis process it became clear that the implications of a *high or low number* of errors or flaws in a woven textile as well as the *type* of flaws present merited further exploration since, as has been pointed out by Walton and Eastwood, "Faults and irregularities in the weave can be invaluable in determining which system is the warp and …can provide evidence as to the type of loom used." (Walton and Eastwood 1988, 12). In the interest of recording the flaws observed in the Winchester textiles, copies of the scanned images were marked-up to indicate the errors in each textile.

The following categories of flaw were identified during this process:

1. Paired threads (not including intentionally paired threads as observed in multiple Coppergate selvedges);
2. Floating thread(s);
3. Missing or broken threads (Not including broken threads in heavily deteriorated areas of the textile);
    a. If the visibly broken thread resulted in paired threads, the paired threads were not counted as a separate flaw;
4. Knots or loops.

The following approach was taken when marking the images:

1. Probable weaving/threading errors were marked with a teal circle or ellipse;
2. Anomalies such as knots or loose yarn ends were marked with a purple circle or ellipse.

Although scanned images of the Coppergate textiles were not captured, a similar approach was applied making use of the digital photographs and some composite images created with copies of the reflected light micrographs. Because the digital photographs did not all provide the requisite level of detail to identify woven flaws and the micrographs did not provide a complete high-resolution overview of each textile there is some risk of a missed number of errors in the Coppergate textiles. By accounting for any flaws identified through this modified method and accounting for flaws and inconsistencies noted during the macro analysis stage, it was possible to develop a rudimentary comparative weaving flaw tally for the textiles in both textile groups. This process highlighted the value of the ASLab textile scanning method when recording the frequency of characteristics such as flaws across a whole textile.

6.8 Summary

Many data collection methods were tested during the textile analysis stage of this research that have generated a broad array of data sets. In short, the key data sets selected for final analysis and comparison can be summarised as follows:

Quantitative

- Fibre diameters
- Raw silk filament diameters
- Woven textile thread counts
- Yarn diameters
- Yarn angle of twist

Qualitative

- Fibre Characteristics
- Yarn Characteristics
- Textile Characteristics

The rationale for eliminating certain methods at various stages of this research has been discussed throughout this chapter. The overall guiding principle during data collection has been a focus on data that can be clearly linked to production methods and that, by extension, may be indicative of differences in locations of silk manufacture. Nonetheless, the quantitative data provide important, measurable points of reference that allow for comparison between sample sets and may be useful to future research as well.

The data collection methods applied to both the experimental silk samples and the 2 groups of archaeological textiles have resulted in a refined selection of data collection methods that can produce a useful range of qualitative and quantitative data. In Chapter 7, the results of the analysis of the experimental silk reference collection will be presented, followed by the results of the analysis of the archaeological silk textiles in Chapter 8.

7 Results: Analysis of Experimentally-produced Silk

7.1 Introduction

The silk-processing experiments have provided meaningful insight into many practical and haptic aspects of medieval silk production. These insights are useful for understanding the technical choices made during the silk manufacture process, but do not provide a full picture of the impact these choices have on the physical properties of silk.

An assessment of the impact of technical variations on the physical characteristics of the silk produced is key to answering the question of whether the provenance of archaeological silk textiles can be determined through yarn and fibre analysis. The driving question behind this analysis was: do variations in silk-processing methods influence the physical characteristics of reeled silk? As will be discussed in greater detail, the brief answer to this question, based on both quantitative measurements and visual analysis, is yes. The microscopic analysis of a selection of fibre samples from the experimental silk reference collection has led to the positive identification of the technical choices that have a measurable influence on **fibre diameter**, **filament diameter**, and the **morphology** of the silk fibres and filaments. The results presented in this chapter are divided broadly into 4 Topics:

1. **Fibre diameters** in relation to stage of reeling, cocoon quality, type of reeling-frame, water temperature, and methods of crossing or wrapping;
2. **Filament diameters** in relation to number of cocoons reeled, crossing/wrapping method, water temperature, and stage of reeling;

3. **The visual analysis of fibre and filament characteristics** and the impact of the experiment variables on filament cohesion, fibre spacing, filament shape, and sericin integrity;
4. **New observations** resulting from the visual analysis related to differentiating between raw and partially degummed silk, identification of water temperature in reeled silk, crossover indentations, and the assessment of silk yarn twist and ply.

These 4 broad topics cover a wealth of new information, which is pertinent to the analysis of archaeological silk textiles. The key findings of this analysis will be summarised at the conclusion of this chapter.

7.2 Diameter Measurements from Experimental Silk Fibres

As was discussed in Chapter 6 measurements from both cross-section and whole-mount slides were analysed to identify significant variations in fibre diameter and any associated trends. Most measurement data was gathered from whole-mount slides following the comparison of measurements from the same samples captured using both methods. The results presented below are exclusively from diameters captured from whole-mount slides.

Previous research has suggested that the size and shape of silk fibres may be an indicator of the region in which the silk was produced, or at least “grown”. Nunome (1989) particularly, had suggested a link between fibre measurements and reeling methods. This led to the formation of a hypothesis that additional factors beyond natural variation within the silk may influence the diameter of reeled silk fibres.

A key consideration explored during this analysis in relation to the topic of natural variation is the influence of the section of the silk cocoon from which a fibre is extracted. As discussed in chapter 2, it is commonly reported that fibre diameters from the exterior of the cocoon are generally thicker than those taken from the remainder of the cocoon, which eventually narrow to even thinner diameters in the interior. This is supported by multiple studies (Chapter 2.3.6.1). It was therefore predicted that the larger diameter measurements collected would be associated with the exterior fibres of the cocoon, while the smallest diameters would be associated with the interior fibres, and the measurements associated with the middle of the cocoon would fall somewhere in between the 2 extremes. As will be discussed, there were methodological complications to evaluating this hypothesis, which ultimately provided information that is likely more useful to understanding the morphology of silk fibres in relation to silk-reeling processes.

A comparison of mean fibre-diameter measurements demonstrated notable variation across samples (Figure 7.1). Different degrees of variation in the fibre diameter recorded per sample were also observed (Figure 7.2).

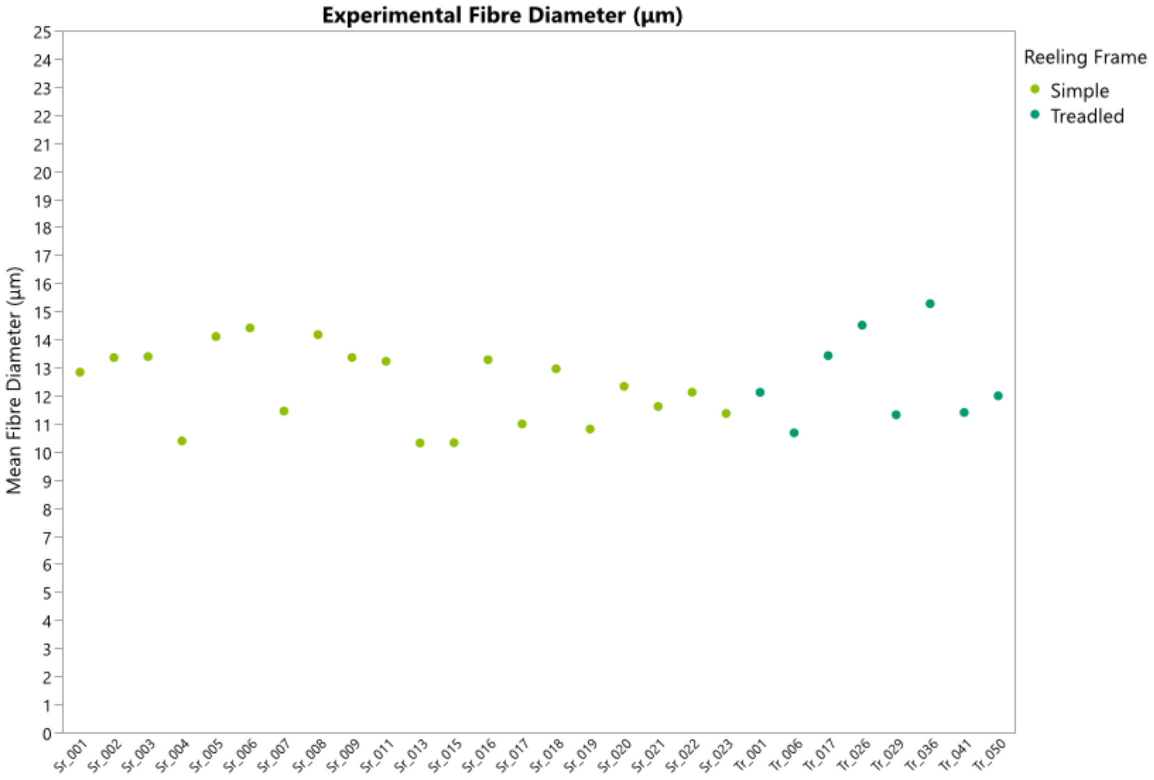


Figure 7.1:Scatterplot of the mean fibre diameter of each experimentally reeled silk sample, colour-coded by type of reeling-frame

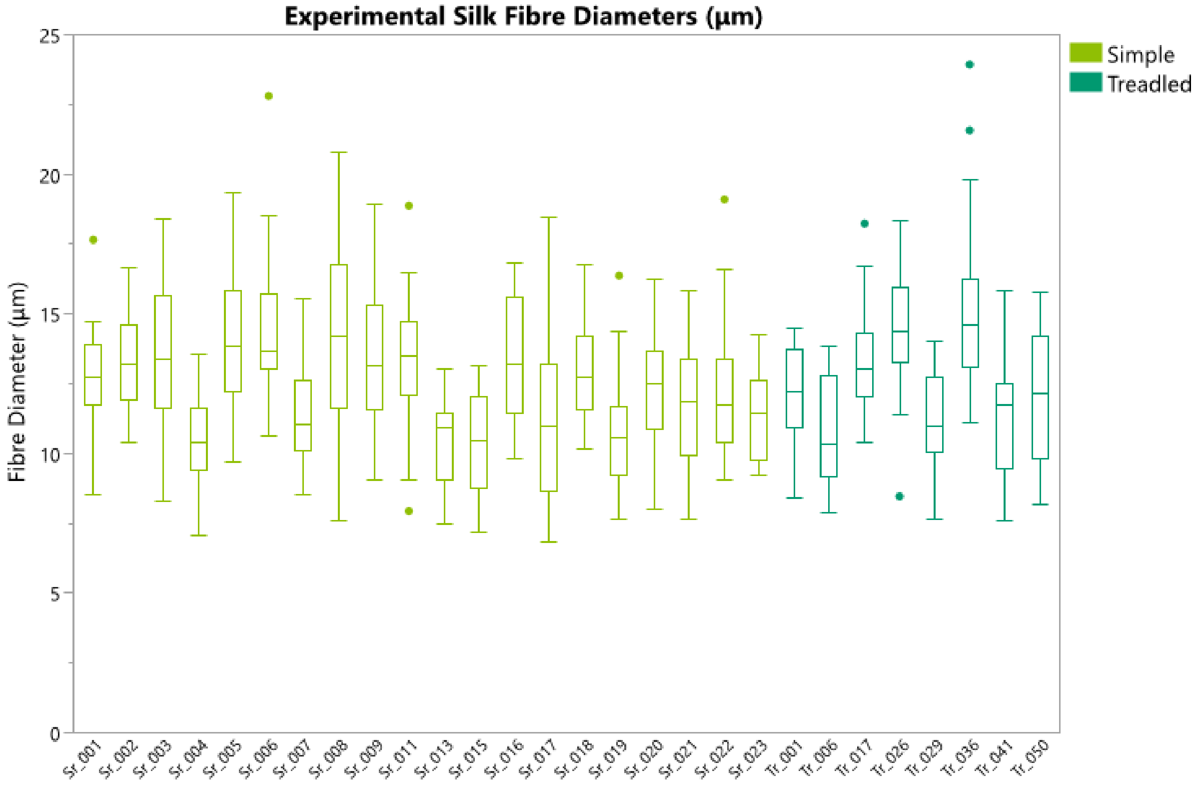


Figure 7.2: Box plots showing range of fibre diameters collected from each experimentally reeled silk sample, colour-coded by type of reeling-frame

Having determined that the fibre-diameter measurements did not follow a normal distribution, the statistical significance of the variation between these measurements was confirmed by Kruskal-Wallis and Median tests, which respectively rejected null hypotheses of the measurement groups having identical mean ranks and medians. This confirmation supported further exploration of the hypothesis that additional factors beyond minute natural variation within the silk itself influence the diameter of reeled silk fibres.

7.2.1 Fibre Diameter vs stage of reeling

As described in Chapter 4, samples from each silk-reeling experiment were gathered from the beginning, middle, and end-stages of reeling.

This sampling aimed to extract silk from different layers of the cocoons for comparison, with the beginning of the reeling process correlating with the exterior of the cocoon, the middle of the process with the middle of the cocoon, and the end of the process with the interior.

The fibre diameters grouped by stage of reeling showed identical mean values from the beginning and middle stages, and a lower mean value from the end stage, while also indicating a broader range of fibre diameters in samples from the middle stage of reeling (Figure 7.3). Together, the overall larger minimum of fibre diameters from the beginning of the reeling process and smaller maximum diameters in fibres from the end of the reeling process seem to support the notion that thicker exterior fibres would be present at the start of reeling, and thinner interior fibres would be present at the end of reeling. However, the hypothesis that the fibre diameters from the middle stage of reeling would fall somewhere between these 2 ranges was proven false.

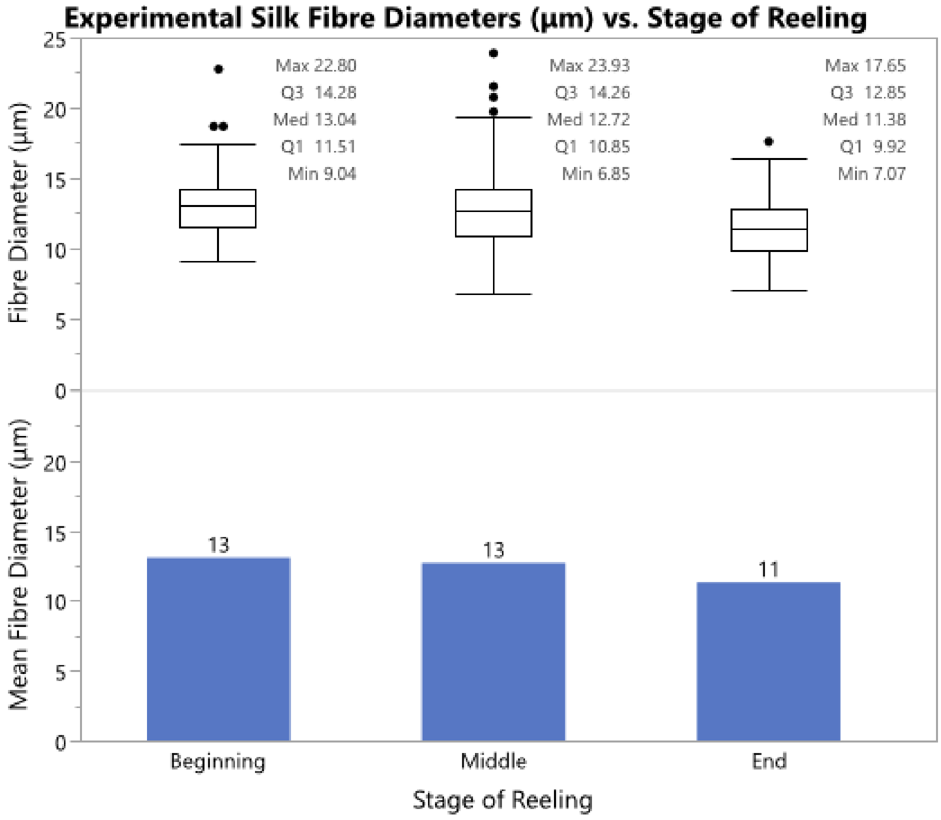


Figure 7.3: Box plots and Bar chart showing the range of fibre diameters and mean fibre diameter from each stage of reeling.

A broader range of mean values per sample was also observed in the diameter measurements from the middle stage of reeling (Figure 7.4), which demonstrated an overall wider range of diameters collected per sample (Figure 7.5).

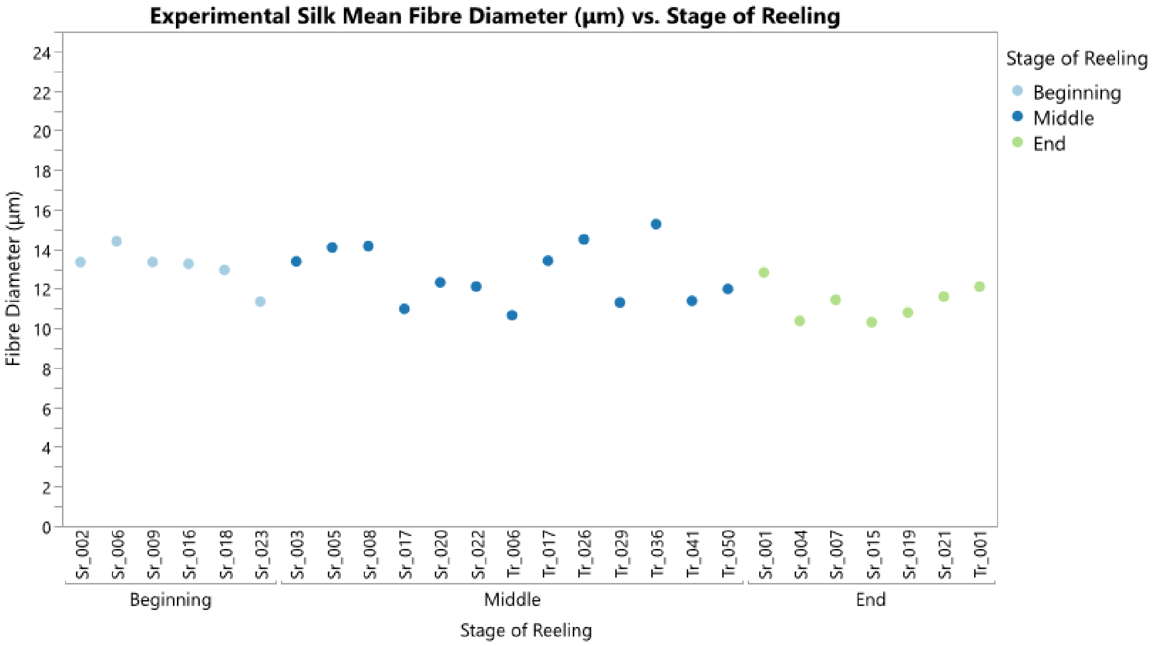


Figure 7.4: Mean diameters of experimental silk fibres plotted in relation to stage of reeling process

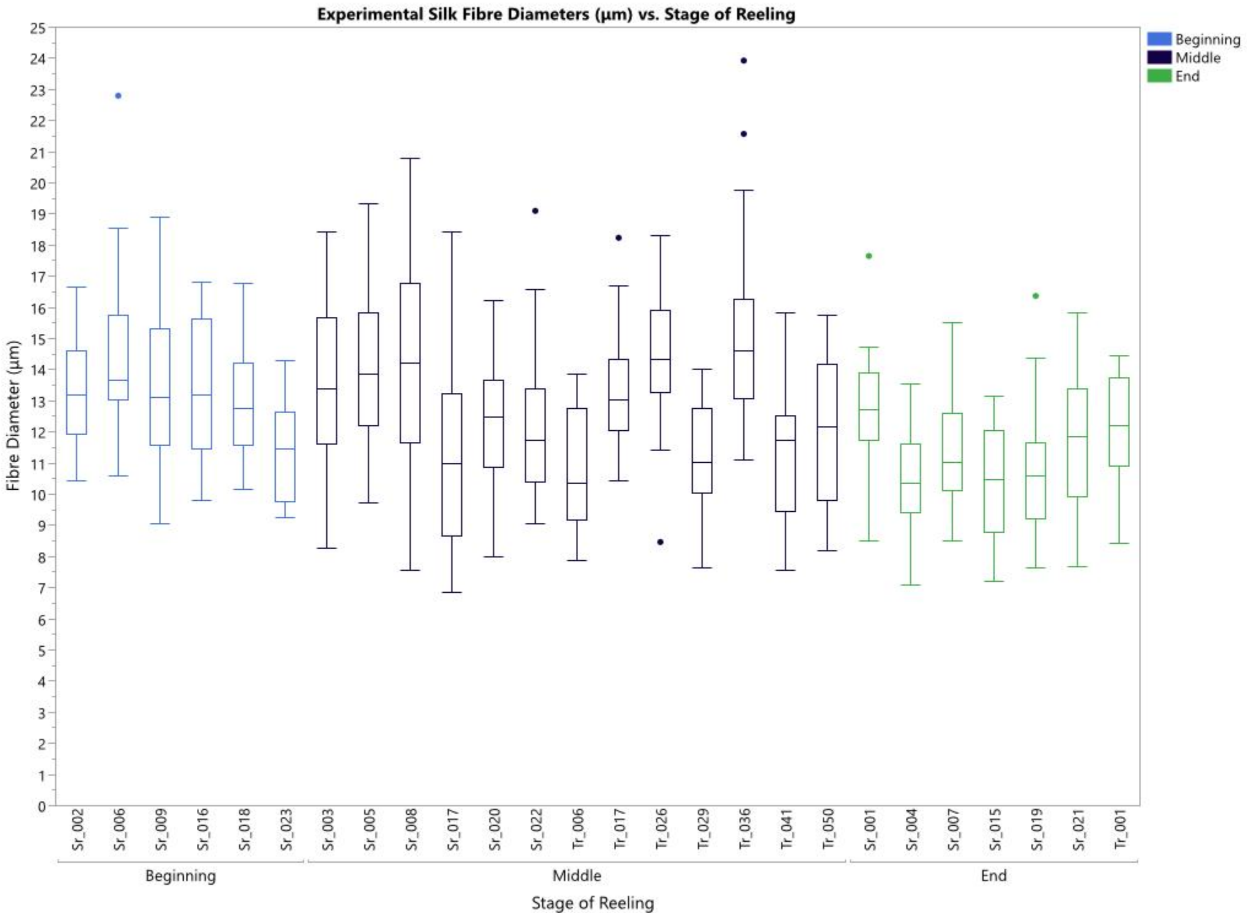


Figure 7.5: Box plots showing range of fibre diameter measurements per sample, organised by stage of reeling

7.2.2 Fibre Diameter vs. Cocoon quality

Of the samples from the middle stage of reeling, most were reeled from Grade A cocoons, while 1, Tr_ 041, was reeled from B&C grade cocoons. That said, the difference in cocoon grade did not appear to result in a more extreme variation in fibre diameters in Tr_041 than the other samples (Figure 7.6). This is unsurprising, as Grade B and C cocoons are designated as such primarily based on level of staining, which is unlikely to affect fibre diameter. Likewise, any minor variations in the shape of grade B and C cocoons do not appear to have had an appreciable impact on fibre diameter in this case, but more data is needed before this can properly be assessed.

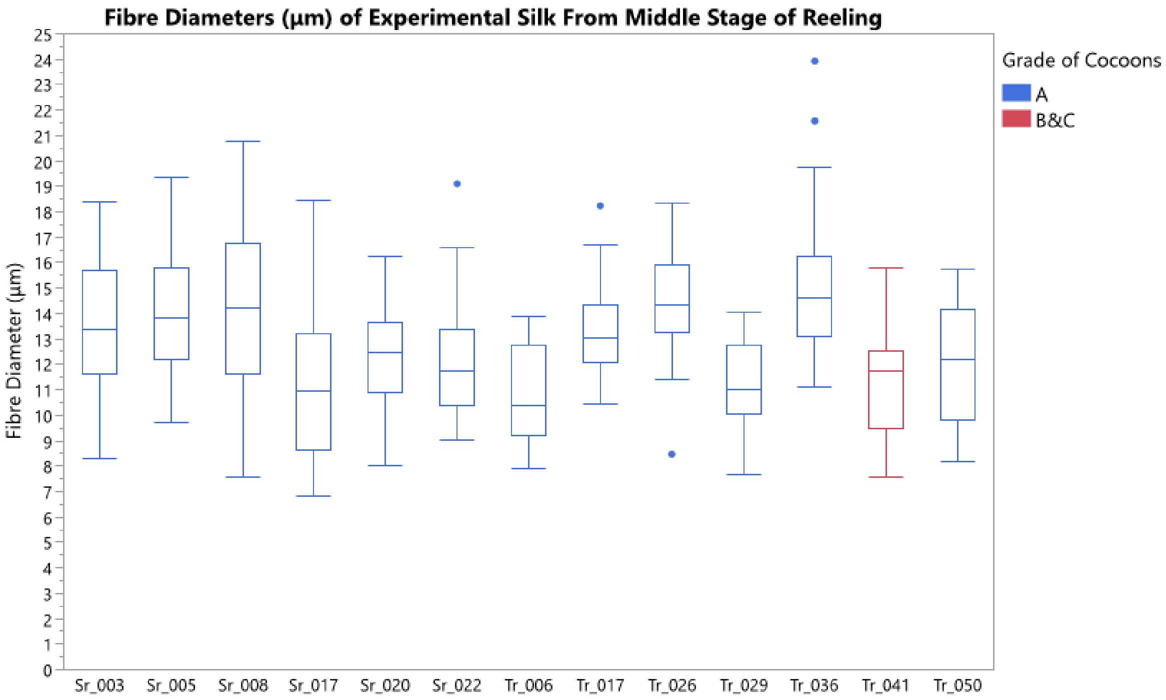


Figure 7.6: Box plots of experimental silk fibre diameters from the middle of the reeling process with grade of cocoons indicated

7.2.3 Fibre Diameter vs. Reeling Frame

The middle-cocoon mean fibre measurements plotted by reeling-frame (Figure 7.7) indicated a slight trend towards smaller fibre diameters when reeled with the treadled reeling-frame. The silk reeled with the treadled reeling-frame showed marginally less variation in measurements compared to the simple reeling-frame. However, the largest diameter mean was associated with the treadled reeling-frame, therefore it cannot be confidently stated that the reeling-frame alone had a meaningful impact on silk fibre diameters.

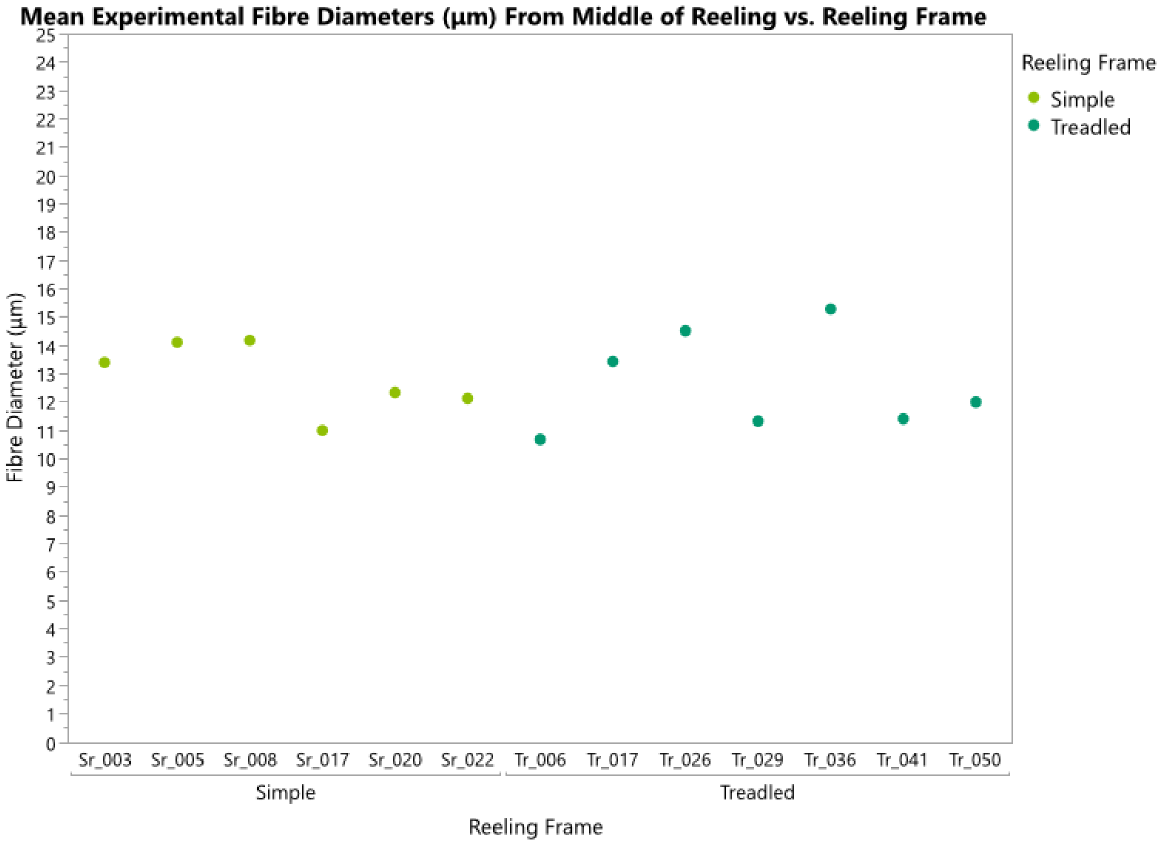


Figure 7.7: Mean fibre diameters from middle of reeling process plotted by type of reeling-frame

7.2.4 Fibre Diameter vs. Water Temperature

Mean fibre diameters from the middle of the reeling process (Figure 7.8) showed significant variation in samples reeled at temperatures below 82°C, while a tighter grouping of fibre diameters was observed for fibres reeled in boiling water, which could indicate that silk fibre diameters are more likely to compress when reeled in high water temperatures.

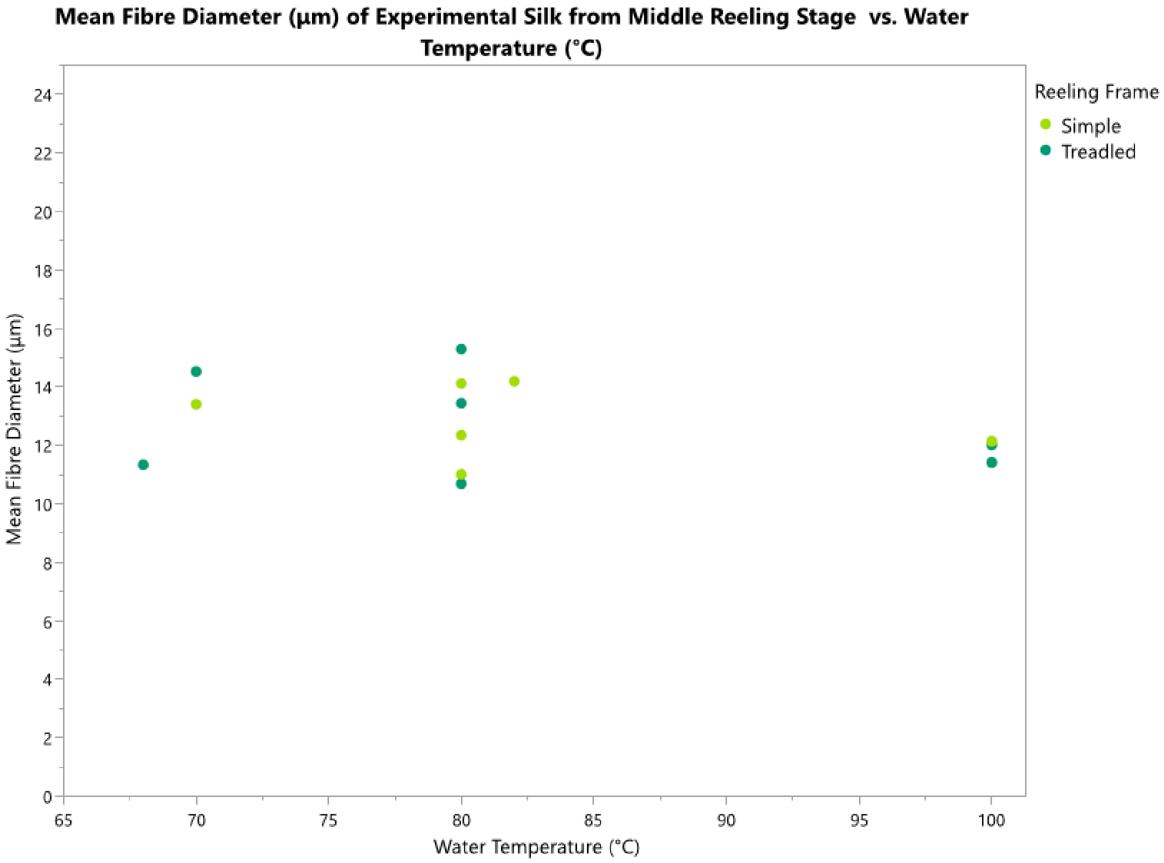


Figure 7.8: Scatter plot of the mean diameters of experimental silk fibres from the middle of the reeling process plotted by temperature of water during reeling

While the sample size of middle-of-reeling fibres reeled in boiling water is significantly smaller than the number of middle-of-reeling fibres reeled at other temperatures, a similar pattern can be found across the mean fibre diameters of all silk samples (Figure 7.9). Plotting diameters by water temperature also confirmed the trend of a wide range of measurements skewing to a larger diameter in the samples from the middle of reeling, in contrast to the beginning and end, regardless of water temperature.

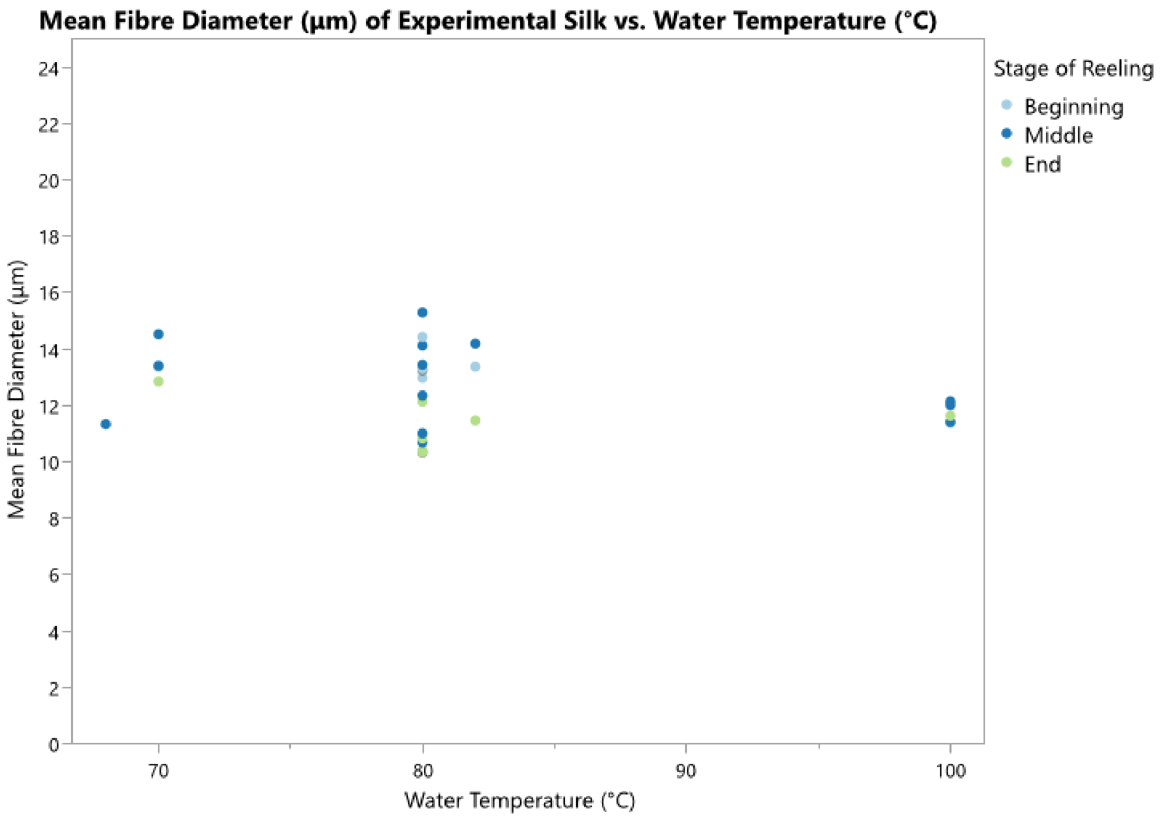


Figure 7.9: Scatter plot of mean Experimental silk fibre diameters from all reeling stages plotted by temperature of water during reeling

7.2.5 Fibre Diameter vs. Methods of Crossing or Wrapping the Reeled Filament

The middle-of-reeling subset of fibre diameters when compared by crossing or wrapping method (Figure 7.10) did not indicate a clear trend, partly because of an uneven distribution of measurements associated with each crossing method.

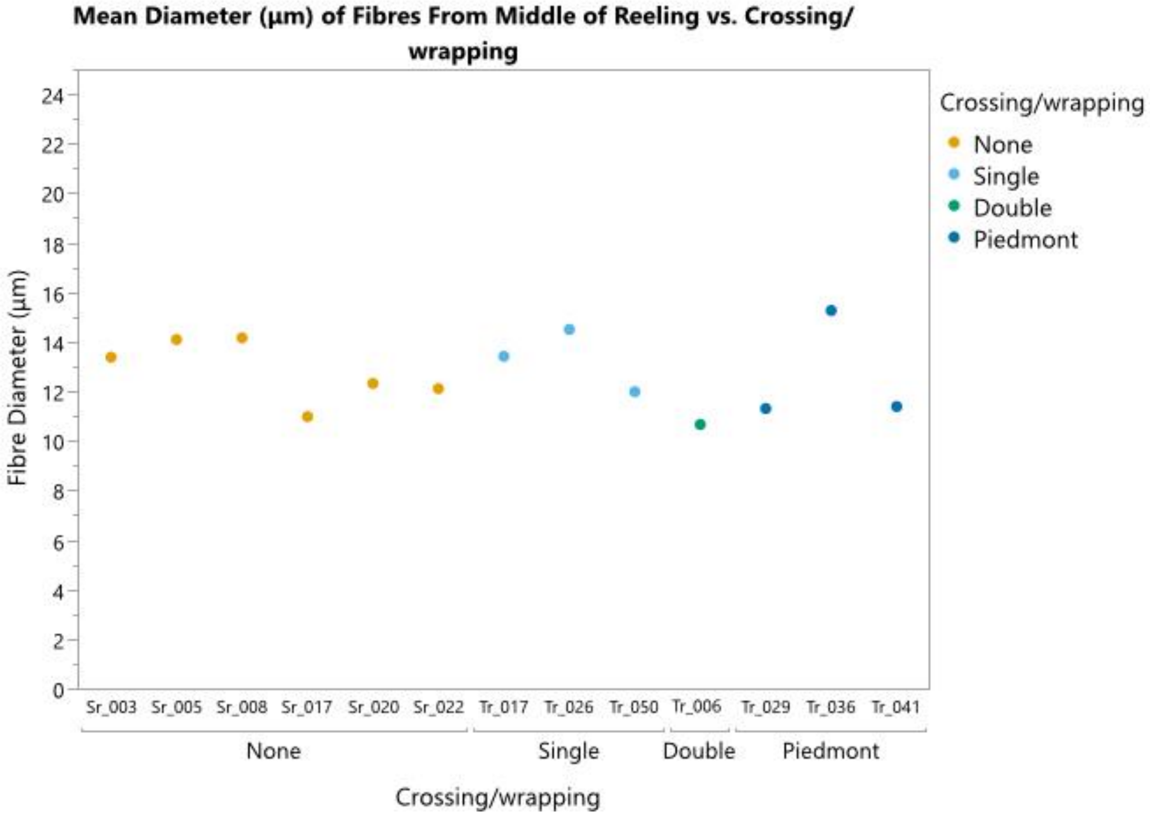


Figure 7.10: Mean fibre diameters of middle-of-reeling silk fibres plotted by crossing/wrapping method

A larger range of fibre-diameter measurements was observed in fibres reeled with no crossing or wrapping at temperatures of 82°C and lower, while single- and double-wrapped samples reeled in the same temperature range show a smaller range of diameter measurements (Figure 7.11). The fibre diameters of samples reeled in boiling water fell within a similar range, regardless of crossing method. This indicates that water temperature may have a greater influence on fibre diameter than crossing method.

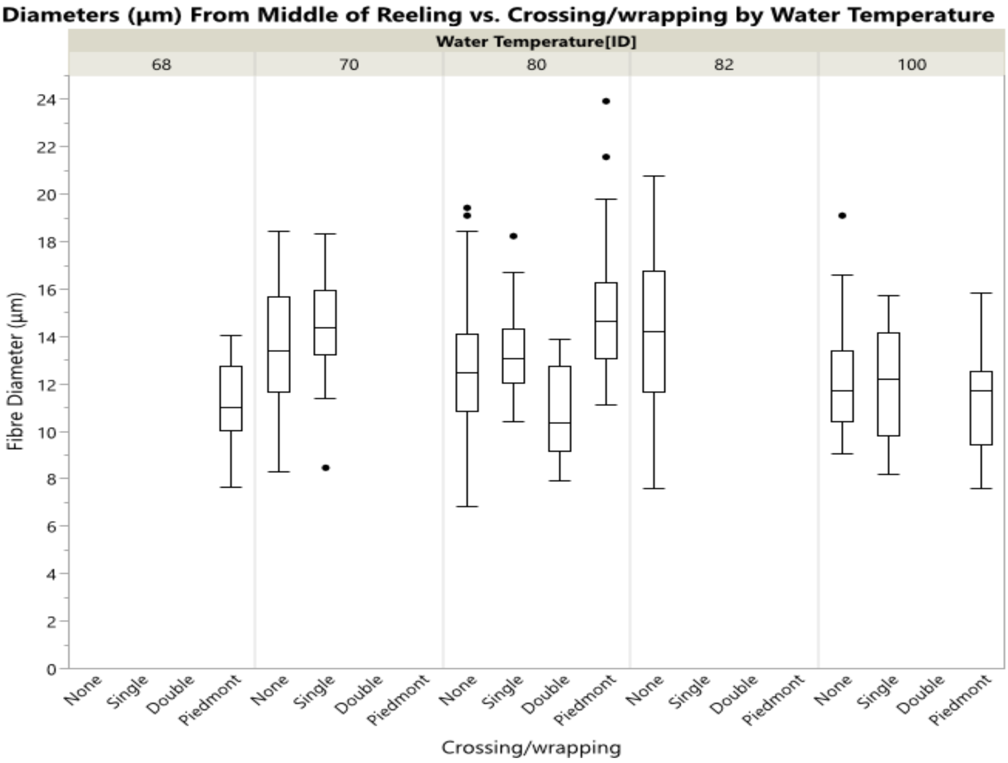


Figure 7.11: Box plots showing the diameters of middle-of-reeling fibres by crossing/wrapping method, grouped according to temperature of water during reeling

7.3 Diameter Measurements from Experimental Silk Filaments

The raw silk filaments (the strands of silk produced during the reeling process, composed of multiple silk fibres held together by sericin) make up most of the experimentally produced silk reference collection. These filaments display more extreme variation in their diameters (Figure 7.12) than individual fibres do.

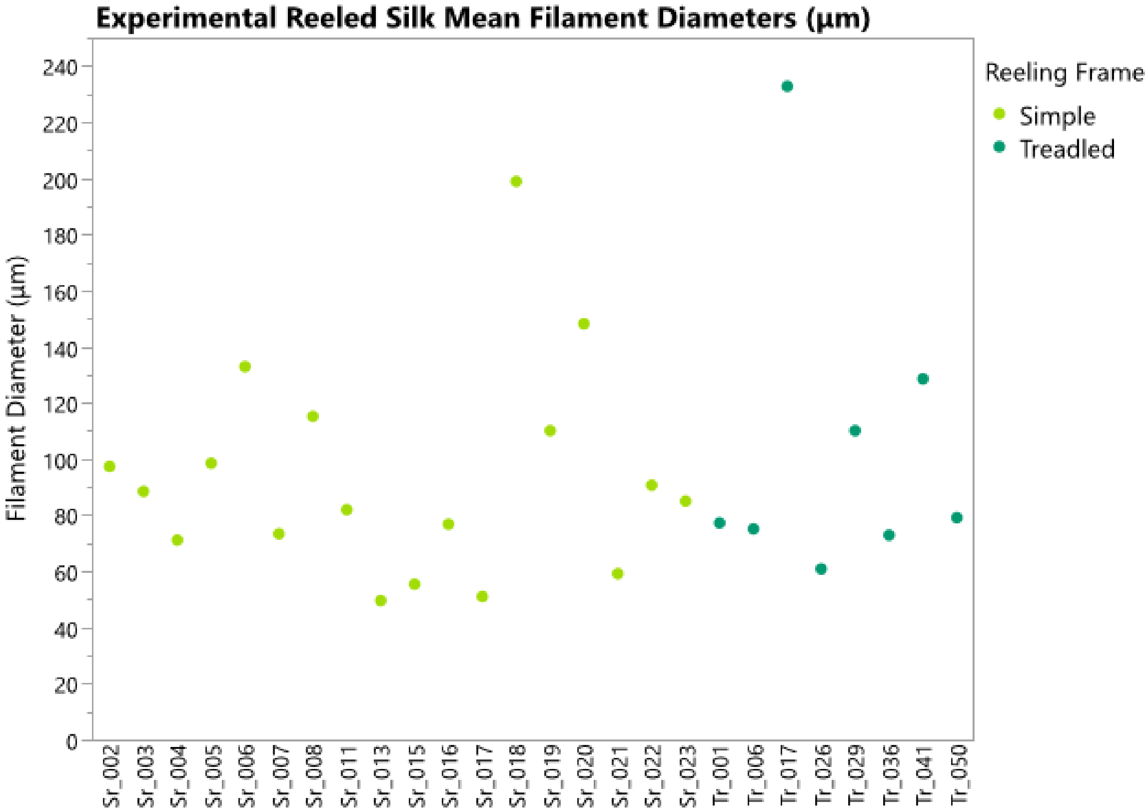


Figure 7.12: Scatterplot of the mean filament diameters of each sample, colour-coded by reeling-frame

Different ranges of diameter measurements were also observed across the filament samples (Figure 7.13). There is a slight trend toward smaller mean diameters and smaller ranges of measurement per sample in filaments reeled using the treadled reeling-frame, though not enough to negate the influence of other variables.

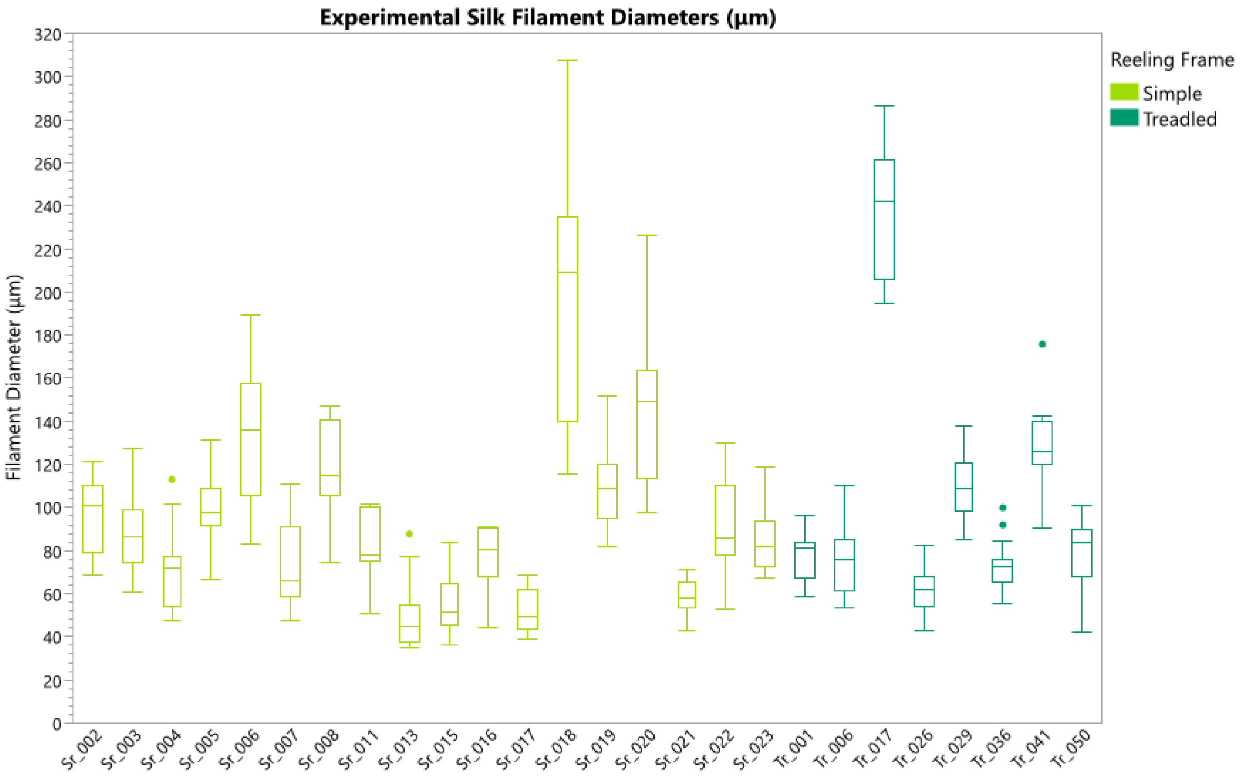


Figure 7.13: Boxplots showing the range of Experimental silk filament diameters, colour-coded by reeling-frame

7.3.1 Filament Diameter vs. Number of Cocoons

Preliminary observations during the silk-reeling experiments identified a relationship between the number of cocoons reeled, and the diameters of raw silk filaments, as filaments reeled from higher numbers of cocoons were generally observed to be thicker and more resistant to breaking under tension than the filaments reeled from a low number of cocoons. A comparison of the experimental filament measurements has confirmed that higher numbers of cocoons generally result in larger filament diameters; there is a non-linear relationship between the 2 variables, and a number of samples generated higher mean diameters than samples with a larger number of cocoons (Figure 7.14) This suggests that number of cocoons is not the only variable influencing the diameter of the reeled filaments.

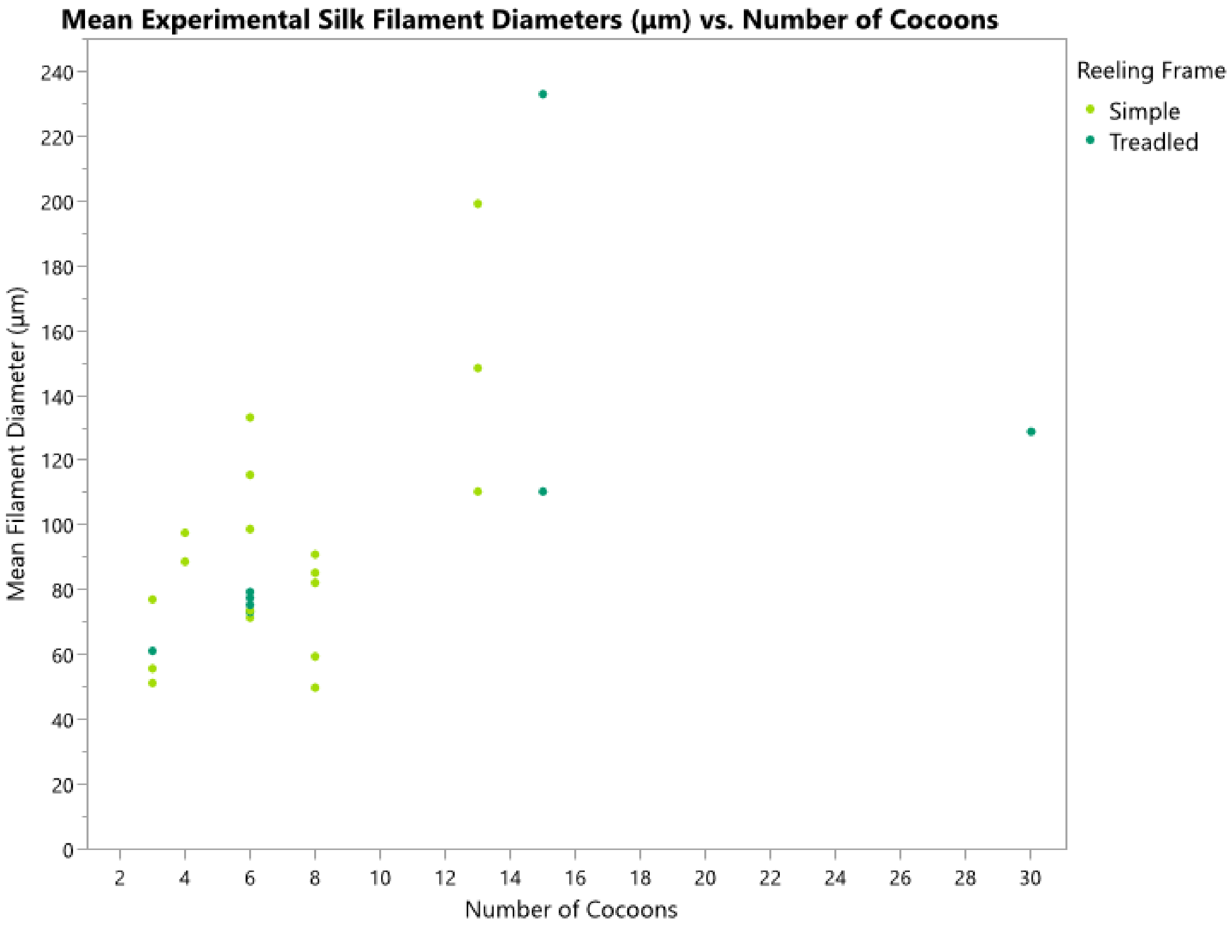


Figure 7.14: Scatter plot of Mean Experimental filament diameters vs the number of cocoons reeled, colour-coded by reeling-frame

7.3.2 Filament Diameter vs. Crossing/Wrapping Method

Mean filament diameters were compared relative to crossing/wrapping method. When number of cocoons were also factored into this comparison (Figure 7.15) a clear trend emerged.

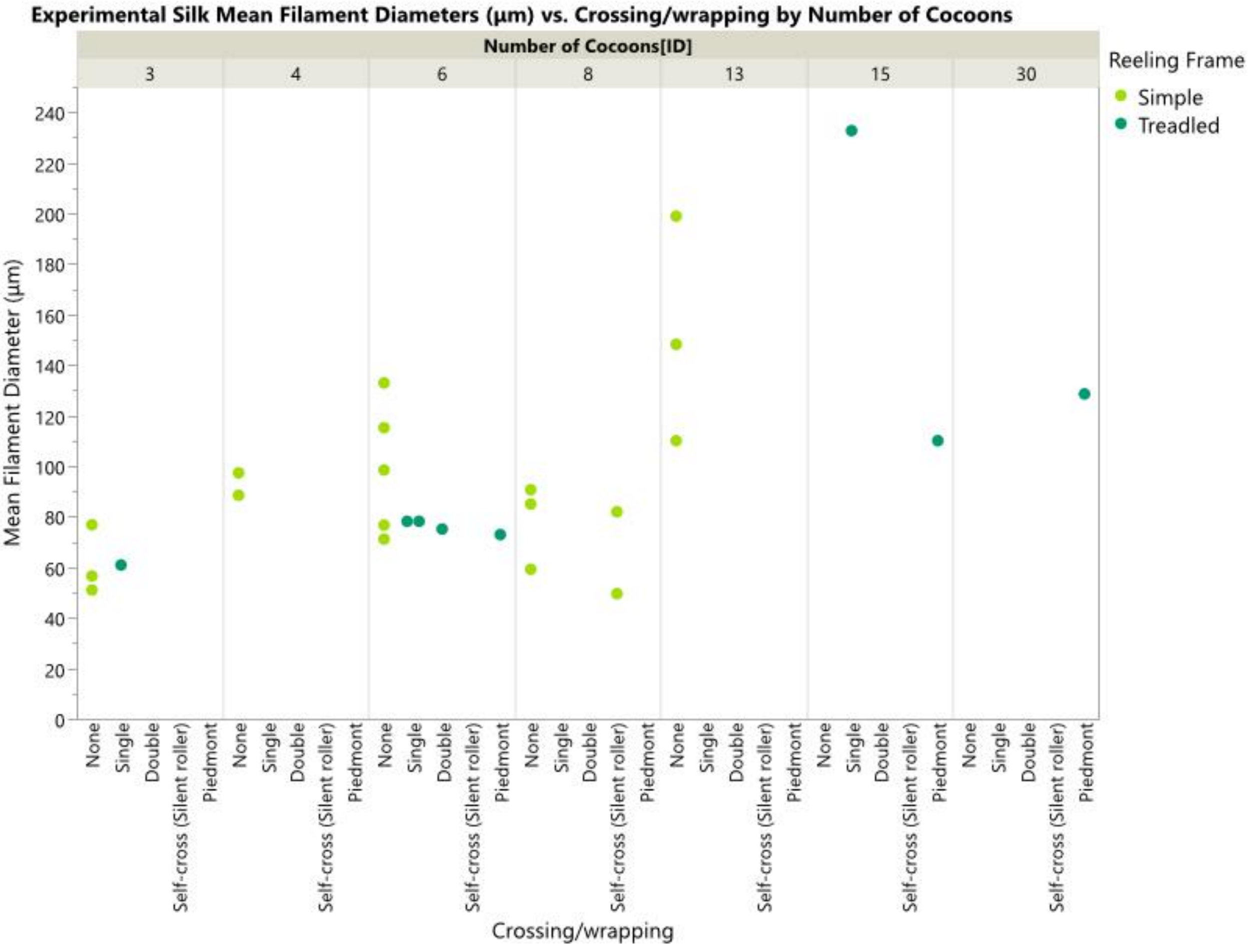


Figure 7.15: Scatter plot of mean filament diameters vs crossing/wrapping methods used during reeling, grouped by number of cocoons reeled

Overall, larger diameter measurements were recorded from filaments reeled with no crossing or wrapping method than from filaments reeled using any other wrapping method. Filaments reeled with no crossing or wrapping methods also displayed the most variation in mean diameters, and larger ranges of recorded diameters per sample (Figure 7.16). This indicates that variability of filament diameter is influenced by both crossing method and number of cocoons, with the degree of variation visible in filaments reeled with no crossing or wrapping method increasing in range as the number of cocoons increase. The same trend can be seen for the Piedmont crossing method, which shows the smallest diameter range at 6 cocoons (barring 2 outliers), while that range increases as the number of cocoons do. Viewing the diameter measurements from filaments reeled from 6 cocoons in isolation highlights a trend of smaller filament diameters correlating to methods that involve a higher number of wraps or times self-crossed (in order: single, double, self-cross, and Piedmont). Additional comparative data for each reeling method would help confirm this.

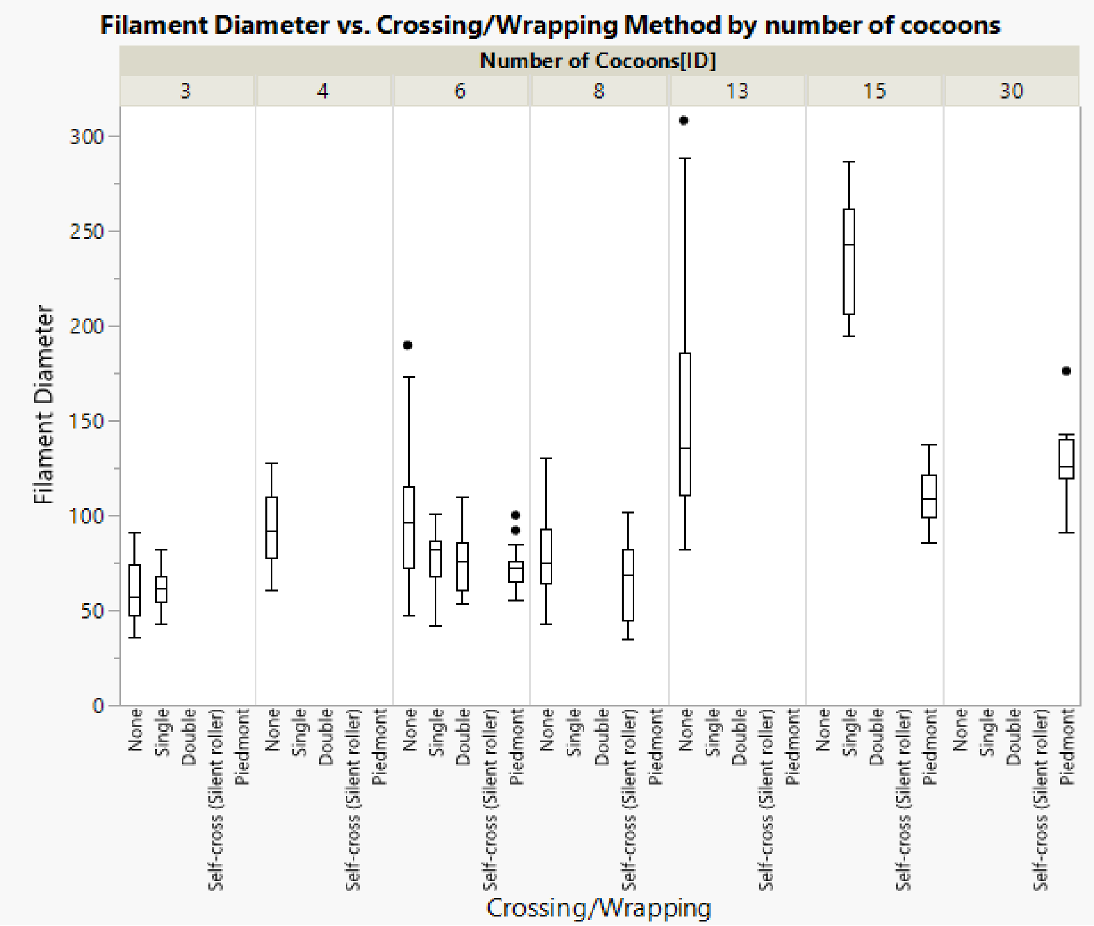


Figure 7.16: Box plots of all experimental filament diameters according to crossing method, grouped by number of cocoons reeled

7.3.3 Filament Diameter vs. Water Temperature

To compare filament diameters by temperature of water during reeling, it was necessary to isolate the other variables of crossing/wrapping method and number of cocoons already determined to influence filament diameter. Unfortunately, the resulting sample size was too small to be considered conclusive (Figure 7.17); though there is some indication that a higher temperature may correlate to a smaller filament diameter and a smaller range of diameters per sample. More data would be needed to explore this further.

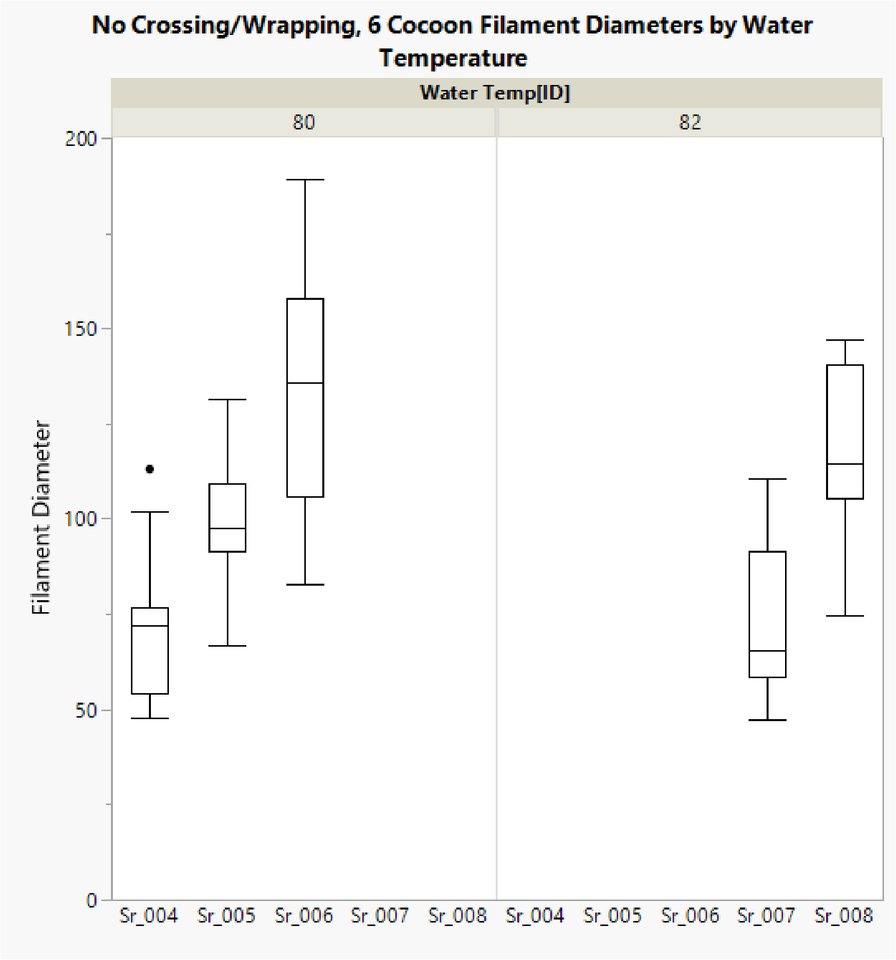


Figure 7.17: The filament diameter in relation to water reeling temperature of silk samples reeled with no crossing methods from 6 cocoons

7.3.4 Filament Diameter vs. Stage of Reeling

Finally, as the stage of reeling/location in the cocoon was determined to have some influence on fibre diameter, filament diameter was assessed in relation to stage of reeling, factoring in number of cocoons reeled. The diameters of filaments that had been reeled without crossing were isolated for this assessment, the results of which indicate a relationship between stage of reeling and mean filament diameter (Figure 7.18), with an overall trend in higher diameters measured from filament samples from the beginning of the reeling process, narrowing in samples from the middle, with most of the smallest diameters being found in filament samples from the end stage of reeling. Exceptions to this were Sr_015 which, although from the end of the reeling process, had a higher mean filament diameter than its corresponding sample from the middle of reeling, and Sr_022, a middle-of-reeling sample with larger mean diameter than its corresponding beginning-of-reeling sample. There are also no data from the end stage of reeling for the samples reeled from 4 cocoons, as the filament cohesion of this sample was so low that it was impossible to collect diameter measurements.

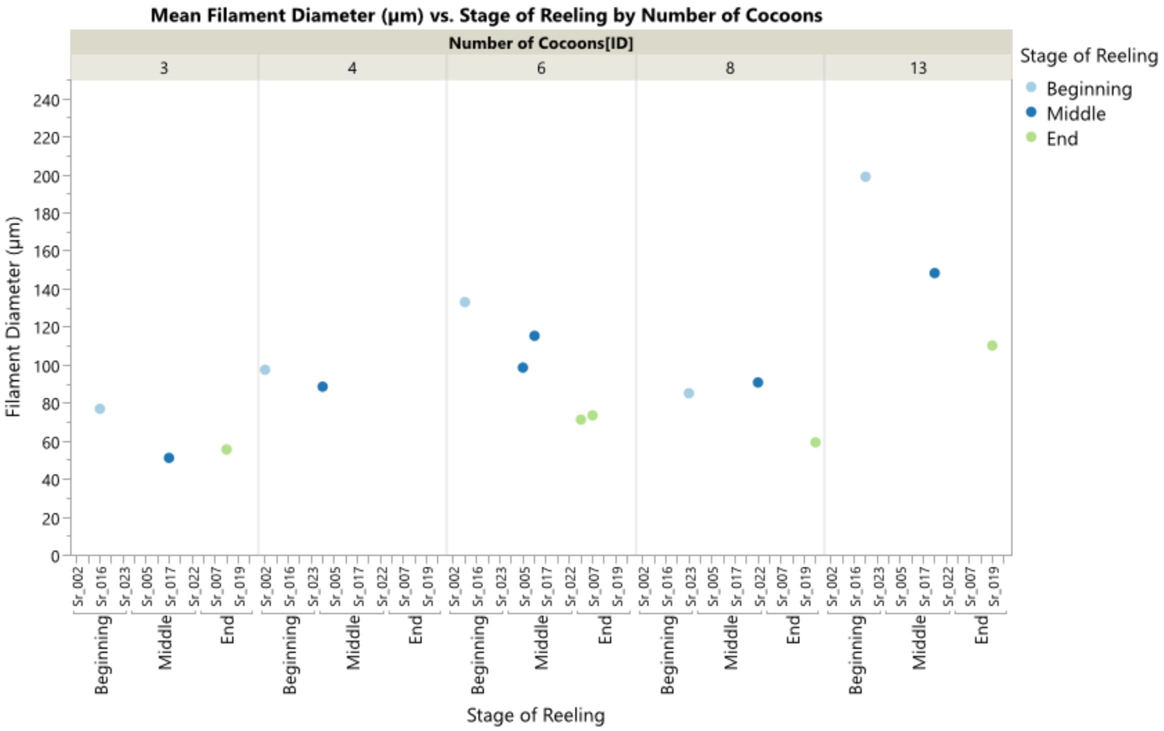


Figure 7.18: Scatter plot of mean filament diameters vs stage of reeling, grouped by number of cocoons

Filament cohesion of each sample will be discussed in greater depth in this chapter in relation to the results of the visual analysis of the experimental silks. In the interim, one final note of import is that the range of diameter measurements for each sample shows a trend of larger ranges in filament diameters from the beginning of the reeling process, narrowing in the middle, and at their smallest range at the end of the reeling process (Figure 7.19). There are, however, exceptions to this trend, particularly in the previously mentioned samples Sr_015, and

Sr_022, both of which show a larger range of filament diameter measurements than in their corresponding samples. It is unclear what other variables might influence this difference in filament diameter variation, but this is a question that could be explored through further experimental trials.

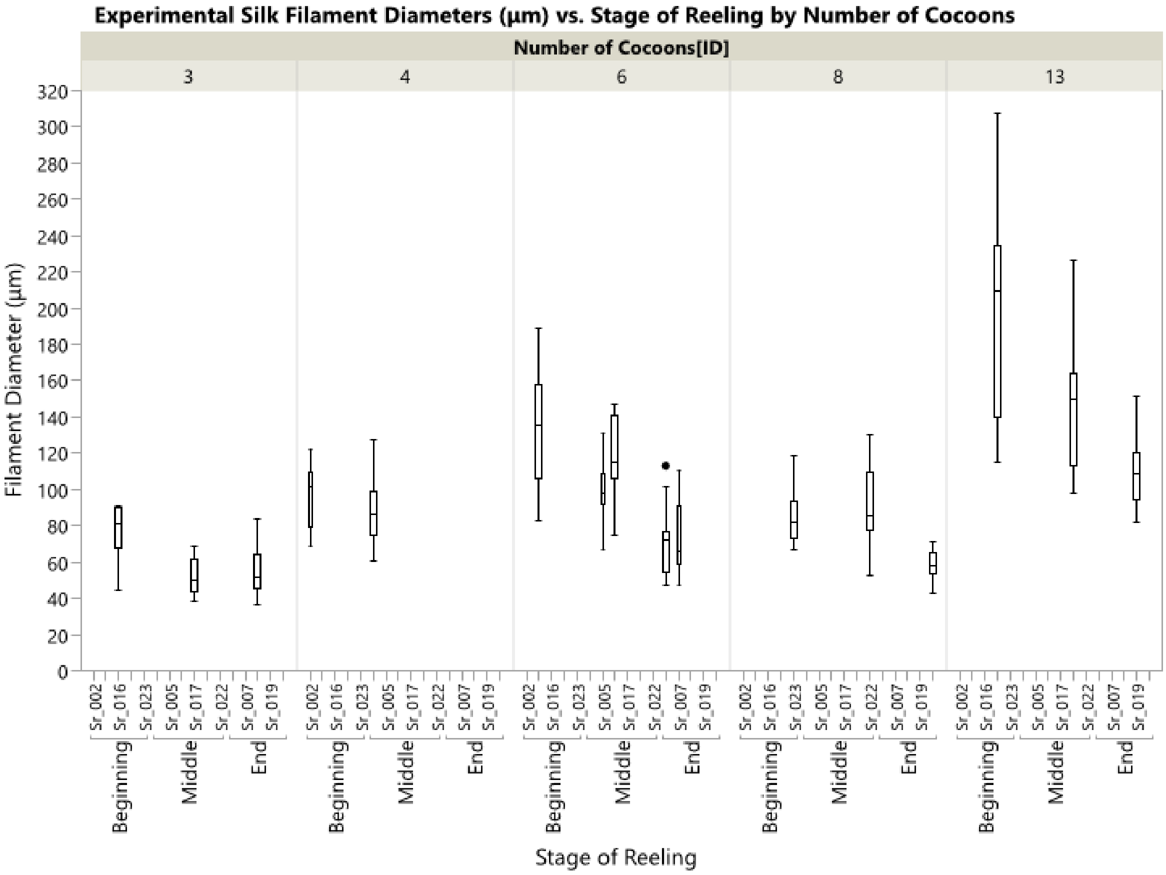


Figure 7.19: Box plots of experimental filament diameters in relation to stage of reeling, grouped by number of cocoons reeled

7.4 Visual Analysis of Fibre and Filament Characteristics

As previously discussed, the single silk element forming a cocoon is called a *bave* and is composed of 2 fibres, called *brins*, bound together with sericin. During the reeling process, multiple silk baves are unravelled from their cocoons to form a larger filament. While fibre-diameter measurements have demonstrated some quantifiable indications of the impact of different silk-reeling methods on silk fibres and filaments, this data only tells part of the story.

The visual analysis of the experimental silk has allowed for the characterisation of the morphology and structural integrity of the raw filaments, in addition to sericin morphology and level of degradation. This provides insight regarding the effects of silk-processing methods that are not evident through diameter measurements alone. When recording the results of the visual analysis, the morphology and integrity of the silk filaments and sericin were described using the categories of **filament cohesion**, **fibre spacing**, **filament shape**, and **sericin integrity**. The first 3 factors were approached with the understanding that they are interrelated and may have a bearing on fibre diameter. These characteristics were assessed in relation to silk-reeling variables, which established some patterns in the way in which reeling influences the appearance of silk. An important additional variable analysed was the degumming process, which provided particularly useful information regarding the influence of different degumming approaches on **filament cohesion** and **sericin integrity**.

7.4.1 Filament cohesion

Filament cohesion (Figure 7.20) – the extent to which a reeled silk sample holds together as a single filament rather than splitting into its subordinate fibres – is likely to influence the strength and texture of a given silk sample. It is therefore useful to understand which variables influence filament cohesion.

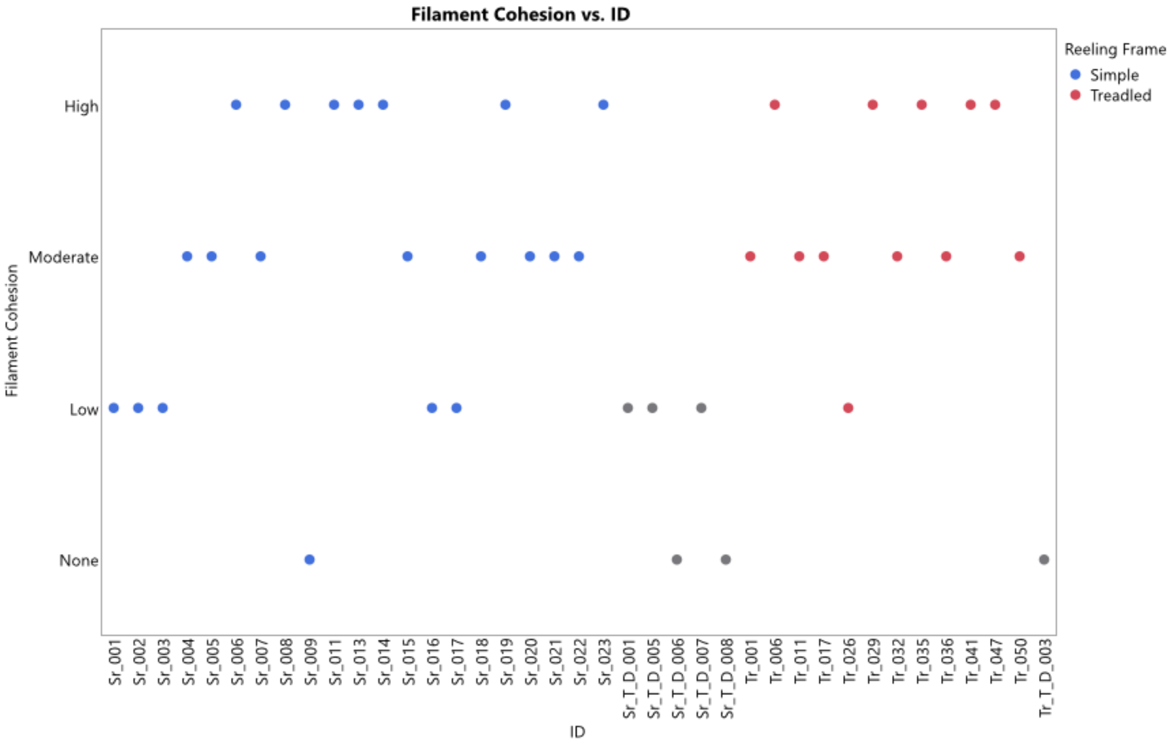


Figure 7.20: Scatter plot showing Filament Cohesion of each sample analysed

In contrasting the simple and treadled reeling-frames (Figure 7.21), a significantly higher proportion of samples produced with the treadled reel showed moderate to high filament cohesion compared with the number of samples that showed low filament cohesion. The simple reeling-frame produced a higher proportion of samples with low filament cohesion compared to the samples produced by the treadled reel, and 5% of simple reeling-frame samples showed no filament cohesion at all. This has demonstrated a higher degree of filament cohesion in silk produced with the treadled reel, but other variables must also be considered, as the majority of samples produced with the simple reel still displayed moderate to high filament cohesion.

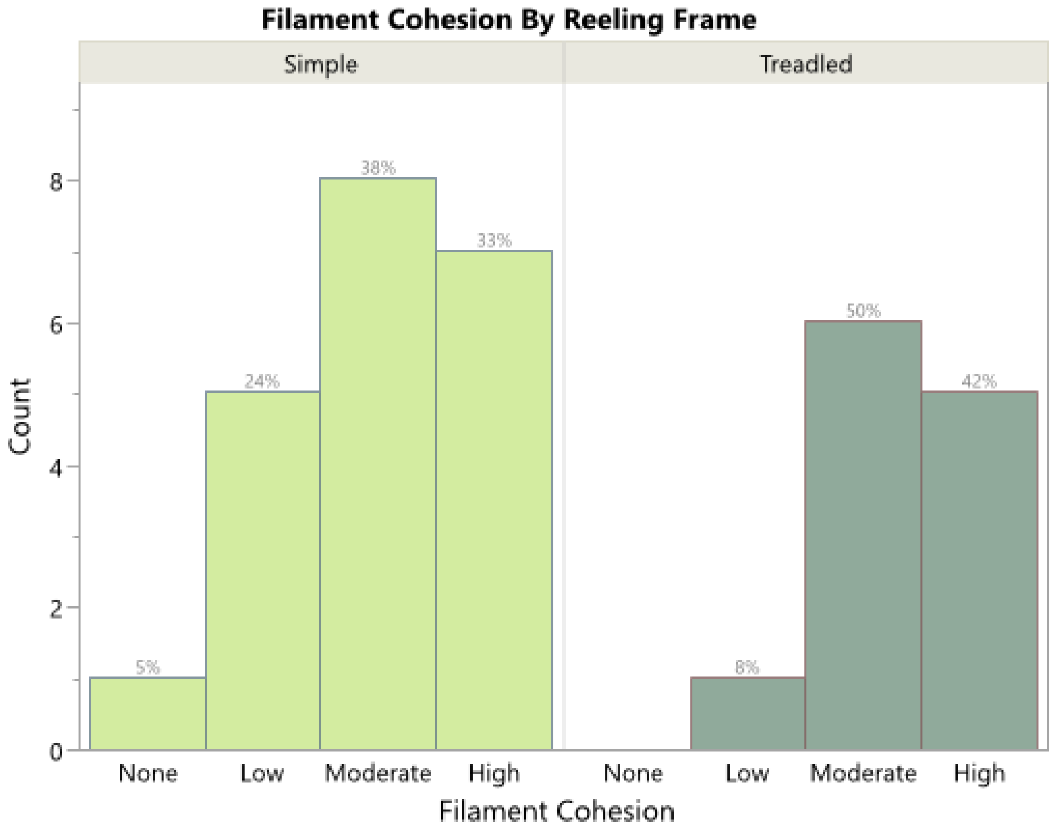


Figure 7.21: Filament cohesion of samples produced with the simple and treadled reeling-frames

When grouped by water temperature during reeling (Figure 7.22), there is not a clear trend, but silk reeled in boiling water showed moderate to high filament cohesion, while lower degrees of filament cohesion were more pronounced in samples reeled in water temperatures of 82°C or lower.

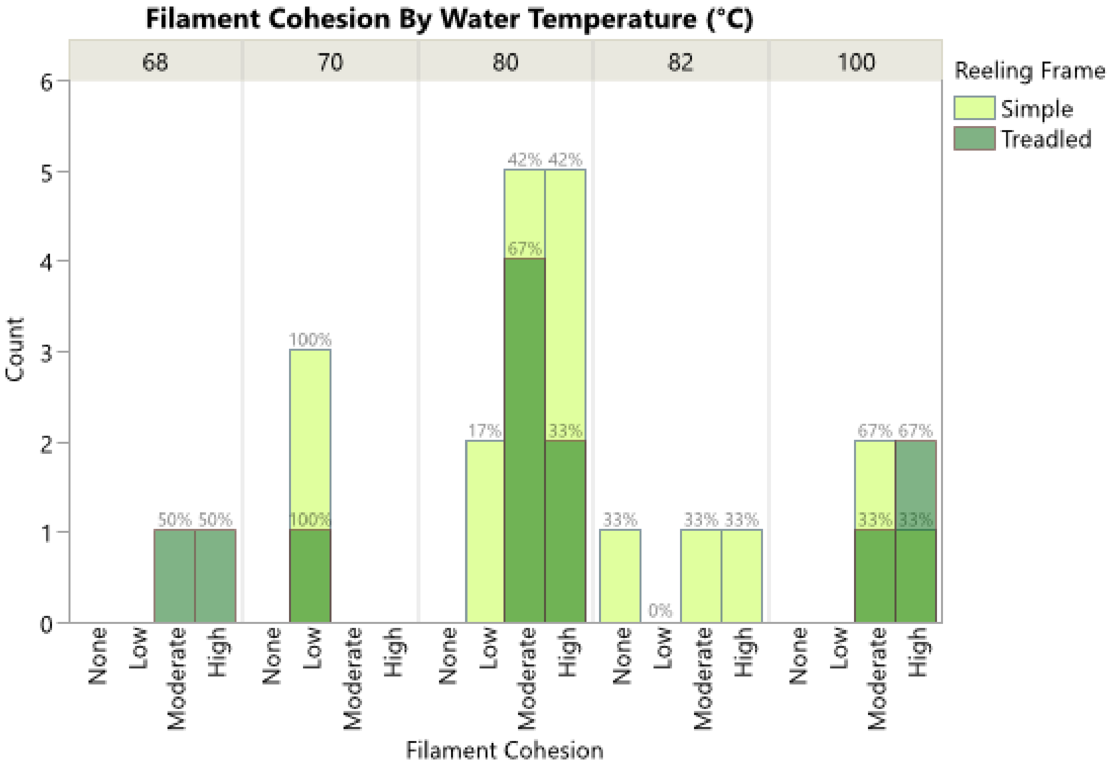


Figure 7.22: Reeled silk filament cohesion in samples organised by water temperature during reeling

Finally, the method of crossing or wrapping the silk during the reeling process appears to have an influence on filament cohesion (Figure 7.23), adding further depth to the trends observed by reeling-frames. The silent-roller method, used in combination with the simple reeling-frame only produced silk samples with a high degree of filament cohesion. The Piedmont crossing method had a 60% success rate of producing silk with high filament cohesion, while the remaining 40% showed moderate cohesion. The double-winding method produced a comparatively high degree of filament cohesion, while most samples produced using the single-winding method had only moderate levels of filament cohesion. Reeling methods using no method of crossing or wrapping produced highly variable results.

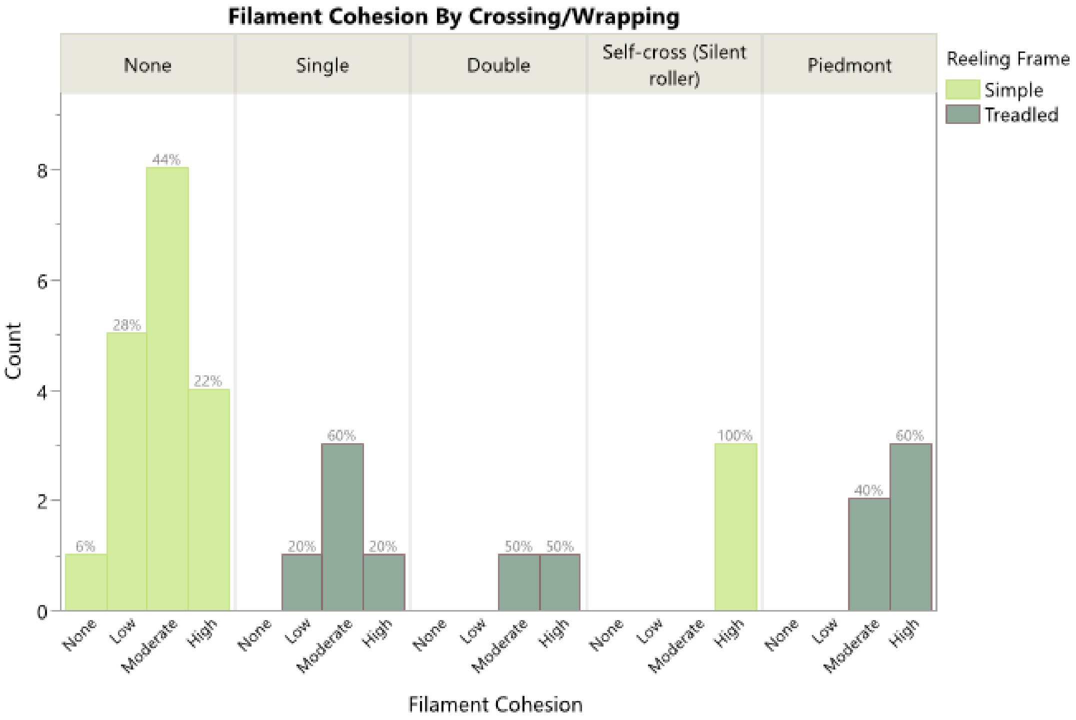


Figure 7.23: Reeled silk filament cohesion in samples organised by type of wrapping/crossing method during reeling

7.4.2 Fibre Spacing

Fibre spacing – which may be considered relevant to filament cohesion – was also assessed in relation to reeling-frame, water temperature, and crossing method (Figure 7.24).

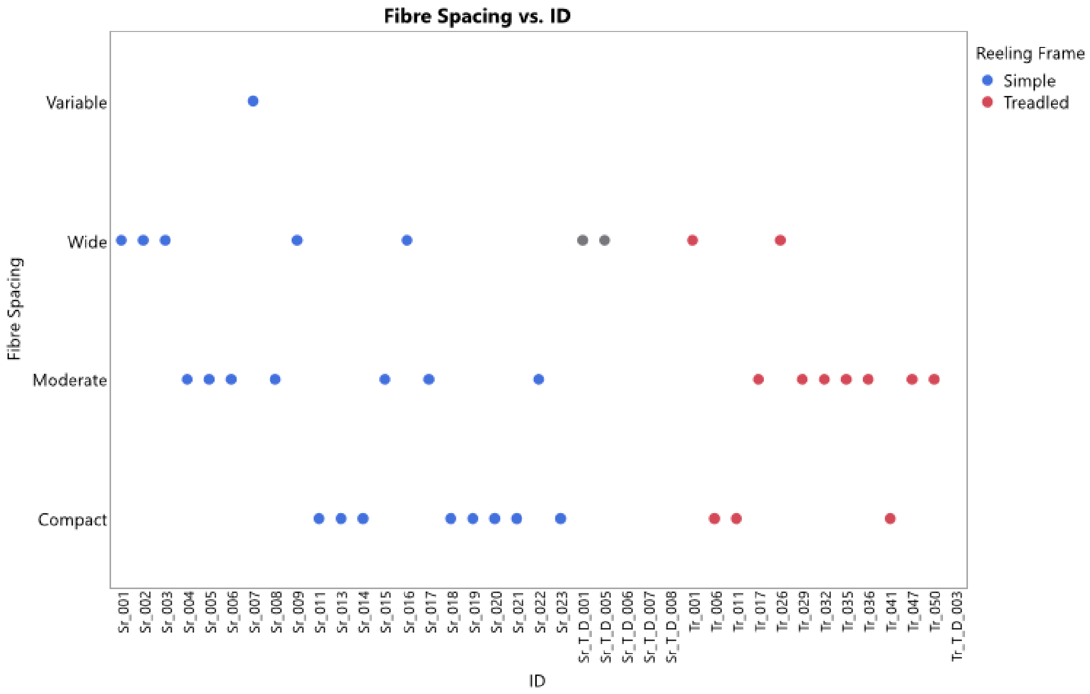


Figure 7.24: Scatter plot showing the fibre spacing of each filament sample

In this case the treadled reel produced a lower proportion of compactly spaced fibres than the simple reel did (Figure 7.25). The simple reel also, however, produced more varied results in terms of fibre spacing.

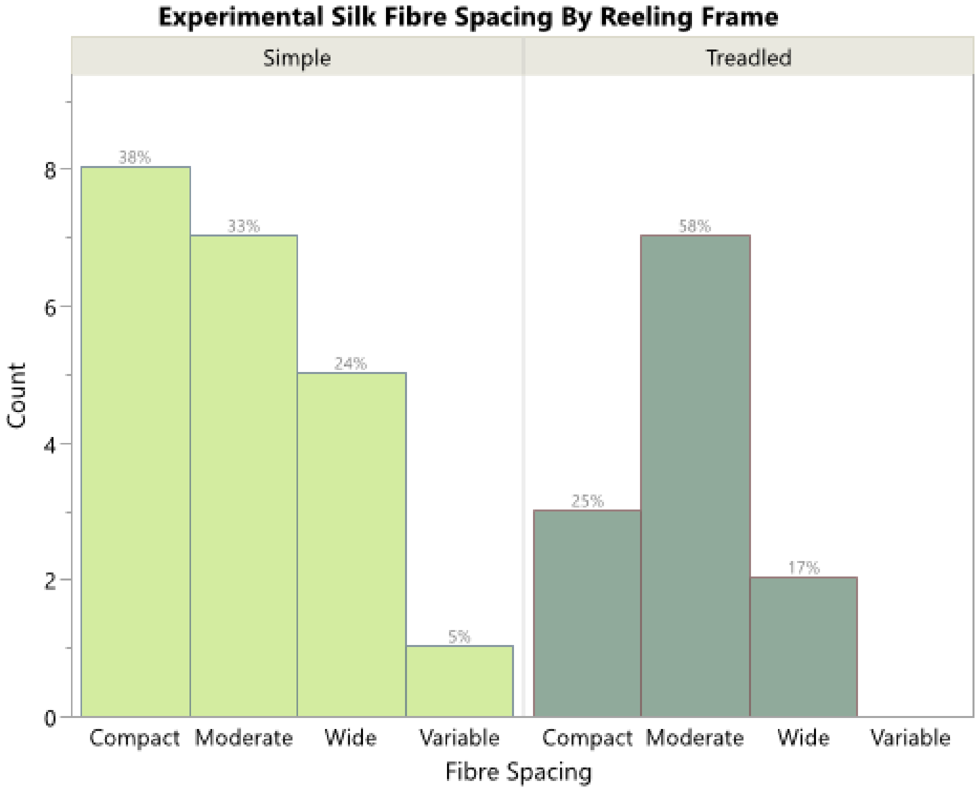


Figure 7.25: Spacing of fibres within raw filaments as observed in samples produced by the simple reeling-frame and the treadles reeling-frame

There also appears to be some relationship between fibre spacing and water temperature (Figure 7.26), with higher rates of wide to moderate spacing occurring at lower temperatures, and an absence of wide spacing in samples reeled in boiling water. It should also be noted that there are some unusual patterns of spacing in the samples produced in 82° and 68° water that may support further investigation in future.

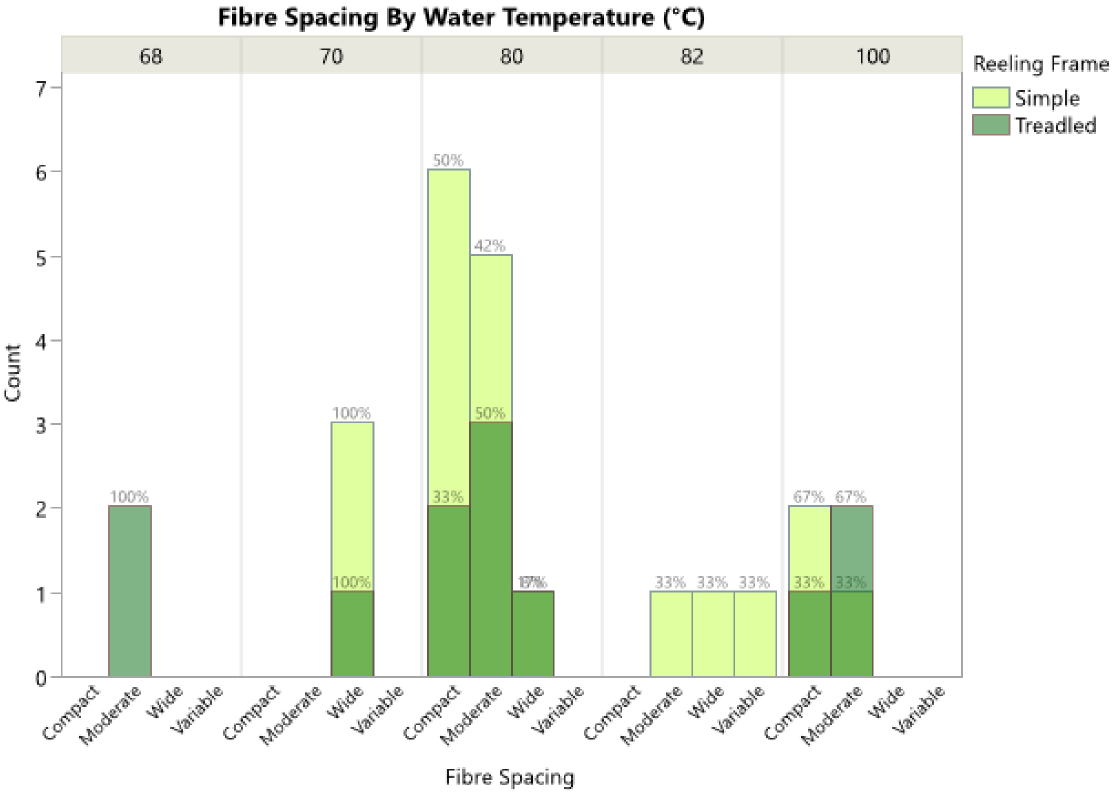


Figure 7.26: Spacing of fibres within raw filaments as observed in samples reeled in different water temperatures

Finally, crossing/wrapping has a clear influence on fibre spacing (Figure 7.27), as double-winding and the self-cross method produced only samples with compactly spaced fibres, while the piedmont crossing method produced some compactly spaced fibres and many moderately spaced fibres. The single-winding method produced a mixture of moderate and widely spaced fibres, while no crossing or wrapping method produced a variable range of fibre spacing.

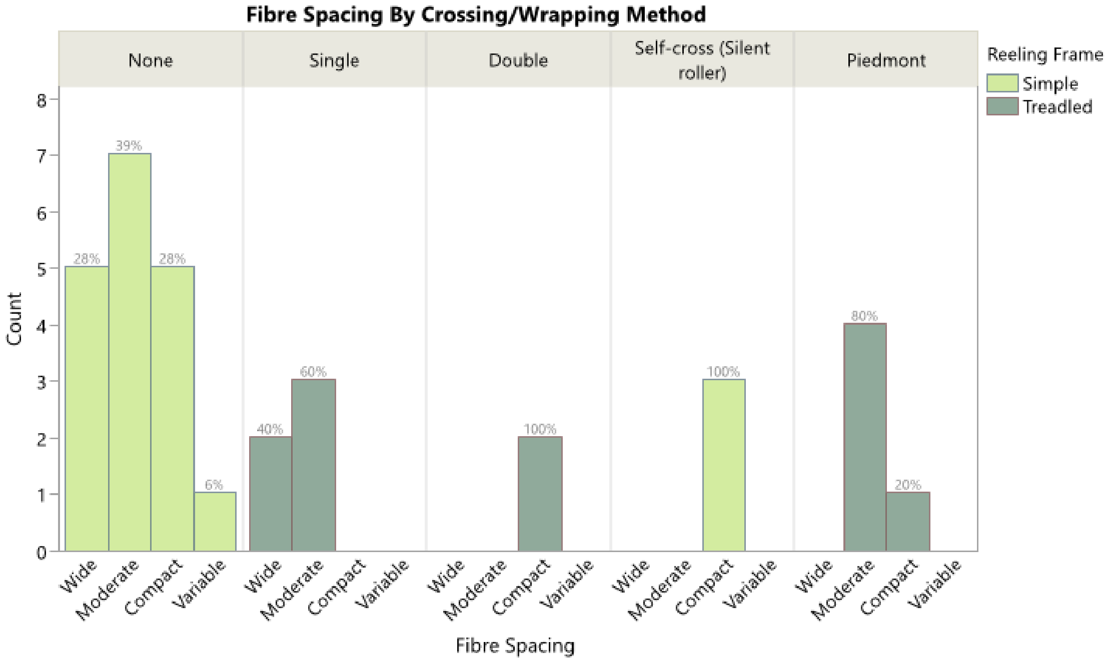


Figure 7.27: Spacing of fibres within raw filaments as observed in samples produced using different methods of crossing and wrapping during reeling.

7.4.3 Filament Shape

Filament shape (Figure 7.28), a characteristic frequently referenced by Kuhn (1988, 353,372), was observed to be *flat* in a narrow majority of the silk produced by the simple reeling-frame (Figure 7.29), while half of the analysed samples produced with the treadled reeling-frame were round in shape. Both reeling-frames also produced filament samples that were a mixture of flat and round.

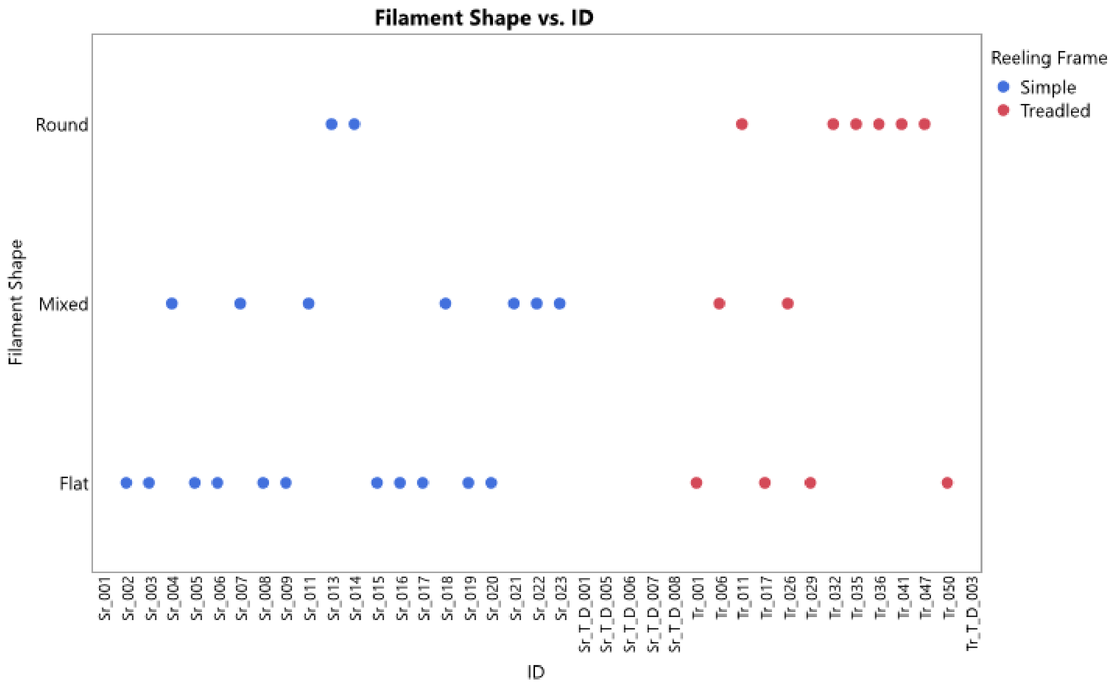


Figure 7.28: Scatter plot showing filament shape of each sample

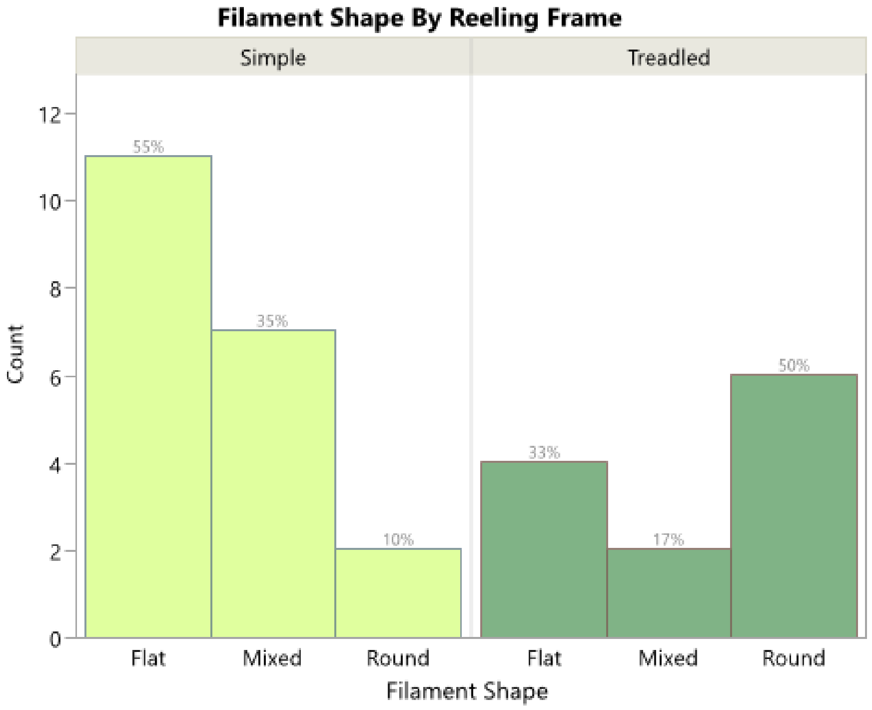


Figure 7.29: Filament shape in samples produced by the simple and treadled reeling-frames

Water temperature had no clear impact on filament shape (Figure 7.30), and any trends in the temperature categories can easily be explained by their association with particular reeling-frames.

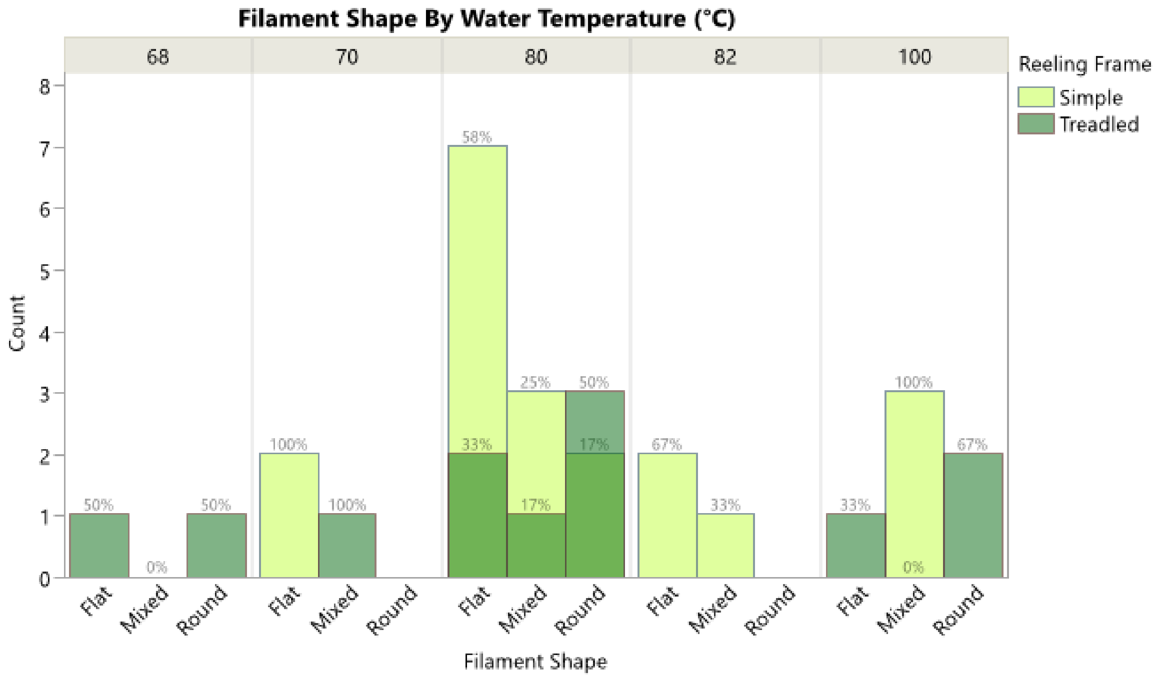


Figure 7.30: Filament shape in samples reeled in different water temperatures

Crossing methods once again showed a strong influence in relation to filament shape (Figure 7.31), as round filaments appear only to be produced through some manner of crossing. It also appears that the methods that involve a higher level of wrapping or higher number of crosses have a better rate of producing round filaments. The combination of mixed and round samples associated with double-wrapping and self-crossing may highlight the possibility of other unexplored variables from the reeling process that may also influence shape.

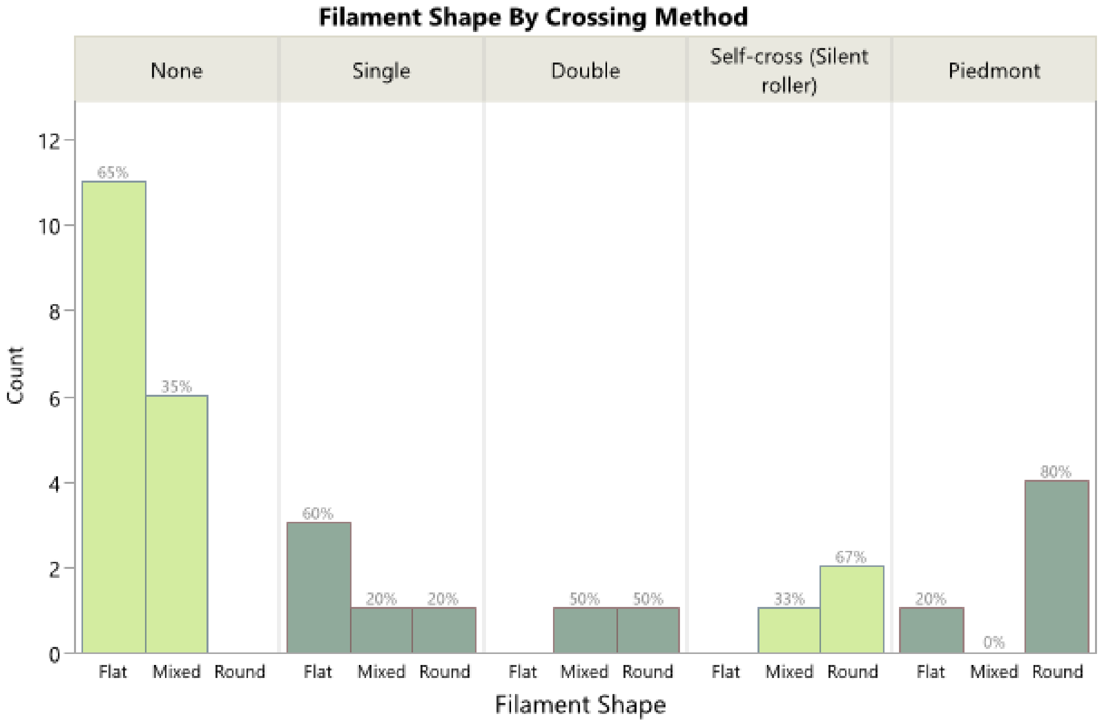


Figure 7.31: Filament shape in samples produced by different crossing/wrapping methods

7.4.4 Sericin Integrity

Sericin integrity (Figure 7.32) is an important consideration when evaluating whether a silk sample has undergone any degumming processes.

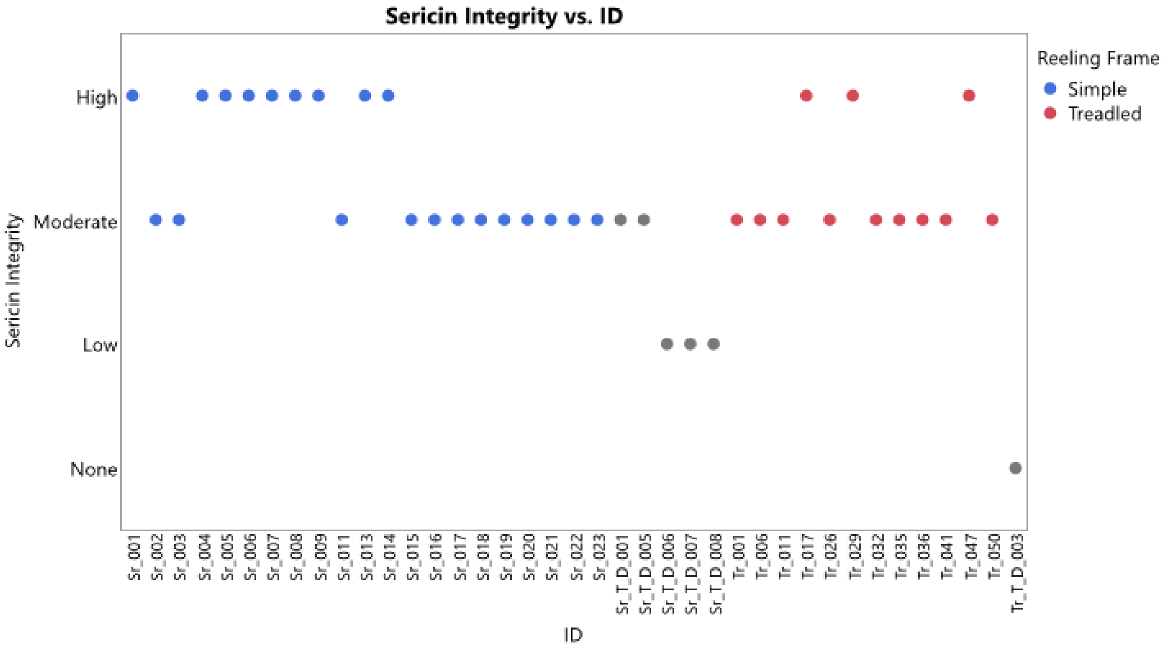


Figure 7.32: Scatter plot showing the sericin integrity of each sample

This characteristic was first assessed in relation to degumming methods (Figure 7.33) that, unsurprisingly, based on preliminary observation during experimentation, demonstrated high and moderate levels of sericin integrity in samples that had been left raw. Samples degummed according to water pH displayed no sericin integrity, while low to moderate levels of sericin integrity were observed in samples that were processed by weight of degumming agent in water with a more neutral pH of 7.

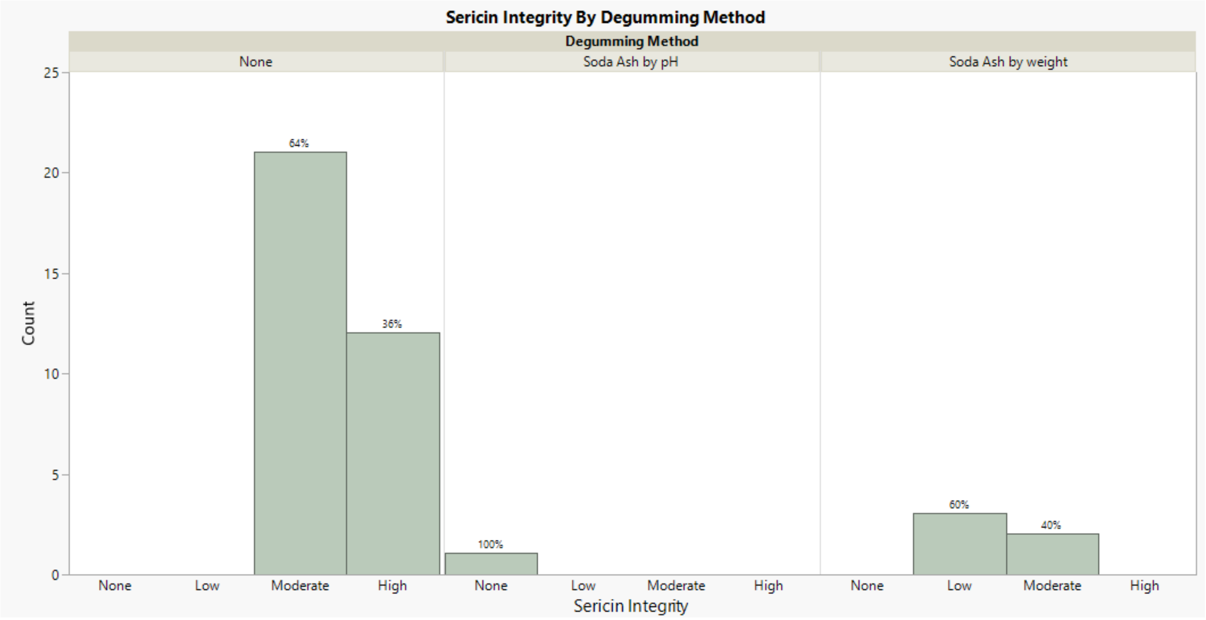


Figure 7.33: Sericin integrity of experimental silk samples by degumming method

Assessment of sericin integrity in raw silk samples by reeling-frame (Figure 7.34) did not indicate a clear influence, as most raw samples were already confirmed to have moderate levels of sericin integrity.

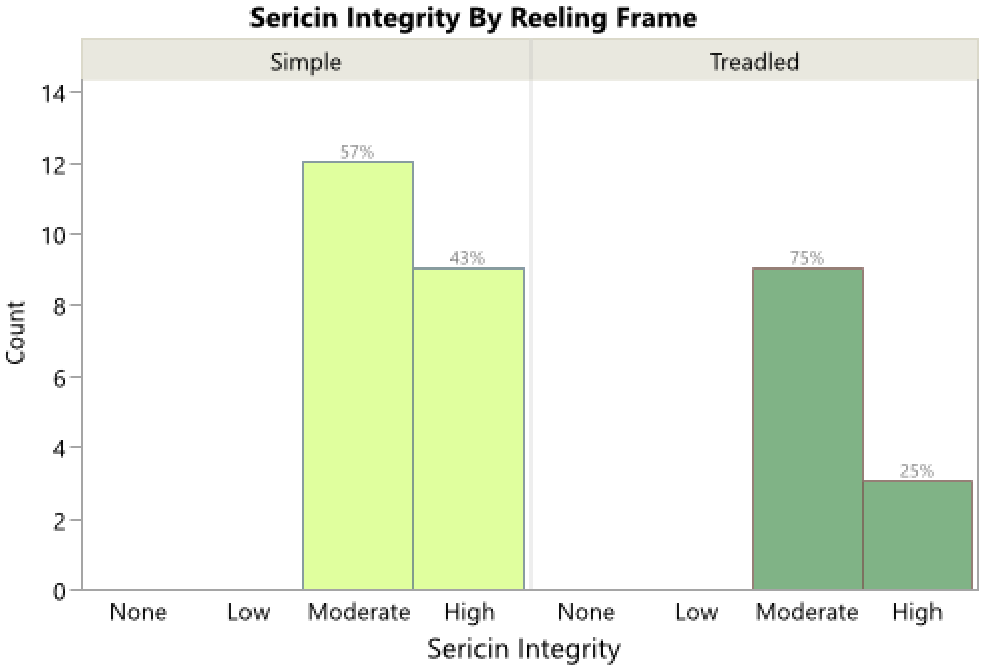


Figure 7.34: Sericin Integrity of silk samples by reeling-frame

Water temperature (Figure 7.35) could have some influence, as there appears to have been some reduction in sericin integrity associated with silk produced using the simple reeling-frame with boiling water, but this is not necessarily the case for silk reeled using the treadled reel, so there may be another factor influencing this.

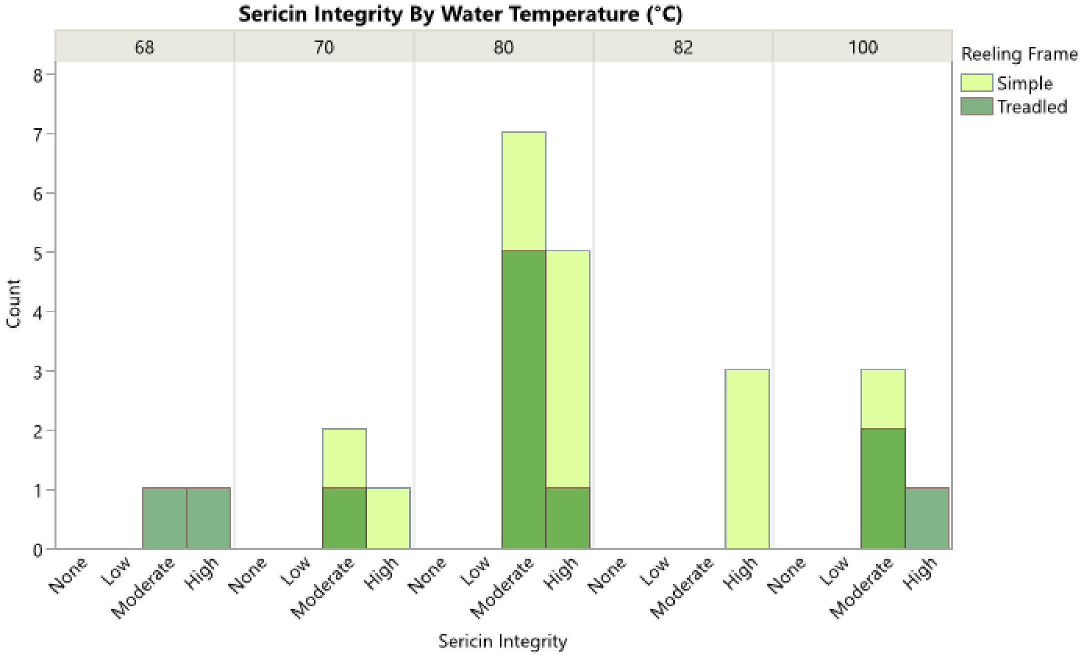


Figure 7.35: Sericin integrity of silk samples by Temperature of water during reeling

Wrapping and crossing methods (Figure 7.36) appear to have an impact on sericin integrity, particularly in association with the treadled reeling-frame, as methods with more crossing/wrapping appear to reduce the percentage of samples with high sericin integrity, possibly due to increased friction. The exception to this trend is the silk produced with the simple reel and self-cross method, which shows a larger proportion of samples with high sericin integrity than samples produced with no crossing method. It is unclear if this is an anomaly or if another unidentified aspect of this method increases the likelihood of sericin preservation.

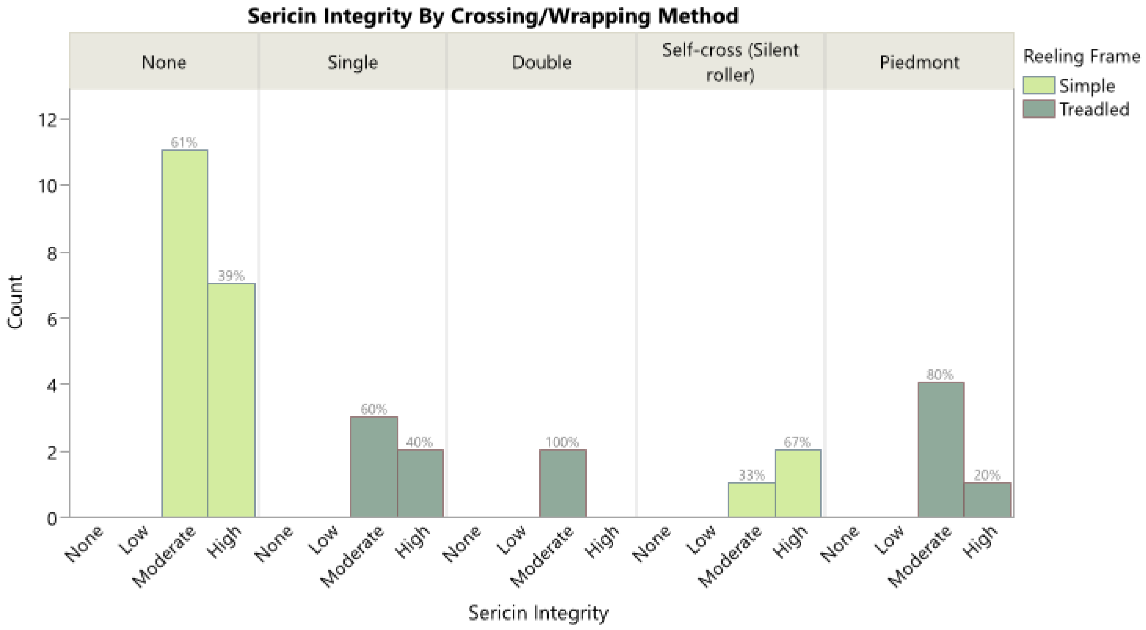


Figure 7.36: Sericin integrity of silk samples by Crossing/wrapping method during reeling

7.5 New Observations resulting from Visual Analysis

7.5.1 Differentiating Between Raw and Partially Degummed Silk

Raw silk with low filament cohesion may be difficult to distinguish from partially degummed silk, as both processes result in the preservation of fibre groups as well as fibre pairs, and both may show sericin flaking/deterioration. One clear distinguishing feature noted in the partially degummed experimental samples are cubic crystalline structures sitting on or partially embedded in the sericin (Figure 7.37). This feature is not visible in raw silk samples, which suggests the structures are formed as part of the degumming process, possibly from the alkaline additives used as degumming agents.

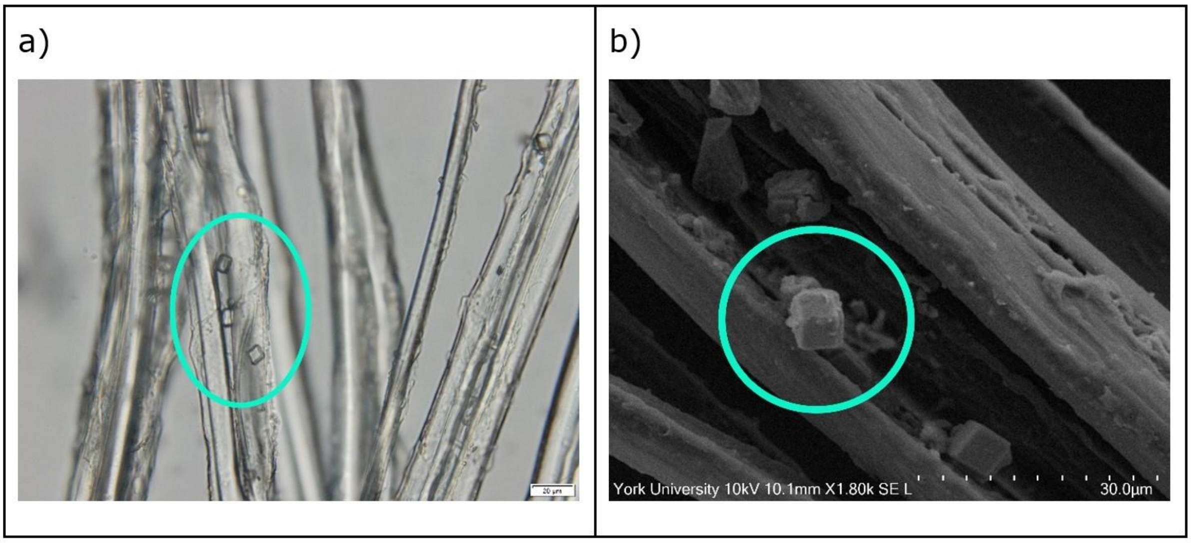


Figure 7.37: Transmitted light micrograph of Sr_T_D_001 viewed at 400x magnification (a) and SEM micrograph of Sr_T_D_005(b) showing crystalline objects after partial degumming.

This may not be useful in the analysis of archaeological silk samples though, as these inclusions may not survive post-deposition, but chemical analysis of degummed and partially degummed samples would provide further information on these inclusions.

One notable trait of partially degummed silk is that, while smaller groupings of fibres may be preserved at low levels of degumming, filament cohesion appears to break down prior to the dissolution of sericin (Figure 7.38). The degrees of variation between the breakdown of filament cohesion and sericin dissolution could be further explored through future experimentation, but the results of the degumming experiments indicate that partially degummed silk will exhibit at least some fibre separation even if the sericin remains mostly intact, resulting in an appearance similar to raw silk reeled from methods resulting in low fibre cohesion, but with somewhat lower sericin integrity (Figure 7.39).

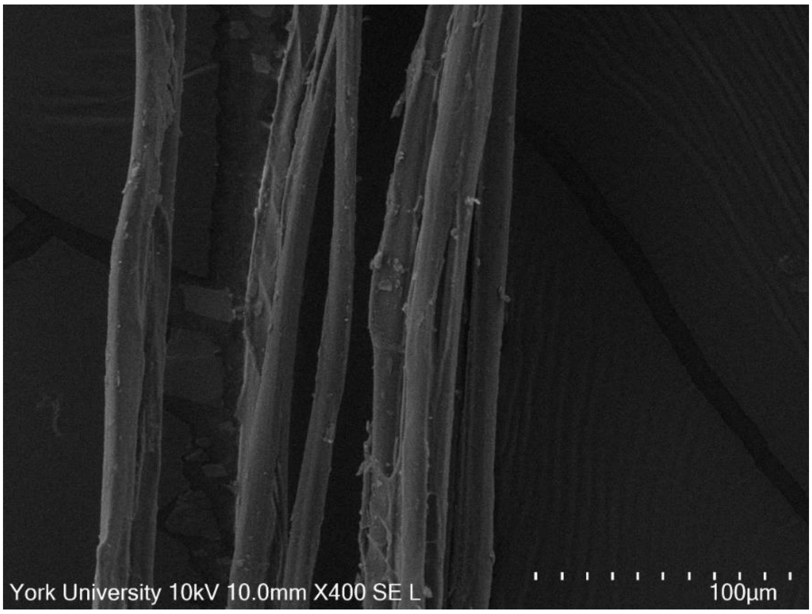


Figure 7.38: SEM micrograph of Tr_T_D_008, showing appearance of partially degummed fibres

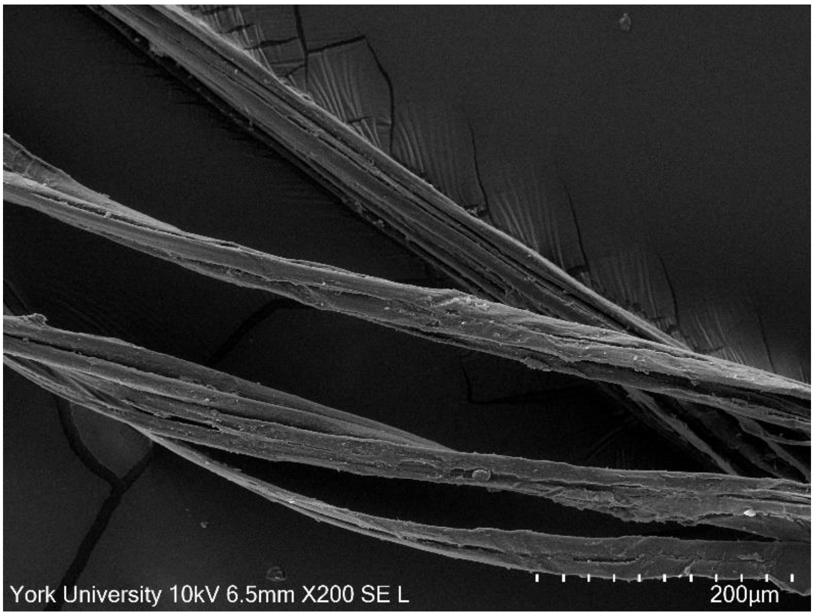


Figure 7.39: SEM micrograph of Tr_011, showing appearance of raw silk with low filament cohesion

The fully degummed samples showed no filament integrity, meaning that it was impossible to distinguish between separate filaments combined to produce the yarn, and no groups of fibres were observed, but some fibre pairs remained. Small flakes of sericin were visible in areas of the fully degummed samples, and it is possible that a thin, barely visible layer of sericin still coated the paired fibres, but this was only noted in SEM micrographs (Figure 7.40).

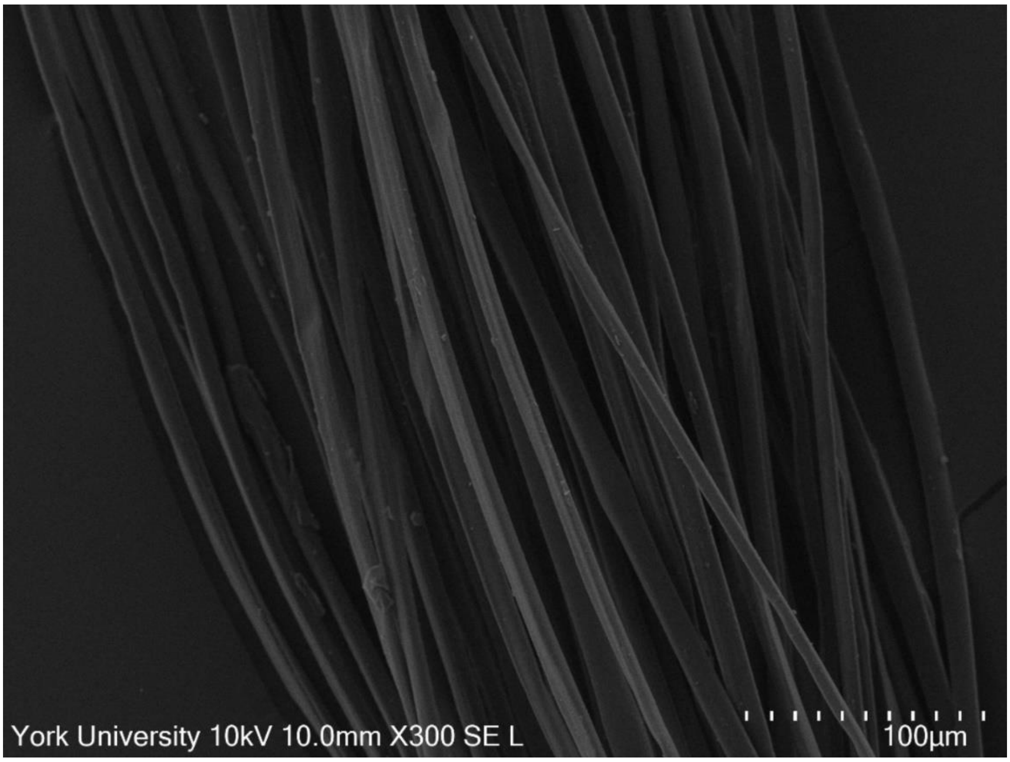


Figure 7.40: SEM micrograph of Tr_T_D_003, showing separated fibres with occasional flakes of sericin

7.5.2 Identifying Water Temperature Through Rippled Fibres

The raw silk filaments that were reeled from boiling water had an interesting physical characteristic in that the filaments, while frequently appearing to have a high level of cohesion and compactly spaced fibres, displayed frequent small loops of a single fibre across the length of each filament, creating a rippled effect (Figure 7.41).

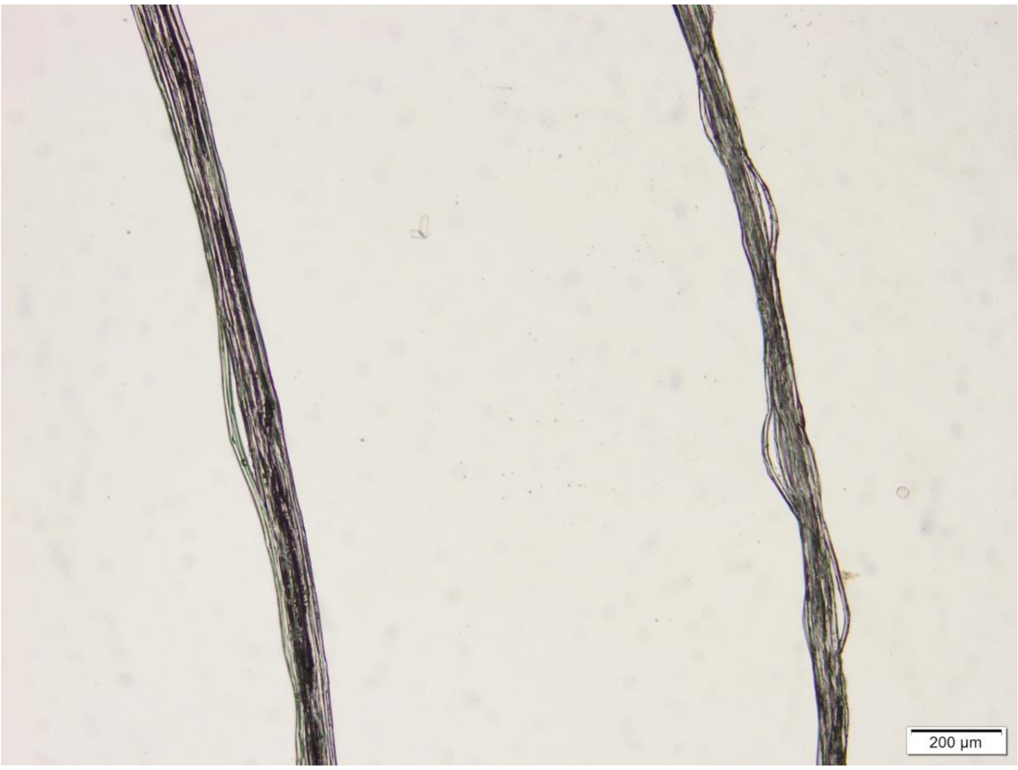


Figure 7.41: Transmitted light micrograph of Sr_022 viewed at 50x magnification showing rippled -fibre effect

This visual effect is distinct from the sort of filament splitting (Figure 7.42) generally observed in filaments reeled at lower water temperatures, and this appears almost exclusively in filaments reeled with boiling water (Figure 7.43). Exceptions to this rule appear to correspond with experiment days that were impacted by poor weather conditions likely to destabilise water temperature. The partly rippled fibres noted at lower temperatures could result from unrecorded temperature spikes or may be coincidental.

Figure 7.42: Transmitted light micrograph of Tr_001 showing typical fibre separation associated with water at a temperature below boiling

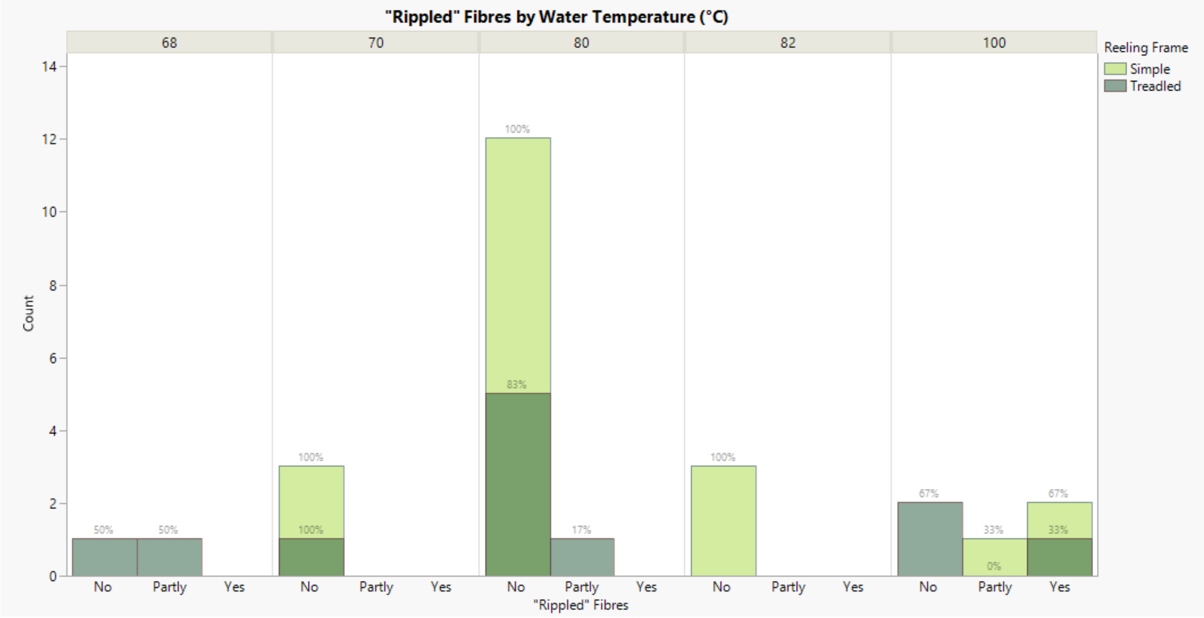


Figure 7.43: Presence of rippled fibres in samples reeled at different water temperatures

7.5.3 Crossover Indentations

Two types of indentation or compression were observed in the experimental silk fibres. The first is a single point of compression impacting the shape of the fibre (Figure 7.44 a), which appears to correspond with Goodway's usage of the term. The second type is a set of closely-spaced paired dents (Figure 7.44 b), which seem to appear in the sericin of raw silk but may also influence fibre shape. These characteristics appear in most of the experimental samples with different degrees of frequency, and it is unclear if they are a characteristic of the fibre, perhaps associated with position in the cocoon, or if they are a result of the reeling process. A more in-depth analysis of these characteristics would be necessary to properly evaluate any correlations between the frequency of these features occurring and potential influencing factors.

"Crossover indentations" are discussed by (Goodway 1987) as characteristic of silk and a potential point for mechanical failure when aged, but the exact causes of these indentations are not explained (i.e. do they result from the formation of the cocoon, or are they a result of silk strands overlapping during the reeling process?). Crossover indentations are also noted in the analysis of a 17th-century bodice (Hernanz et al. 2012, 485); in this case the authors cite a limited number of crossover indentations as one indicator of the fact that the silk fibres were well preserved. This provides an interesting contrast with the varying numbers of indentations observed in the experimentally produced silk, which suggests that preservation or absence of these indentations does not correlate to age of material.

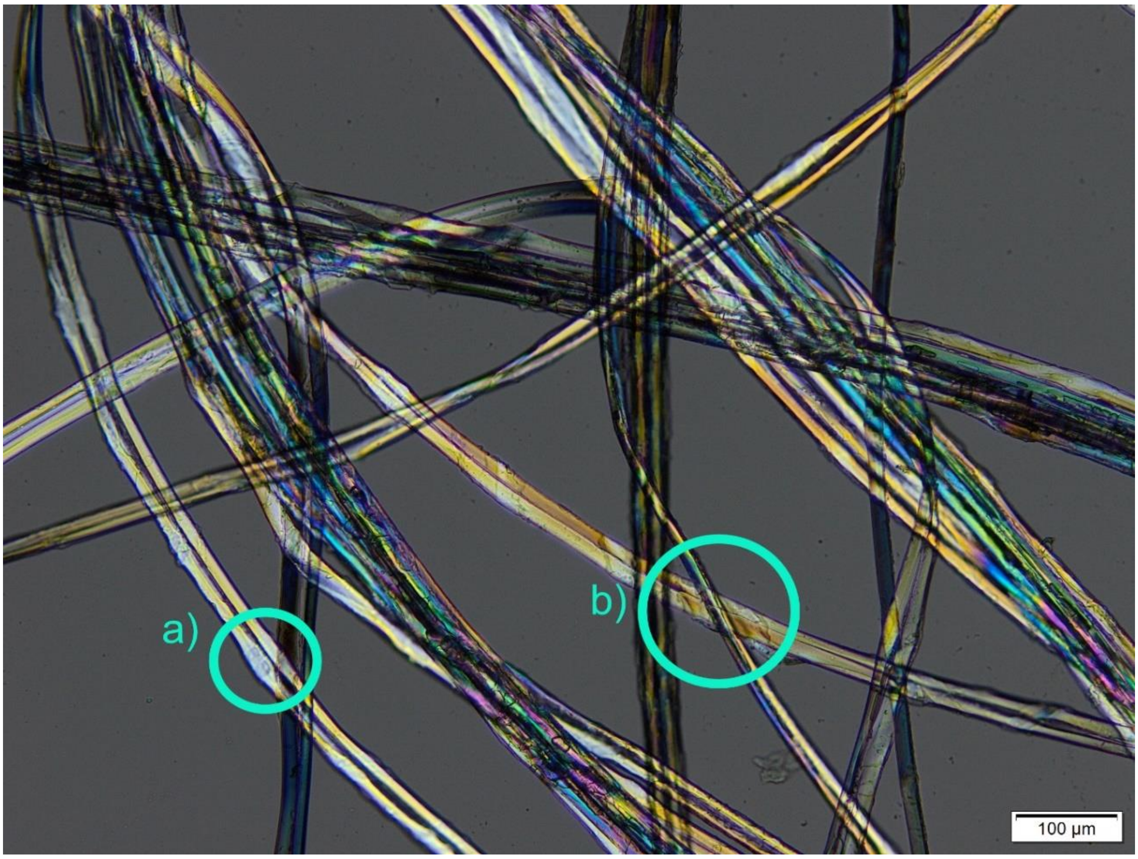


Figure 7.44: Polarised light micrograph of Sr_003 viewed at 100x magnification showing both larger points of compression (a), and paired dents (b) along the silk fibres

7.5.4 Silk Yarn Twist

As described in Chapter 5, the process of twisting silk was identified as a bottleneck in the time taken to produce silk yarn. The silk yarn samples resulting from the silk throwing experiments showed overall low levels of twist that were extremely difficult to measure accurately, and ultimately could not be correlated with the levels of twist observed in the archaeological silk samples that will be discussed in Chapter 8. Despite this, the thrown silks in combination with other contemporary twisted silk samples provided a useful reference point for developing a new approach to identifying when a reeled silk yarn has been plied.

7.5.4.1 Ply Analysis

Analysis of experimental and contemporary samples generated the 2 ply-analysis flow charts presented in chapter 6.7.2 as well as some additional observations relevant to the study of archaeological silk textiles. Tracing the yarn samples helped identify when separate sub-elements were present (Figure 7.45), and the angle of fibres in relation to the angle of the twisted elements were then marked (Figure 7.46).

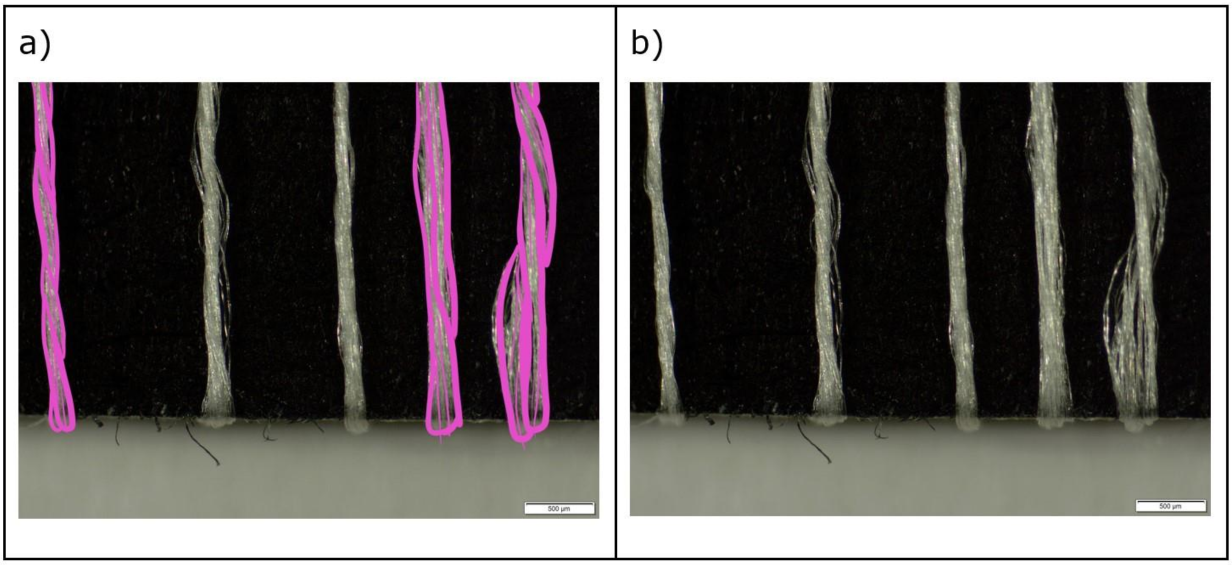


Figure 7.45: Traced indication (a) of ply in experimental sample Tr_T_D_001 compared to unaltered micrograph (b)

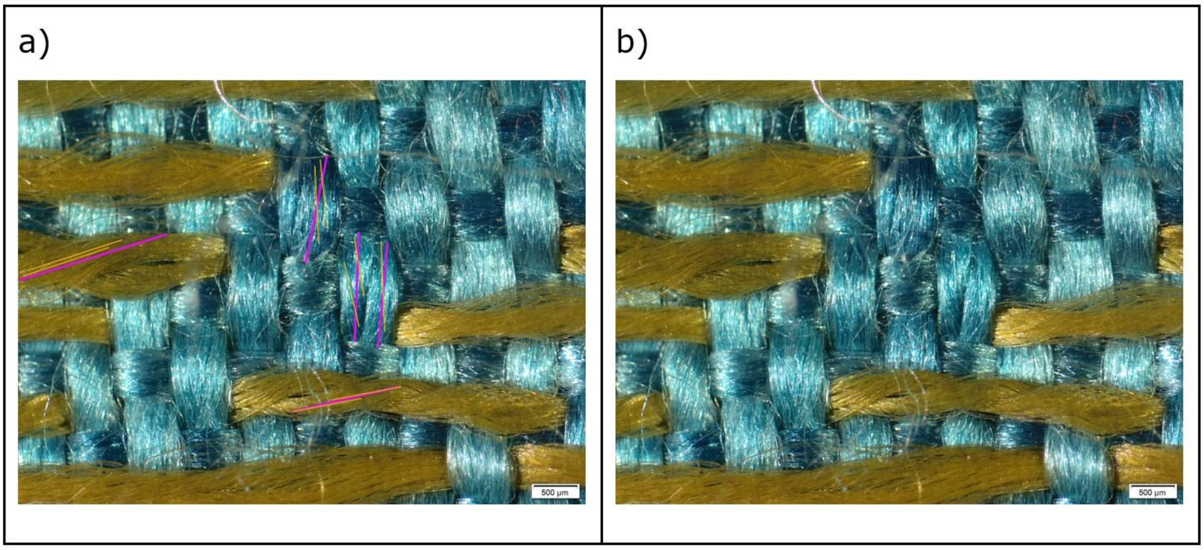
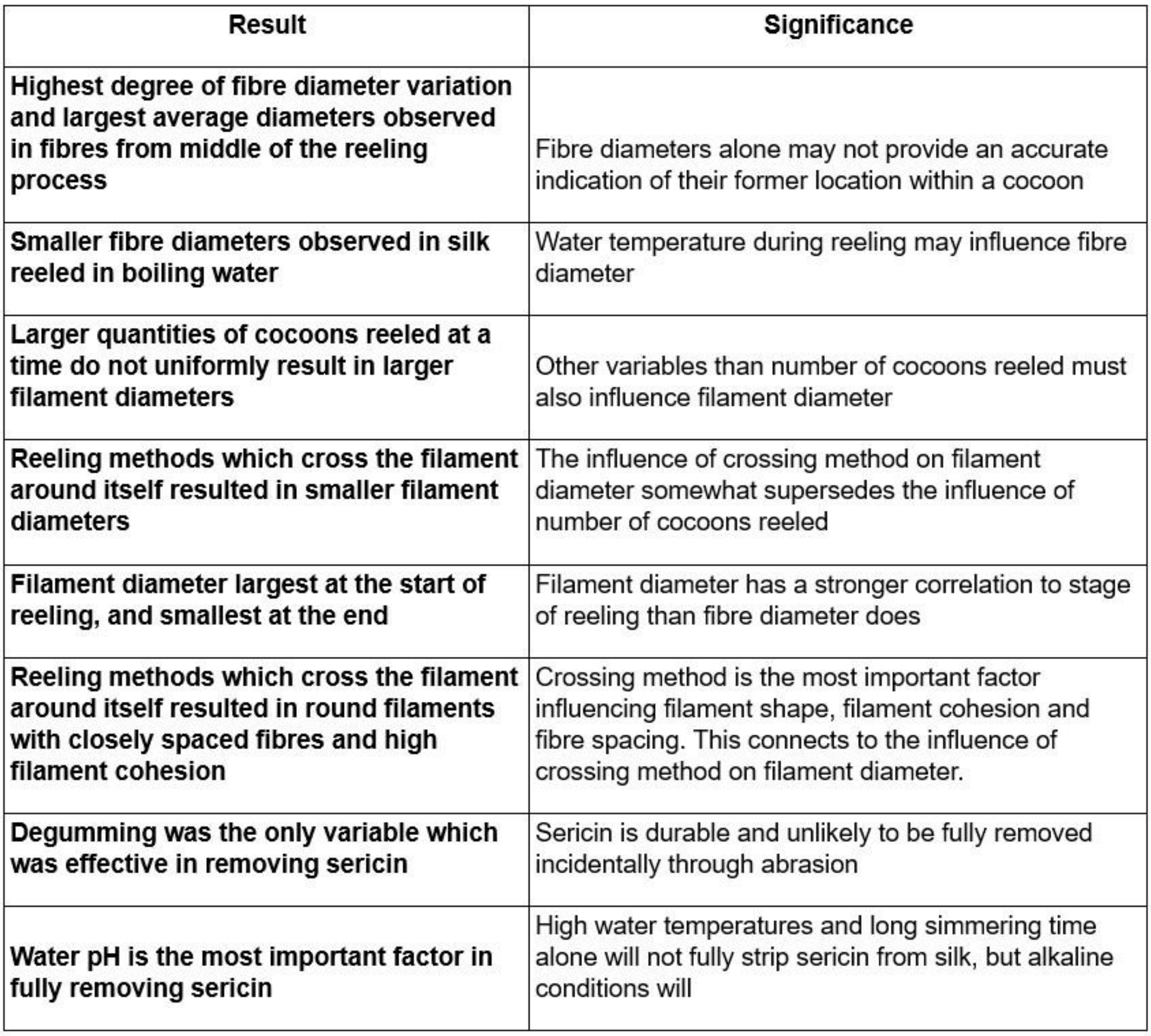


Figure 7.46: Angle of fibres in the threads of a brocaded tabby silk textile marked in magenta (a) compared to the unaltered micrograph (b)

This exercise demonstrated that the fibres in yarn composed of at least 2 elements twisted in one direction and plied in the opposite direction will typically (as should be expected) intersect the axis of the element at an angle corresponding to the angle of twist. When marking the fibre and sub-element angles during analysis, this should result in the fibre and element axes intersecting at opposite angles. This process also demonstrated the importance of assessing multiple areas of a textile, and multiple sections of a single yarn for indications of ply; fibres in low-twist elements may appear to follow the same orientation as the element, and single fibres can appear oriented in the opposite angle to the direction of twist. The latter complication has also been described by Cork et al.(1996, 340). Both the anomalies of (1) fibres in low-twist yarn appearing to follow the direction of ply, and (2) individual fibres in yarn appearing oriented in opposite direction of twist can lead to misclassification of yarn as single rather than plied, particularly if the visual cues denoting separate twisted elements are subtle or partially obscured by intersecting threads when in a woven textile.

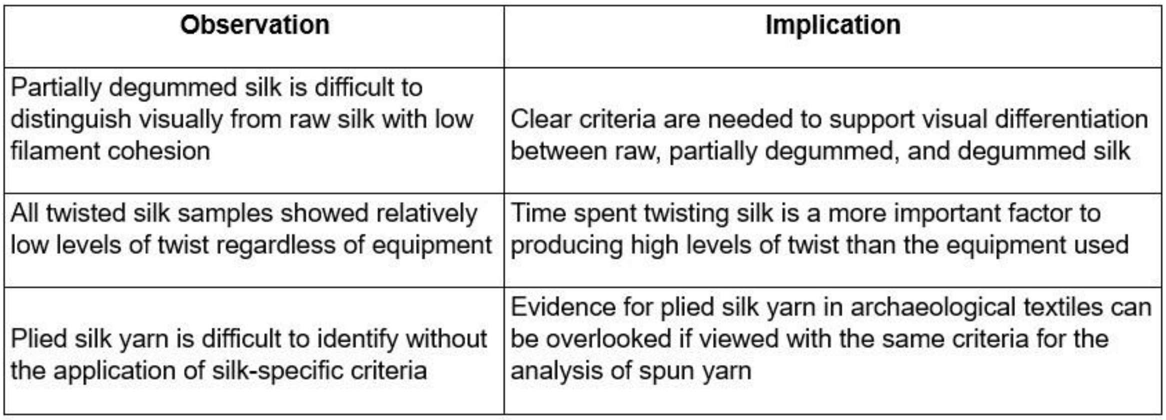
7.6 Summary

The results of the experimental silk analysis have significant implications regarding the influence of processing methods on fibre and filament morphology (Table 7.1). The analysis also generated important observations (Table 7.2) that have informed the analysis of the archaeological textiles discussed in chapter 8.



Result	Significance
Highest degree of fibre diameter variation and largest average diameters observed in fibres from middle of the reeling process	Fibre diameters alone may not provide an accurate indication of their former location within a cocoon
Smaller fibre diameters observed in silk reeled in boiling water	Water temperature during reeling may influence fibre diameter
Larger quantities of cocoons reeled at a time do not uniformly result in larger filament diameters	Other variables than number of cocoons reeled must also influence filament diameter
Reeling methods which cross the filament around itself resulted in smaller filament diameters	The influence of crossing method on filament diameter somewhat supersedes the influence of number of cocoons reeled
Filament diameter largest at the start of reeling, and smallest at the end	Filament diameter has a stronger correlation to stage of reeling than fibre diameter does
Reeling methods which cross the filament around itself resulted in round filaments with closely spaced fibres and high filament cohesion	Crossing method is the most important factor influencing filament shape, filament cohesion and fibre spacing. This connects to the influence of crossing method on filament diameter.
Degumming was the only variable which was effective in removing sericin	Sericin is durable and unlikely to be fully removed incidentally through abrasion
Water pH is the most important factor in fully removing sericin	High water temperatures and long simmering time alone will not fully strip sericin from silk, but alkaline conditions will

Table 7.1: Summary of the key results of the experimental silk analysis and their significance



Observation	Implication
Partially degummed silk is difficult to distinguish visually from raw silk with low filament cohesion	Clear criteria are needed to support visual differentiation between raw, partially degummed, and degummed silk
All twisted silk samples showed relatively low levels of twist regardless of equipment	Time spent twisting silk is a more important factor to producing high levels of twist than the equipment used
Plied silk yarn is difficult to identify without the application of silk-specific criteria	Evidence for plied silk yarn in archaeological textiles can be overlooked if viewed with the same criteria for the analysis of spun yarn

Table 7.2: Summary of key observations made during experimental silk analysis and their implications

7.6.1 Fibre Diameters

Analysis of the experimental-silk fibre diameters suggests a relationship between fibre diameter and stage of reeling, which has also served as a proxy for the position of the silk fibres within the cocoon. The highest degree of fibre variation and the highest average diameter were observed in fibres from the middle of the reeling process, which are interpreted as primarily coming from the middle of the silk cocoon. This disproved the hypothesis that middle fibre diameter measurements would be smaller and fall within a narrower range than the diameters of fibres from the beginning of the reeling process/exterior of the cocoon. Diameter measurements of fibres from the beginning stage of reeling/exterior of cocoon, and end stage of reeling/interior of cocoon, did meet expectations, as fibre diameters from the beginning of the reeling process were generally larger than the diameters of fibres from the end of the reeling process, albeit with some overlap of the minimum and maximum diameters from these 2 sample categories.

This indicates that while other studies have demonstrated that fibre diameter generally decreases the closer it is to the interior of the cocoon, this is not fully reflected in silk fibres that have been reeled outside of a laboratory setting. The significance of this finding is that **fibre diameters extracted from reeled silk samples may not provide an accurate indication of their former location within a cocoon**. The data gathered has indicated that other variables may also influence fibre diameter. Most prominent of these variables is water temperature, however, there is room for further exploration of the relationship between reeling-frame and crossing method through continued experimentation and data collection.

7.6.2 Filament Diameters

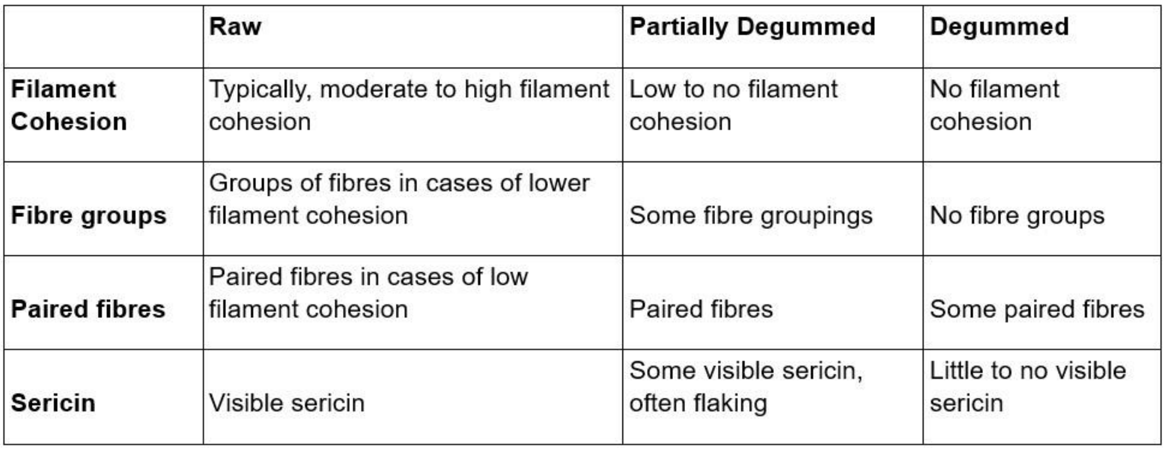
Comparison of the experimentally reeled silk filament diameters has indicated **a strong relationship between the number of cocoons, the**

position of the fibre within the cocoon and the filament diameter. There is also an indication that crossing method influences filament diameter. The influence of crossing methods on filament diameter may also give the impression that type of reeling-frame also influences the diameter. This is because the majority of different crossing methods that produced smaller diameters were used in combination with the treadled reeling-frame alone. Ignoring the crossing methods, the type of reeling-frame does not appear to have a strong influence on filament diameter. The key influencing factor is the combination of apparati that supports a particular crossing method. Meanwhile, it was determined that while water temperature may influence filament diameter**, the relationship between water temperature and filament diameter does not correlate as strongly with filament diameter as other variables do**, and water temperature cannot be confirmed as an influencing variable without further supportive data.

7.6.3 Visual analysis

Comparison of key visual characteristics of the experimentally reeled fibres have indicated that the use (or lack thereof) of **different crossing or wrapping methods have an appreciable influence on the filament cohesion, fibre spacing, and filament shape of reeled silk, and may also have some influence on the sericin integrity**. The reeling-frame style and temperature of water during reeling in isolation did not appear to have strong influences on these characteristics, but this could be explored further in future. Unsurprisingly, **degumming was determined to have the biggest influence on sericin integrity**, **and within the degumming process, water pH was confirmed to be the most important factor in removing sericin from fibres.**

Visual analysis also yielded **new observations** linking fibre and yarn characteristics to production methods. This has supported the establishment of visual criteria for **differentiating between raw, partially degummed, and fully degummed silk** (Table 7.3).



	Raw	Partially Degummed	Degummed
Filament Cohesion	Typically, moderate to high filament cohesion	Low to no filament cohesion	No filament cohesion
Fibre groups	Groups of fibres in cases of lower filament cohesion	Some fibre groupings	No fibre groups
Paired fibres	Paired fibres in cases of low filament cohesion	Paired fibres	Some paired fibres
Sericin	Visible sericin	Some visible sericin, often flaking	Little to no visible sericin

Table 7.3: Summary of visual criteria developed for the differentiation of raw, partially degummed, and fully degummed silk.

The presence of **rippled fibres** in raw silk filaments has been determined to be **indicative of boiling**, supporting identification of the approximate water temperature used to reel silk. Finally, a new workflow has been established for identifying plied silk yarn. This has also demonstrated **the potential for misidentification of silk yarn** from archaeological textiles, as will be explored further in chapter 8.

8 Results: Analysis of Archaeological Silk Textiles

8.1 Introduction

The results highlighted in Chapter 7 provided useful information regarding how silk production methods influence silk fibre and filament diameters, morphology, and behaviour. The goal of producing and analysing the experimental silk reference collection was to create a useful body of data that may be compared to archaeological and historical silk textiles.

The archaeological textiles analysed herein are dated from the early to high Middle Ages (see chapter 1.6), and come from different social, and archaeological contexts. This chapter will present the results of the analysis of the fibres, yarn, and woven structure of the selected archaeological textiles. The areas of analysis covered are fibre diameters, visual analysis of fibres, yarn diameter, yarn degree of twist, thread count and cover factor (density), and the visual analysis of both the overall textiles structures and yarn structures.

8.2 Diameter Measurements from Archaeological Silk Fibres

A comparison of the fibre diameters from both systems of the Winchester and Coppergate textiles demonstrates an overall higher degree of variation in the samples from Coppergate, with a slight trend towards larger diameters (Figure 8.1). While the Winchester fibre diameters also vary, the diameters fit within a smaller range, with significantly lower maximum fibre diameters than Coppergate.

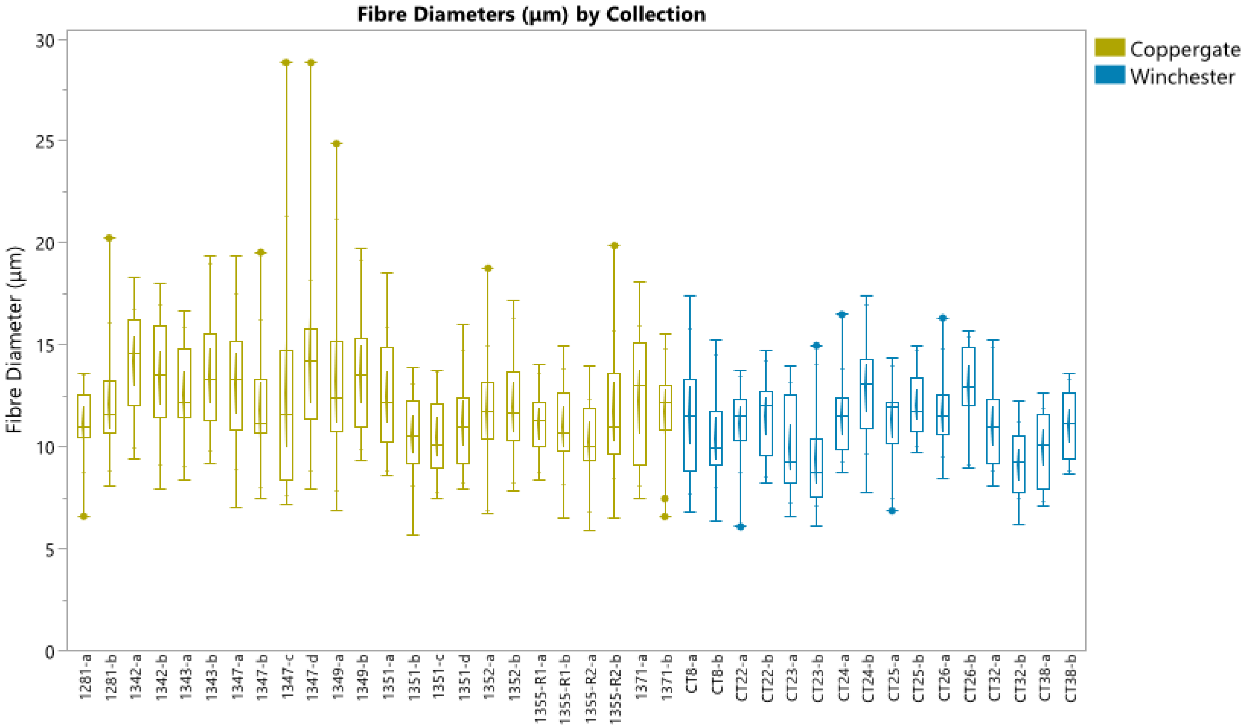


Figure 8.1: Box plots of Archaeological silk fibre diameters

The mean diameters of fibres from each confidently assigned system of the Coppergate and Winchester textiles (Figure 8.2) indicate some correlation between an increase in the fibre diameter of system A and an increase in the fibre diameter in system B. There is also a clear trend toward higher fibre diameters in the Coppergate textiles in contrast to the Winchester textiles.

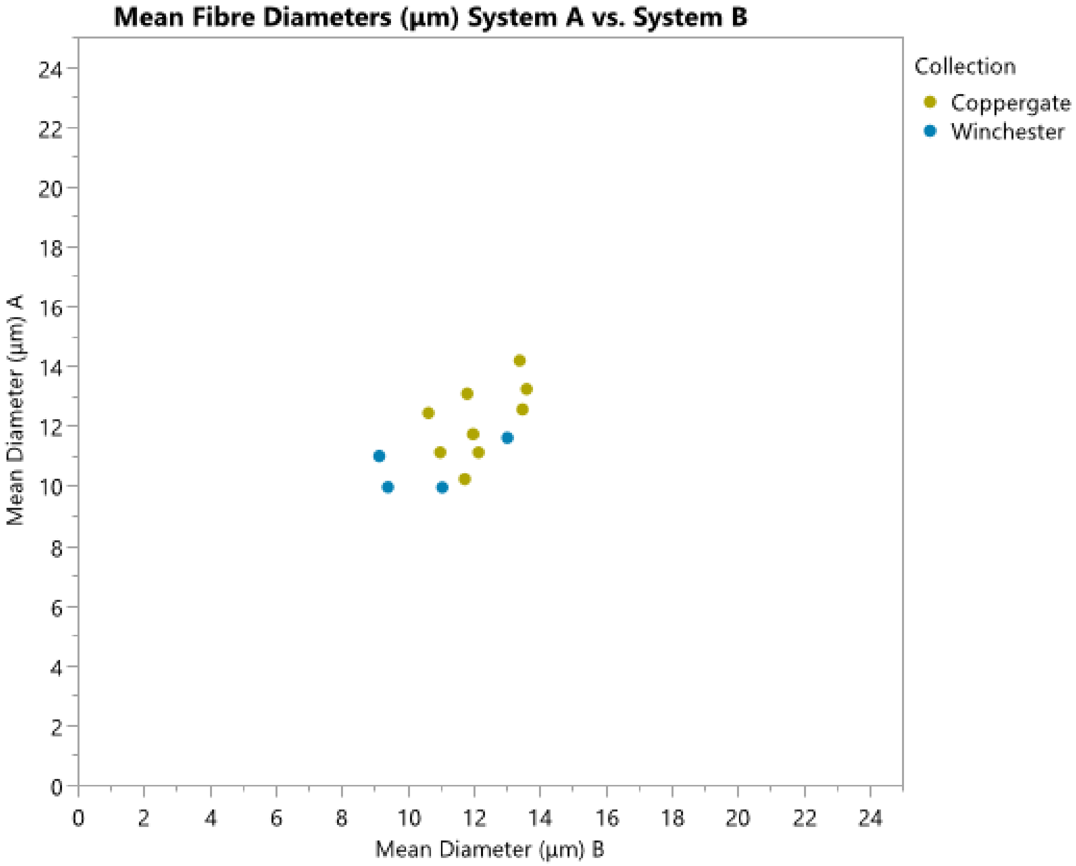


Figure 8.2:Scatter plot of confident subset of fibre diameters from Coppergate and Winchester textiles by thread system

The textiles that shared the same direction of twist in warp and weft system (Figure 8.3) also showed trends in fibre diameter. Close groupings of mean diameters were observed in the SxS compared to the ZxI textiles, which showed a wide range of diameters. Additionally, smaller diameters were observed in the ZxI textiles from Winchester than those from Coppergate.

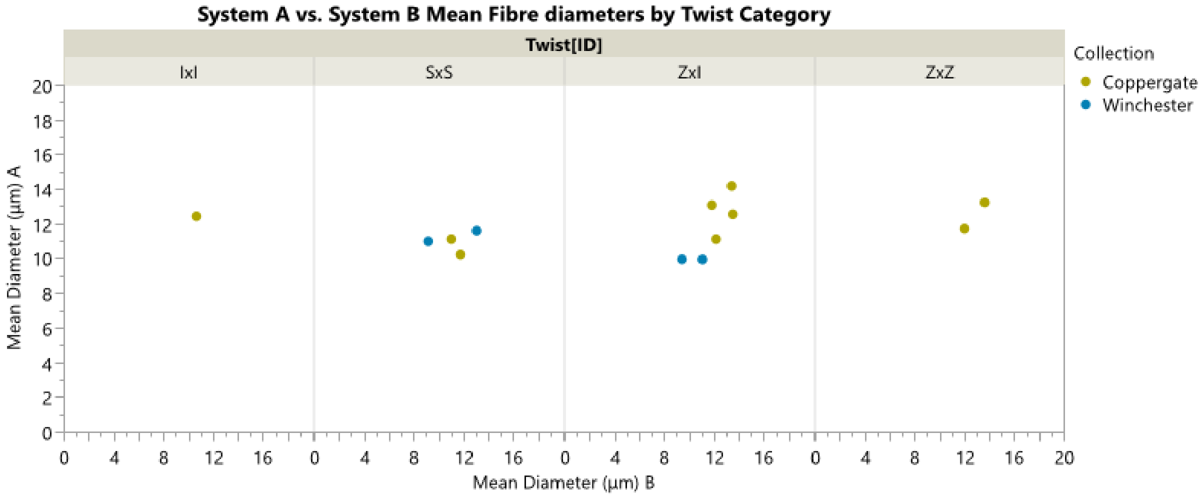


Figure 8.3: Scatterplot of confident subset of mean fibre diameters from Coppergate and Winchester textiles plotted by thread system and grouped by twist category

The observed trends in fibre diameter as grouped by cloth categories is notable, as fibre diameters grouped by direction of yarn twist regardless of system do not show obvious trends, apart from confirming a tendency towards small fibre diameters in I and Z-twisted yarn from Winchester compared to Coppergate (Figure 8.4).

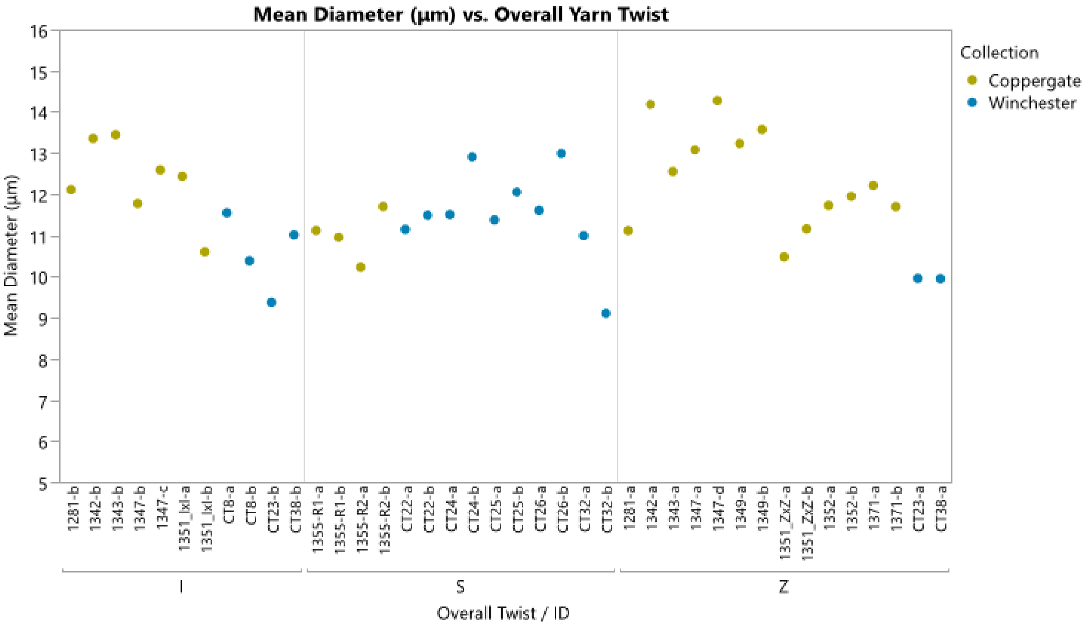


Figure 8.4: Mean Fibre diameters from Coppergate and Winchester textiles grouped by direction of yarn twist

Analysis of fibre diameters from the archaeological textiles indicates notable differences between the fibres from Coppergate and Winchester. While there is some overlap in the fibre diameters recorded, the

Winchester fibres tend to be smaller in diameter with less variation than the Coppergate fibres. Additionally, both collections show further trends when grouped by textile yarn twist categories, with closer groupings of smaller fibre diameters seen in IxI and SxS textiles, partially accounting for the overlap in Coppergate and Winchester fibre diameters, and indicating that these fibres may share processing variables, and perhaps the same origin.

8.2.1 Comparison with experimental fibres

A comparison of all fibre diameters (Figure 8.5), not only confirms the previously described trends in the archaeological textile fibre diameters, but also indicates similarities in the range of diameters seen in the Coppergate textiles and the experimental silk fibres. Given that the experimental fibre diameters provide a sweeping view of the influences of multiple processing methods on silk fibres, as well as other factors such as position in the silk cocoon, this could indicate that the different fibres from Coppergate resulted from a wider variety of production methods than the Winchester silk fibres did.

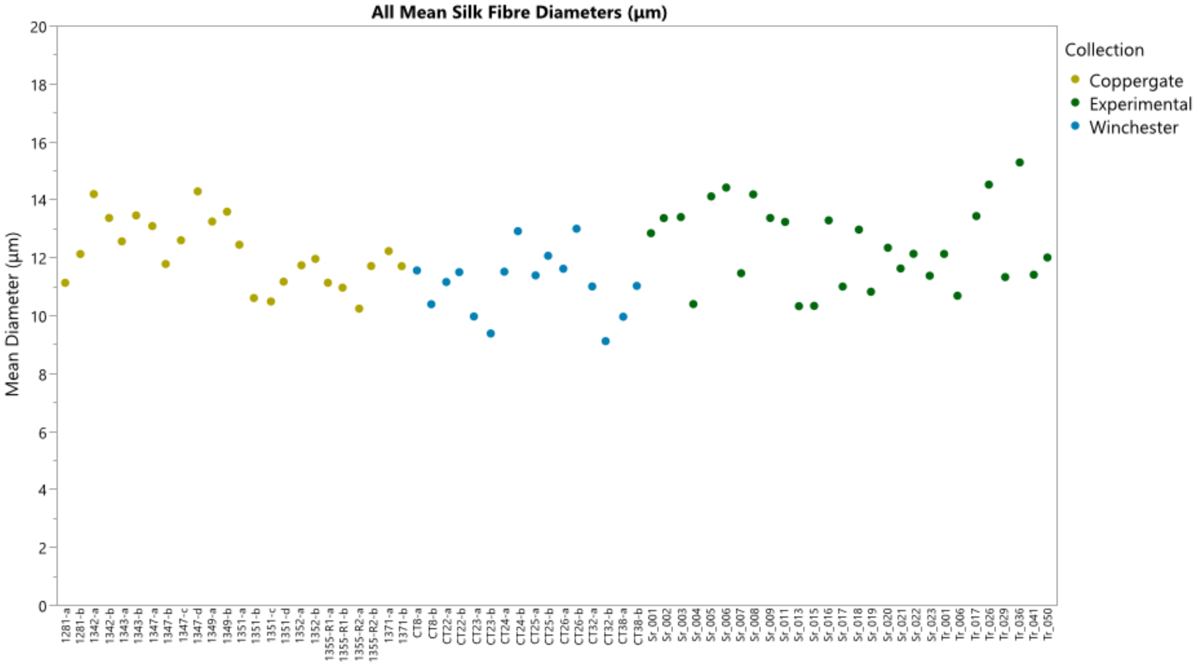


Figure 8.5: Scatterplot of mean fibre diameters from the archaeological and experimental silk fibres

8.3 Visual analysis of Archaeological fibres

Analysis of the physical characteristics of the Winchester and Coppergate silk textiles identified some clear trends related to sericin integrity, fibre behaviour, and overall deterioration. The differences in preservation prevent one-to-one comparison of the appearance of most of the archaeological textile fibres and the experimental silk, but the overall trends observed still provide some useful information. Of particular interest is how sericin integrity, filament cohesion, and the grouping of fibres can indicate whether fibres have been degummed. Also of note was the extent of fibre damage across samples, the presence of other residues, and the inclusion of fibres other than bombyx mori silk.

8.3.1 Sericin Preservation, Filament Cohesion, and Fibre Groupings

Unsurprisingly, the archaeological textiles showed an overall lower level of sericin integrity than the raw experimental silk samples. That said, moderate levels of sericin preservation and groupings of fibres were observed in a higher proportion of the Winchester textiles than the Coppergate Textiles(Figure 8.6).

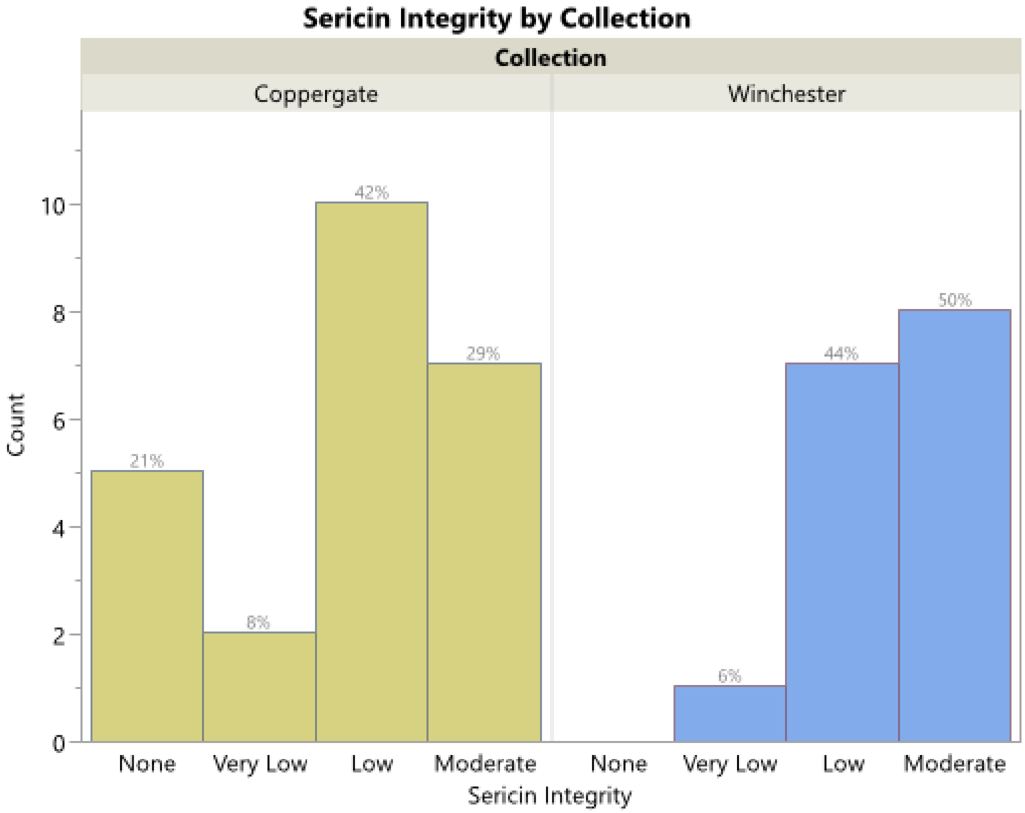


Figure 8.6: Proportions of archaeological fibre sericin integrity grouped by collection

When grouped by thread system (Figure 8.7), a further trend emerged in that the Coppergate textiles showed a larger number of samples with low to no sericin integrity in system B, and an overall higher proportion of low to moderate sericin integrity in system A. The Winchester textiles, in contrast showed equal proportions of low to high sericin integrity in both System A and B, indicating more balance between the sericin integrity in each system overall. At minimum this suggests the yarn from each system underwent similar degumming processes and could in combination with other shared characteristics indicate that warp and weft threads share an origin.

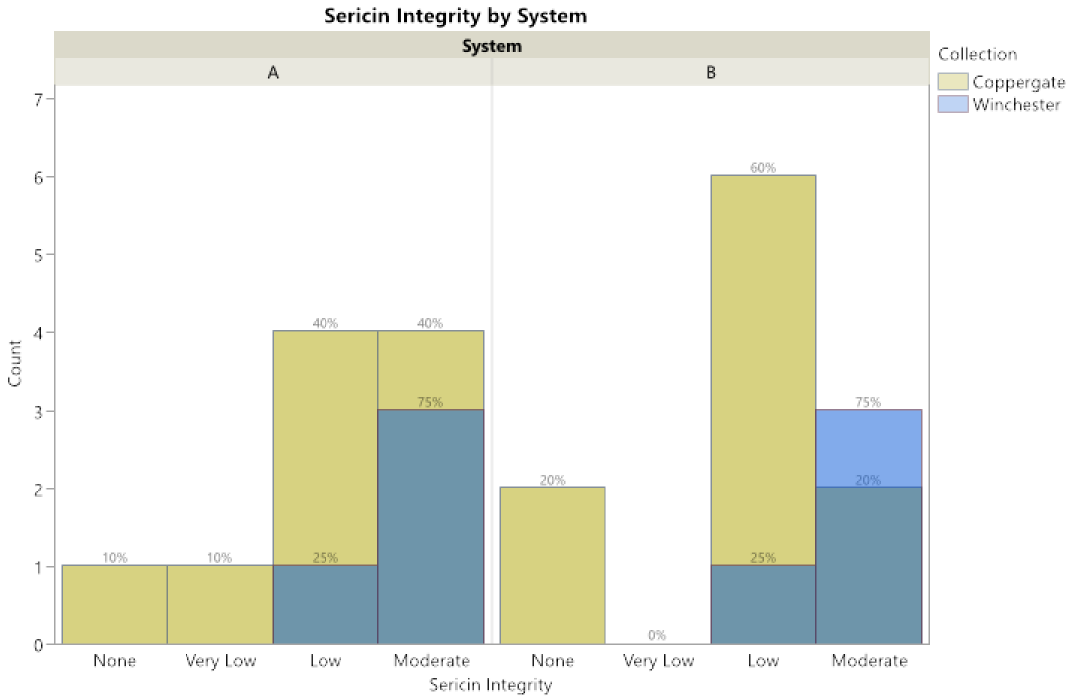


Figure 8.7: Sericin integrity observed in archaeological fibres grouped by thread System within woven structure (confident subset)

Of the archaeological textiles that showed filament cohesion, still only low levels of cohesion were observed. The Winchester textiles showed a higher proportion of samples with low filament cohesion than did the Coppergate textiles (Figure 8.8).

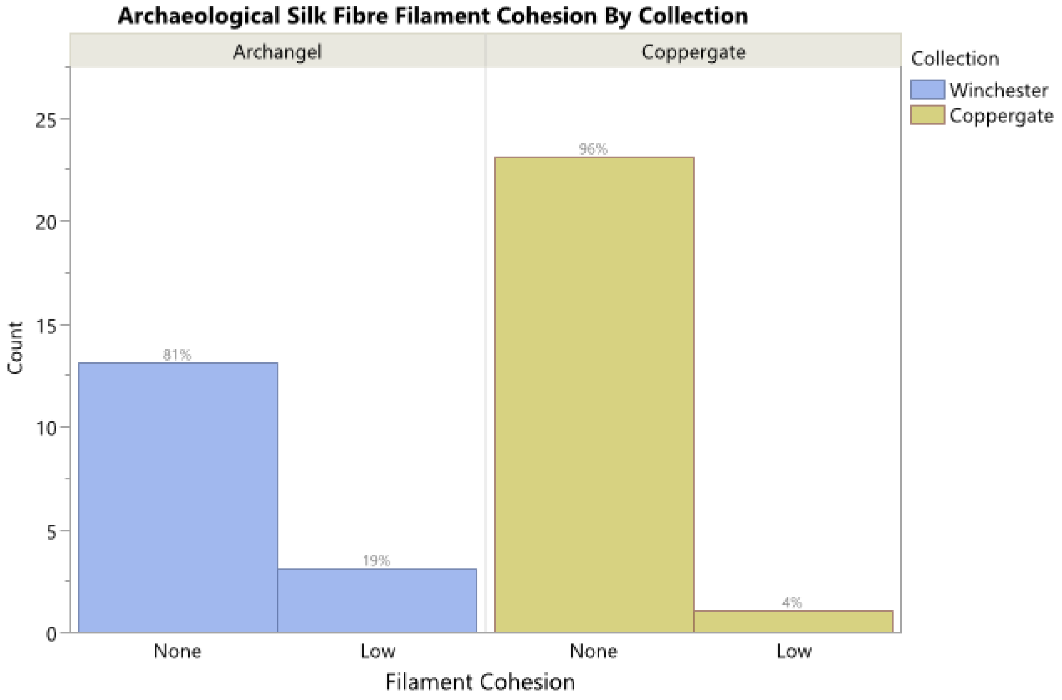


Figure 8.8: Levels of filament cohesion in archaeological textiles by collection

When grouped by thread system (Figure 8.9), it was determined that the Coppergate samples displayed no filament cohesion in system B, while the inverse is true of the confident subset of the Winchester textiles, which showed no filament cohesion in system A. This suggests that the warp yarn of the Coppergate textiles underwent different degumming or reeling processes than the warp yarn of the Winchester textiles, and the same is true of the weft yarns used in each.

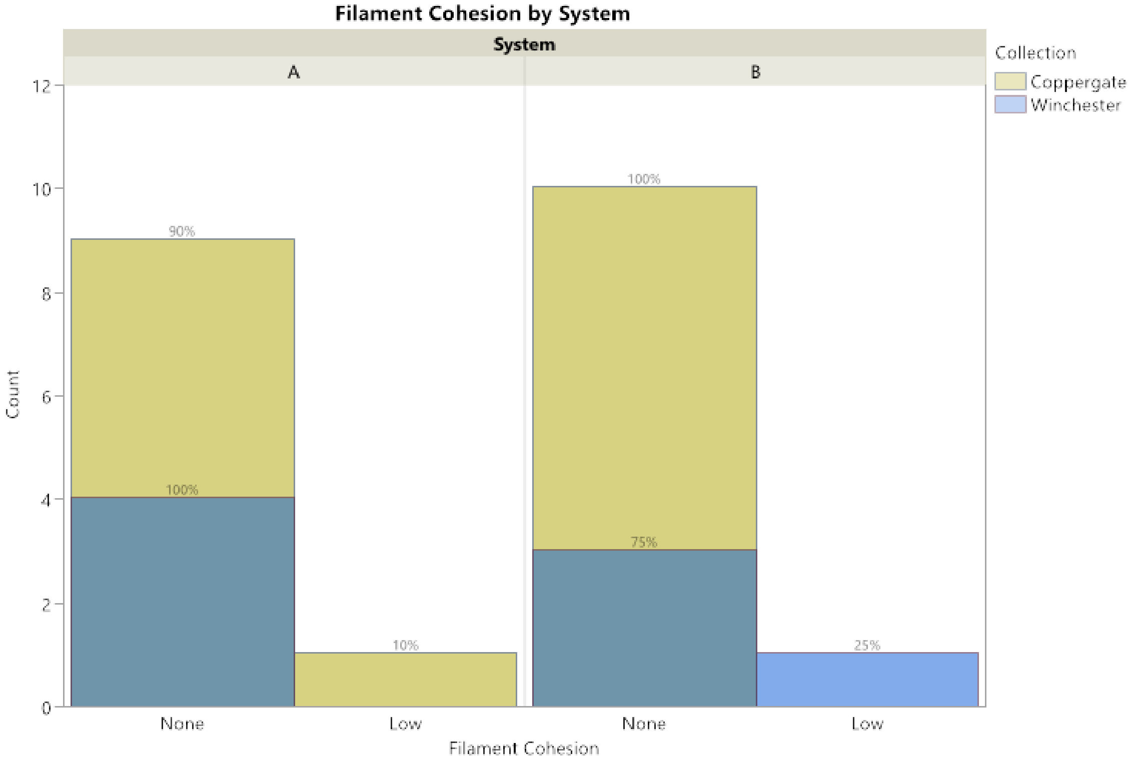


Figure 8.9: Levels of filament cohesion in confident subgrouping of archaeological textiles grouped by thread system

8.3.1.1 Fibre Groups

Groups of fibres-that is more than 2 fibres that appear to be adhered together with sericin-were not present in most of the archaeological textiles, but there were preserved groupings in multiple textiles from each collection (Figure 8.10).

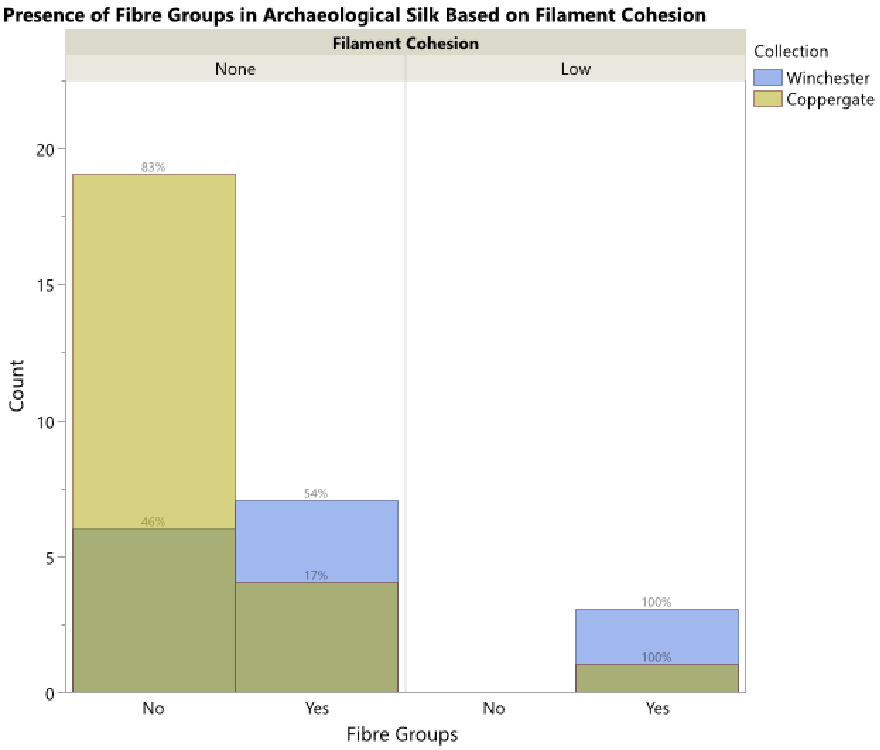


Figure 8.10: Occurrence of fibre groupings in archaeological fibre samples based on filament cohesion by collection

Fibre groupings plotted according to level of sericin integrity (Figure 8.11) also indicated that samples with low to moderate sericin integrity had increased proportions of fibre groupings relative to samples with very low integrity. Relating this to observations of the raw and partially degummed experimental silk (Chapter 7.4.4) this relationship suggests that samples with higher sericin integrity and fibre groupings are more likely to have been left raw or only partially degummed. Of note is the proportion of Winchester silk samples with moderate sericin integrity, as the number of these samples that contain fibre groupings outnumber the samples that do not.

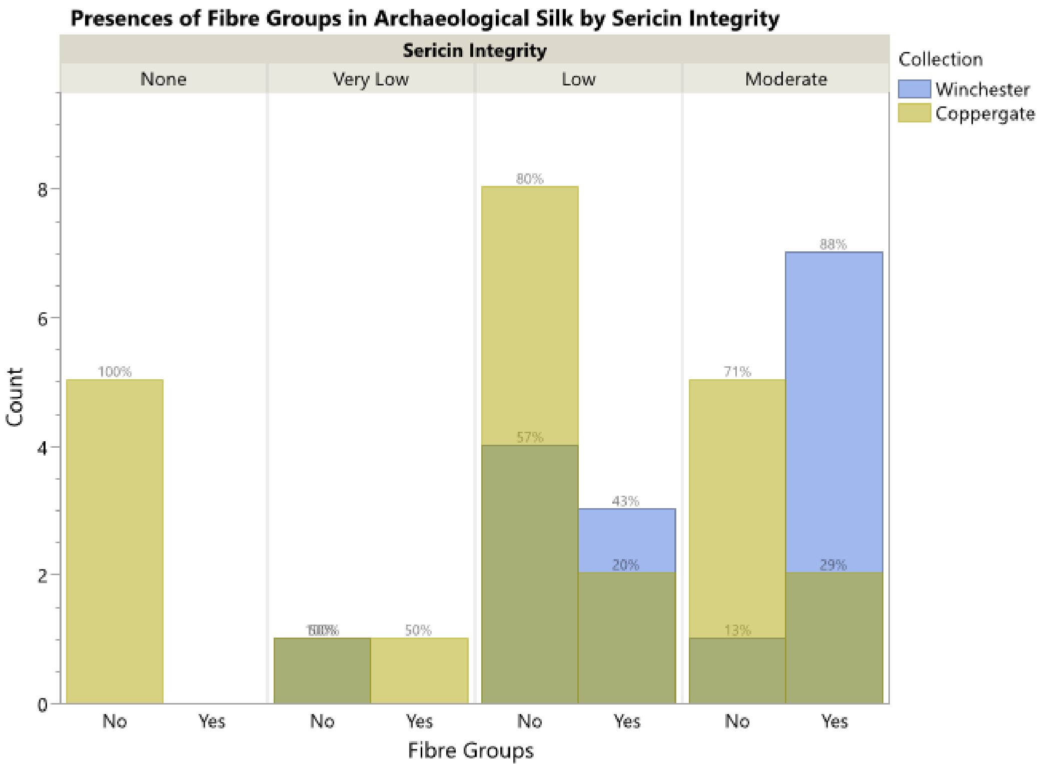


Figure 8.11: Occurrence of fibre groupings in archaeological silk samples according to sericin integrity

8.3.1.2 Identification of Raw and Partially Degummed Silk

Analysis of the experimentally produced silk demonstrated that it is possible to visually distinguish between raw silk and degummed silk. This analysis also determined that raw silk produced using reeling methods that result in low filament cohesion may not be clearly distinguishable from silk that has undergone partial degumming. The experimental silk analysis could not account for the potential for post-depositional deterioration of sericin in archaeological silk textiles.

The different levels of filament cohesion and sericin preservation observed in the silk samples from Coppergate and Winchester indicated that many of the fibre samples likely underwent different degumming processes, and some may not have been degummed at all. To account for possible post-depositional deterioration of sericin, the samples that showed the highest levels of sericin preservation and multiple close groupings of fibres were classified as raw. Samples with less visible surviving sericin but several fibre groupings were classified as partially degummed, and samples with no surviving filament cohesion and little to no visible sericin were classified as degummed. In some cases, classifications were made based on shared characteristics between archaeological fibre samples and specific experimental samples, and the level of deterioration in each sample was taken into consideration. The classifications were also made based on consistency in characteristics across 2 samples, one observed through transmitted light microscopy, the other through Scanning Electron Microscopy.

The textiles woven from yarn with no twist (IxI), Coppergate 1351_IxI, and Winchester CT8 both showed a high degree of sericin preservation relative to the other archaeological textiles and multiple preserved fibre groupings indicative of raw, or at most, lightly degummed silk. This allowed for the comparison of these samples with the experimental samples, an assessment that could not be made for the majority of the other archaeological fibre samples.

Winchester CT8-a shows fibre groupings with moderately close spacing despite overall low filament cohesion (Figure 8.12), similar to Sr_017 (Figure 8.13), which was reeled from 3 cocoons at a time at a water temperature of 80°C with the simple reeling-frame.

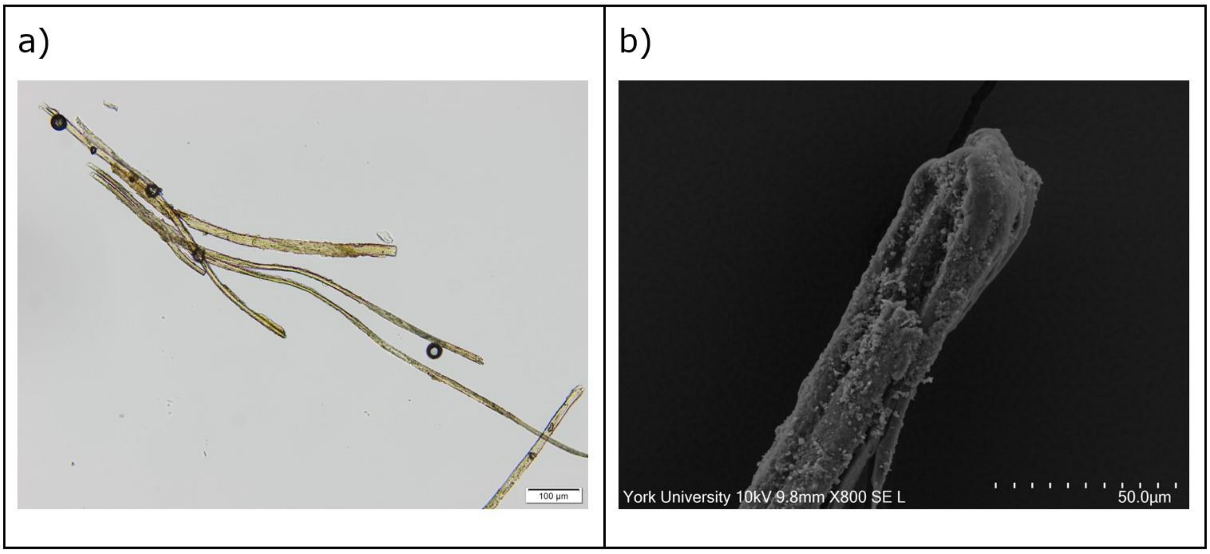


Figure 8.12: Fibres from Winchester CT8-a viewed with transmitted light (a) showing low filament cohesion), and under SEM (b)showing close fibre spacing

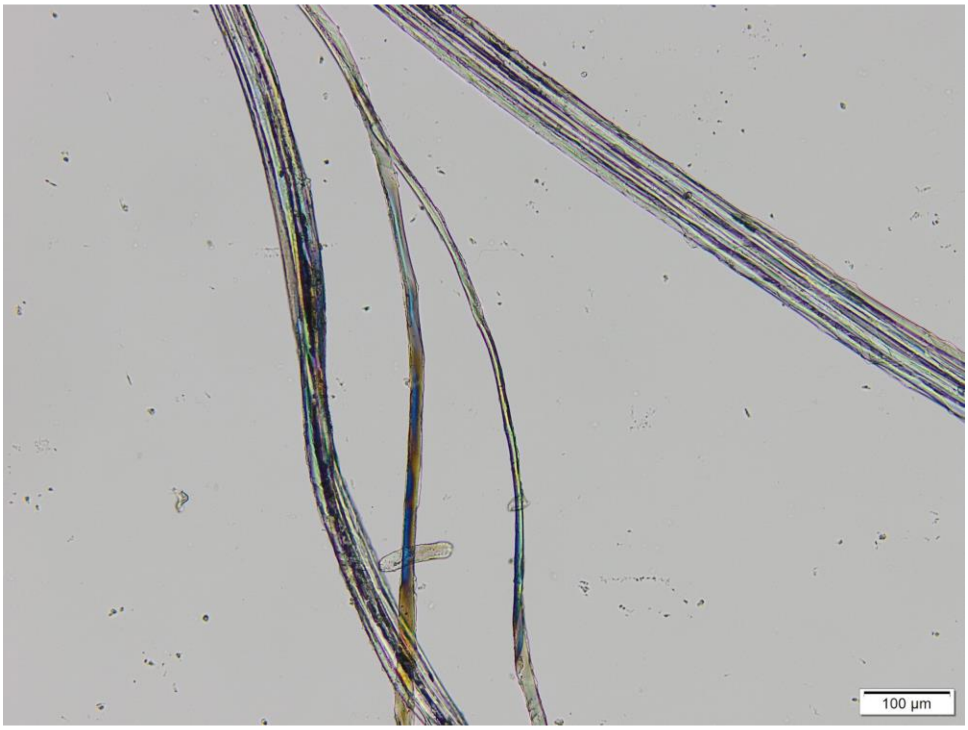


Figure 8.13: Transmitted light micrograph of Sr_017 viewed at 100x magnification with polarising filter showing both low filament cohesion and close fibre spacing

Sr_017 is from the middle of the cocoon/reeling process and is therefore likely to accurately reflect the overall characteristics of the reeled silk, but it is worth noting that Sr_015 and Sr_016 from the same reeling session share similar characteristics. Comparisons could also be made to Tr_026 (Figure 8.14), which was also reeled from 3 cocoons at 80°C but using the treadled reeling-frame, although in this example the fibre spacing appears to skew wider.

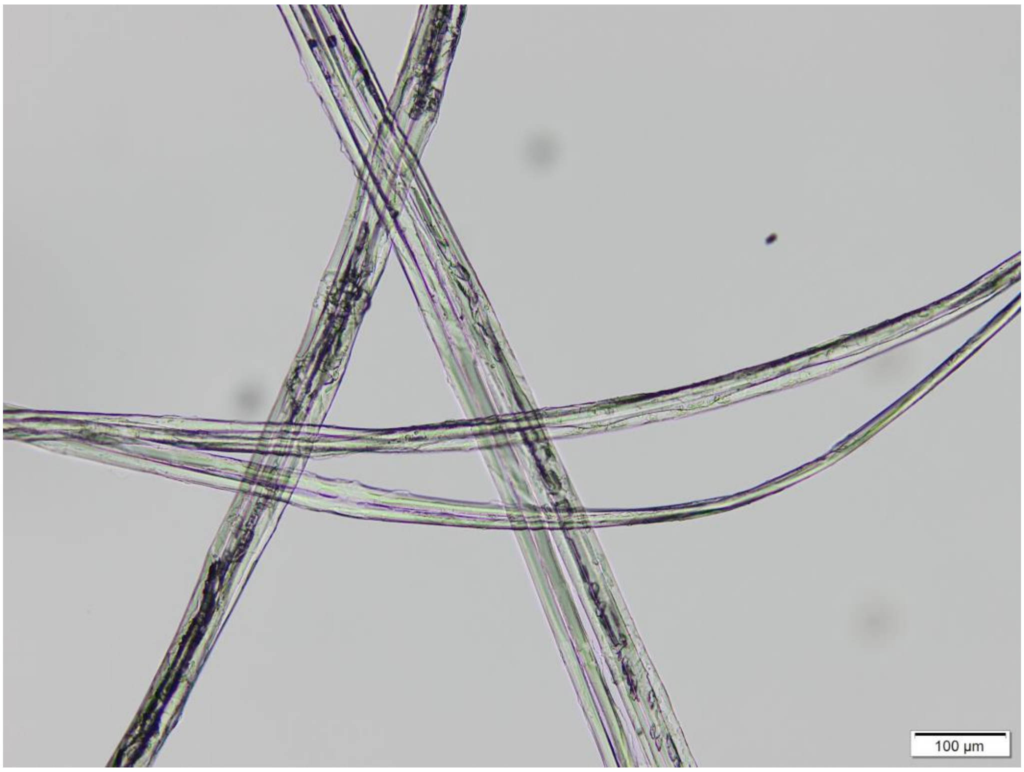


Figure 8.14: Transmitted light micrograph of Tr_026 viewed at 100x magnification showing moderate filament cohesion and wider fibre spacing

Winchester CT8-b shows fibre groupings composed of more fibres with moderate to wide fibre spacing, in the SEM sample (Figure 8.15) and more fibre pairs than groups in the transmitted light micrographs (Figure 8.16), evocative of experimental samples Sr_001-003 (Figure 8.17) that were reeled with the simple reel from 6-8 cocoons, at a lower water temperature than the desired 80°C (max 70°C). Based on these observations, it appears that Winchester CT8 was woven from 2 different qualities of reeled silk, which may have been produced using different approaches.

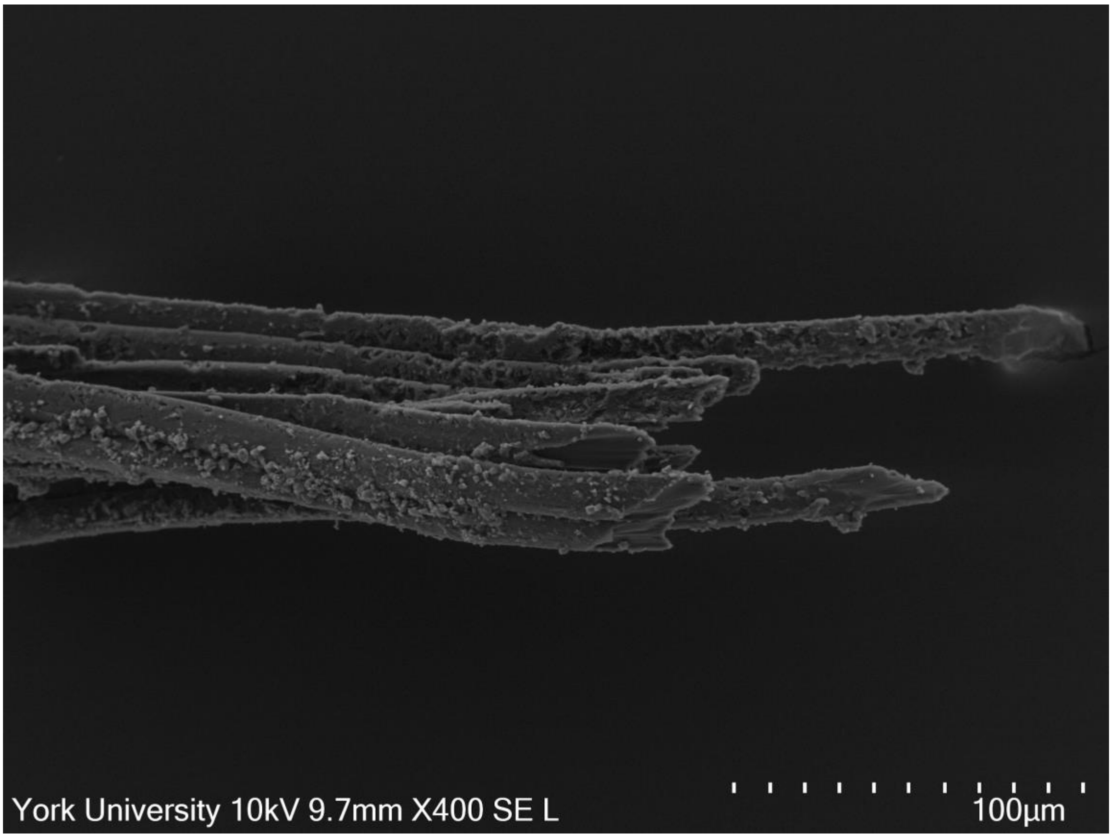


Figure 8.15: Fig. 74: SEM micrograph of Winchester CT8-b showing a fibre group

Figure 8.16: Transmitted light micrograph of Winchester CT8-b viewed at 100x magnification showing paired fibres

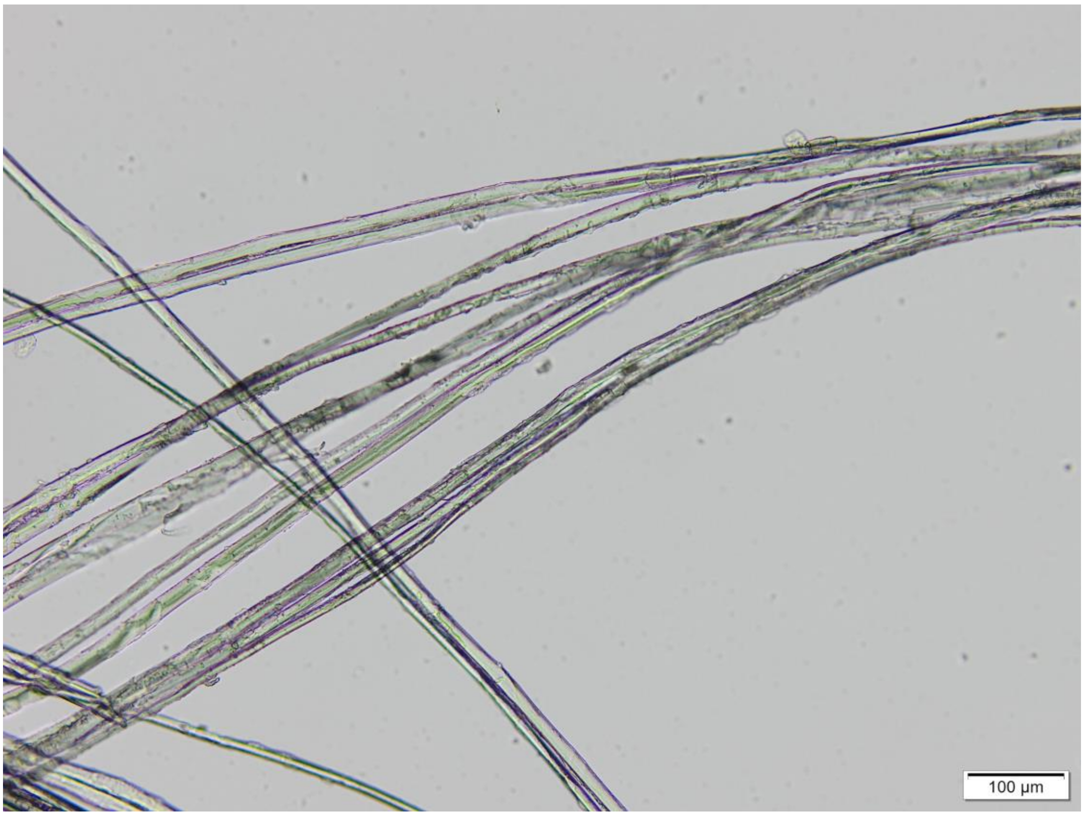


Figure 8.17: Transmitted light micrograph of Sr_003 viewed at 100x magnification showing both dense fibre groups and low filament cohesion

Coppergate 1351-a (Figure 8.18;Figure 8.19), appears to show more sericin preservation than the Winchester samples, or at least displays more sericin spread.

Figure 8.18: Transmitted light micrographs of Coppergate 1351-a viewed at 100x magnification (a) showing multiple fibre groups and 400x (b) magnification showing sericin spread

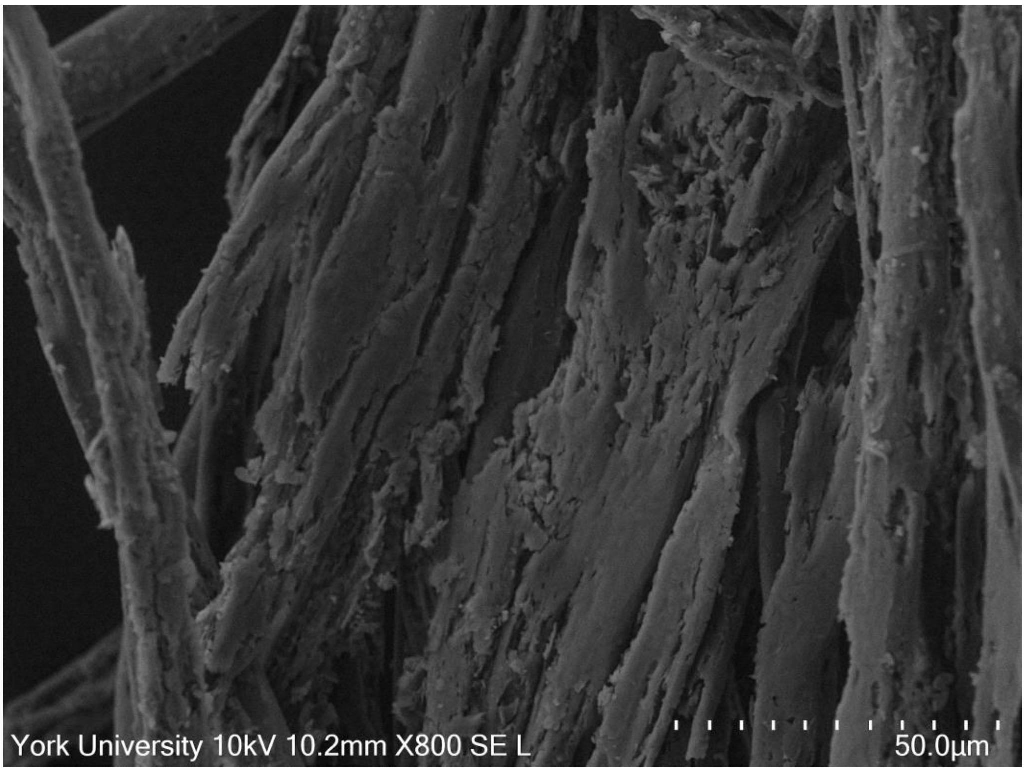


Figure 8.19: SEM micrograph of Coppergate 1351-a showing smeared Sericin

The closest parallel of the experimental samples seems to be Sr_009 (Figure 8.20), which is from the exterior of the cocoon (beginning of the reeling process) and was reeled from 6 cocoons at a target water temperature of 80°C that tended to sit at 82°C in practice. This method also used the simple reeling-frame. The other samples from this experiment, Sr_007 and Sr_008 (Figure 8.21) display similar characteristics but also show an overall higher degree of filament cohesion.

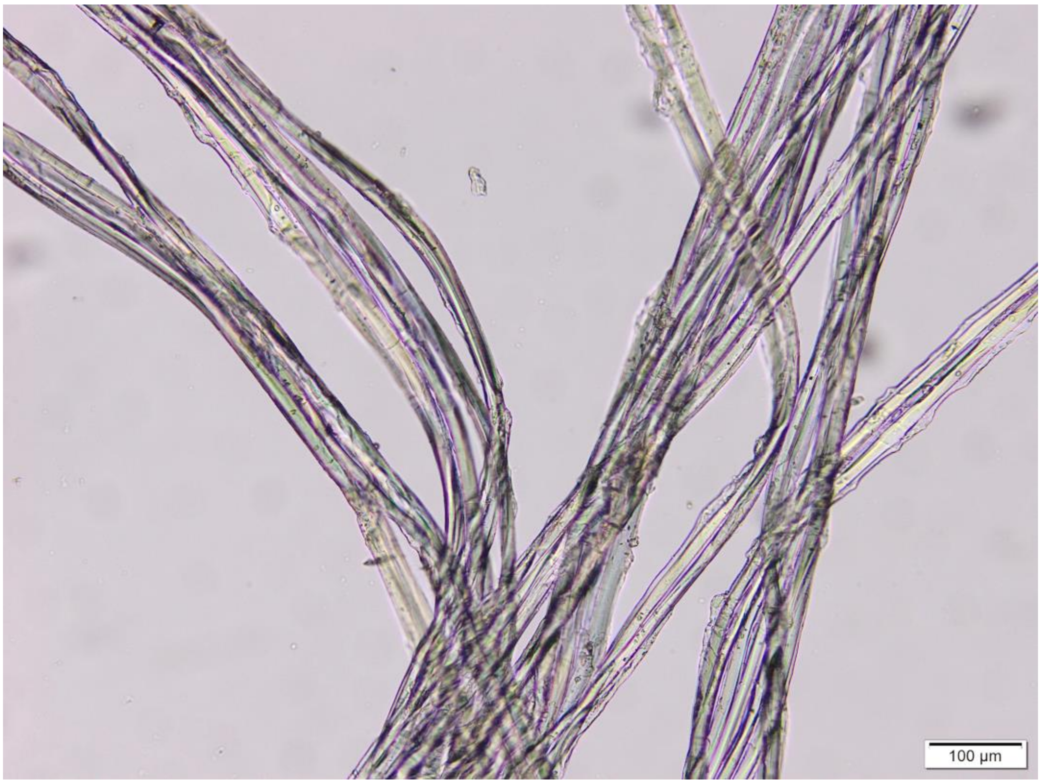


Figure 8.20: Transmitted light micrograph of Sr_009 viewed at 100x magnification showing sericin spread and fibre groupings

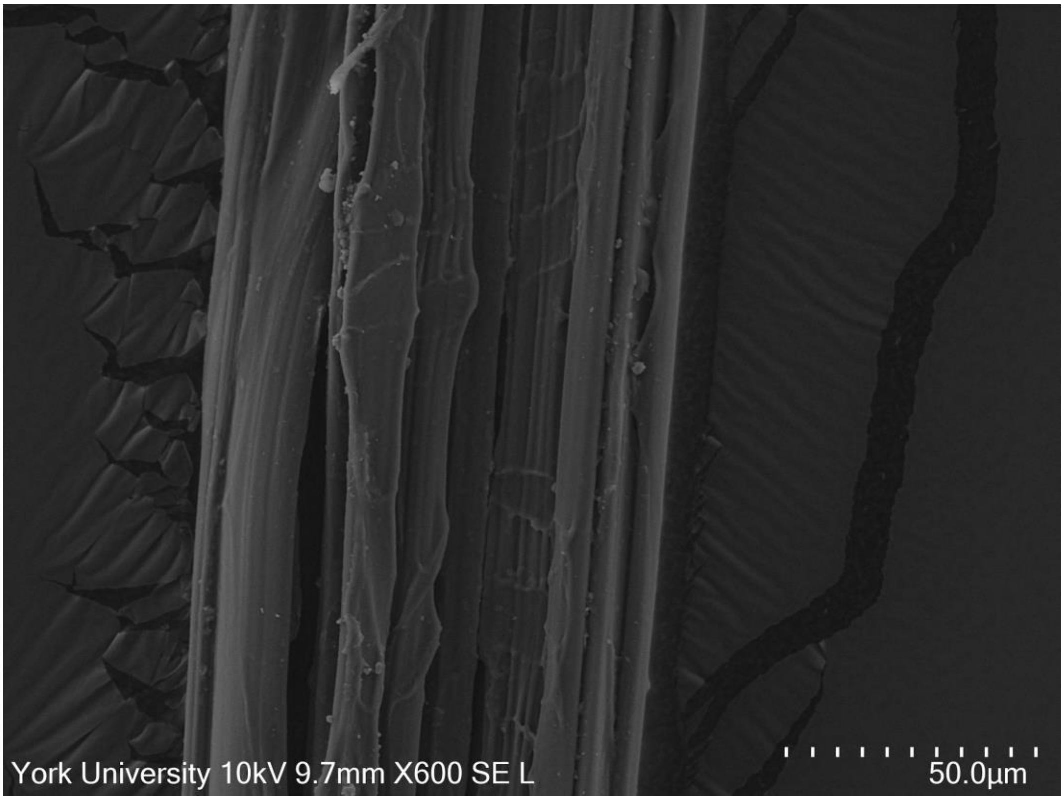


Figure 8.21: SEM micrograph of Sr_008 showing densely grouped fibres and smeared sericin

Coppergate 1351-b (Figure 8.22) appears to show an overall lower degree of filament cohesion than 1351-a, but the fibre groupings preserved are similar in appearance to Winchester CT8-a and by extension, experimental sample Sr_017. Also notable in this sample is the high degree of yarn cohesion in the SEM sample, which gives the impression of numerous fine, raw filaments having been combined without twist to form a thicker yarn (Figure 8.23).

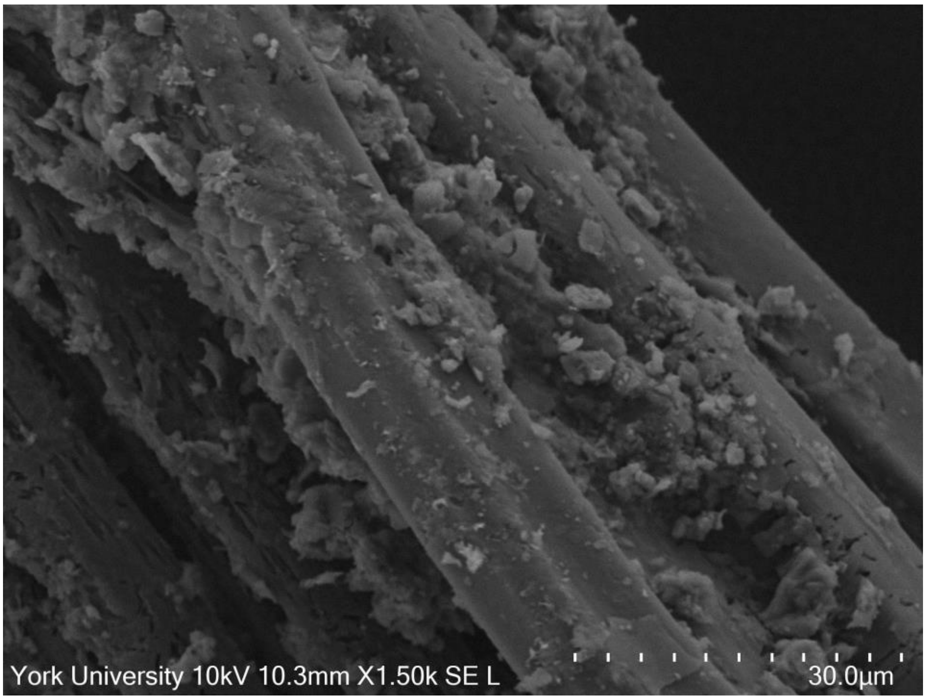


Figure 8.22: SEM micrograph of Coppergate 1351-b showing a detail of grouped fibres

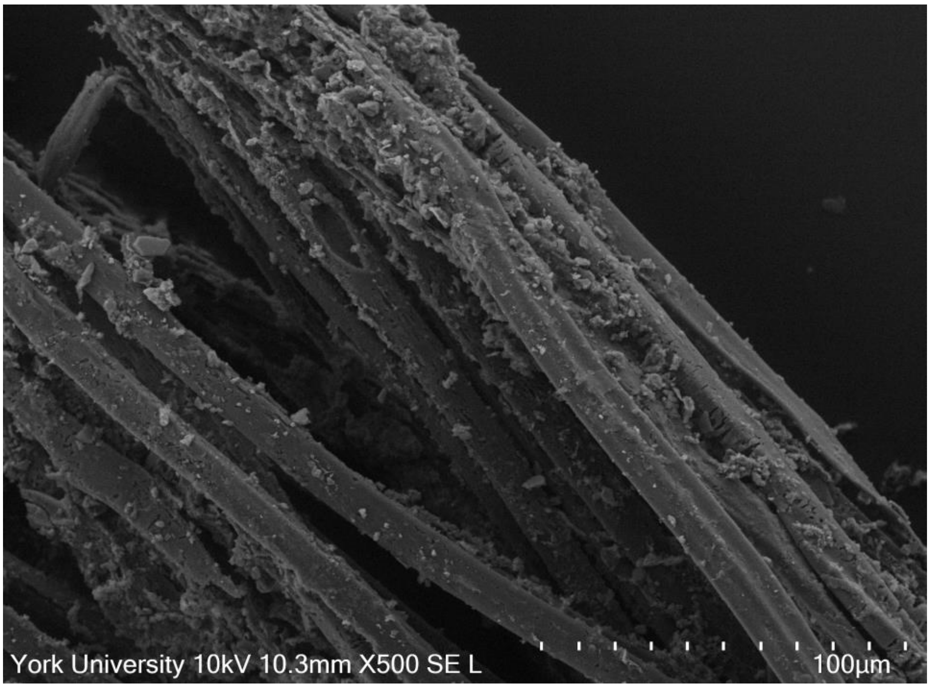


Figure 8.23: SEM micrograph of Coppergate 1351-b showing fibre groups and paired fibres within the fragment of yarn.

The remaining textiles from Coppergate were classified as degummed, except for 1351-c & 1351-d (ZxZ), which were determined to be partially degummed.

The Winchester textiles showed more instances of raw and partially degummed textiles as CT32-a, CT32-b, and CT38-b were classified as raw, while CT22-b, CT23-b, and CT38-a were classified as partially degummed.

These identifications reflect the variation observed in the samples but could be modified to a more nuanced identification of processes following further experimentation or comparison with a larger body of surviving silk textiles. For this reason, IxI textiles were classified as raw in both systems despite variation in filament cohesion and fibre preservation, because they were also overall more rigid in texture and appearance and showed a higher level of yarn cohesion than other textiles that showed similar levels of filament cohesion and sericin preservation.

8.3.2 Other residues

Some fibre samples appear to have been coated in a residue other than sericin, possibly a form of sizing (a coating typically applied to either protect or stiffen yarn or finished cloth) used to treat the threads. Winchester CT38-a included several fibres that appear to intersect at a 90° angle to most of the fibres (Figure 8.24). The sample viewed under transmitted light microscopy included a small bundle of these fibres that appear to be coated in a residue with a deep amber colour (Figure 8.25).

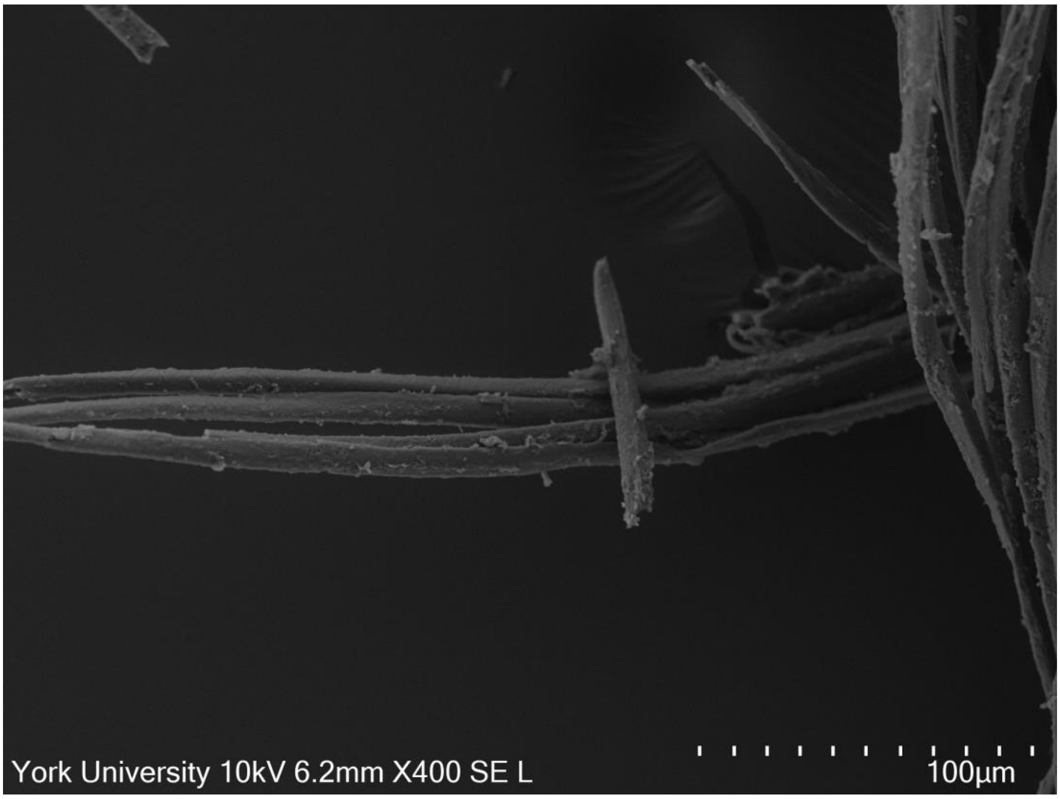


Figure 8.24: SEM micrograph of Winchester CT38-a showing fibre adhered at perpendicular angle to fibre group

Figure 8.25: Transmitted light micrograph of Winchester CT38-a showing fibre groupings in heavy residue

These characteristics could indicate that the perpendicular fibres come from system B of CT38, but had adhered to the fibres extracted from system A. This is more suggestive of an added residue than it is of sericin, but chemical analysis would be necessary to confirm this. CT38-b also included bundles of fibres at perpendicular orientations (Figure 8.26) further supporting the likelihood that a non-sericin residue has caused adhesion between fibres from the 2 different systems.

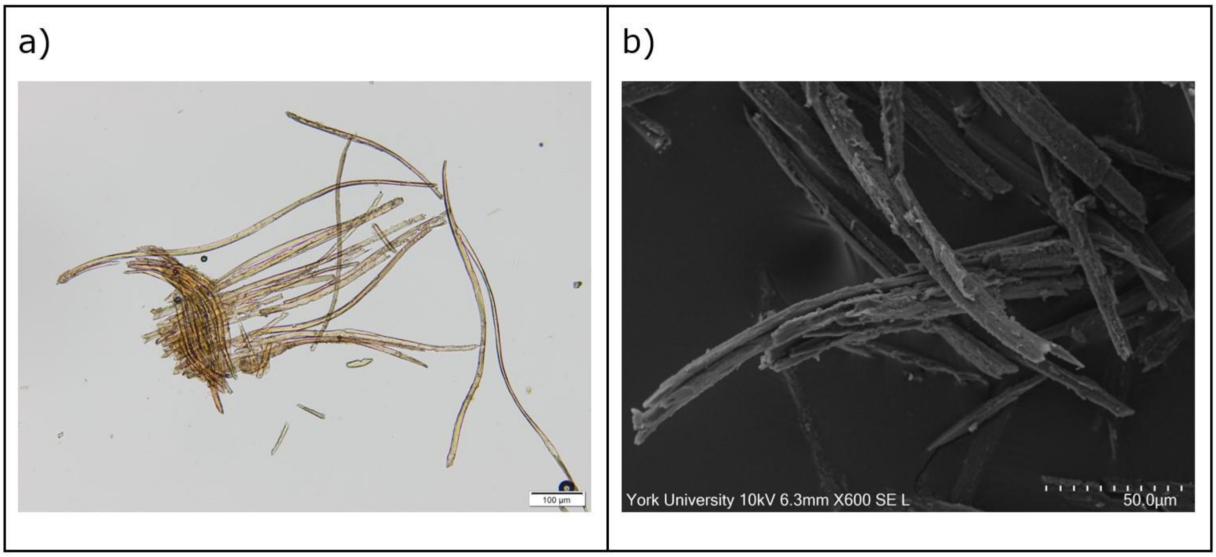


Figure 8.26: Transmitted light micrograph (a) and SEM micrograph (b) of Winchester CT38-b showing perpendicular intersecting fibres

The possibility of an intentional sizing or other coating being preserved in this textile is intriguing and raises questions that merit further exploration of medieval silk yarn treatments both before and after the weaving stage.

8.3.3 Fibre Damage

Fibre damage in the archaeological silk samples ranged from moderate to very high, with overall higher levels of fibre damage observed in the Winchester fibre samples (Figure 8.27).

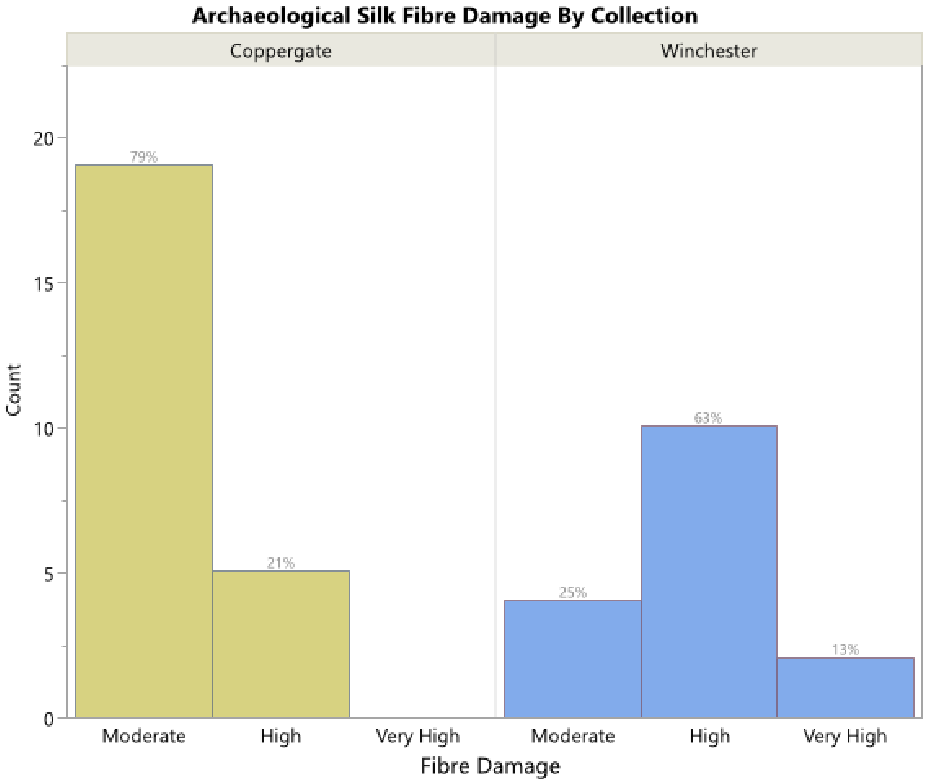


Figure 8.27: Levels of fibre damage observed in the archaeological silk fibres by collection

When plotted by thread system (Figure 8.28) the samples from each collection did not show a meaningful pattern of distribution.

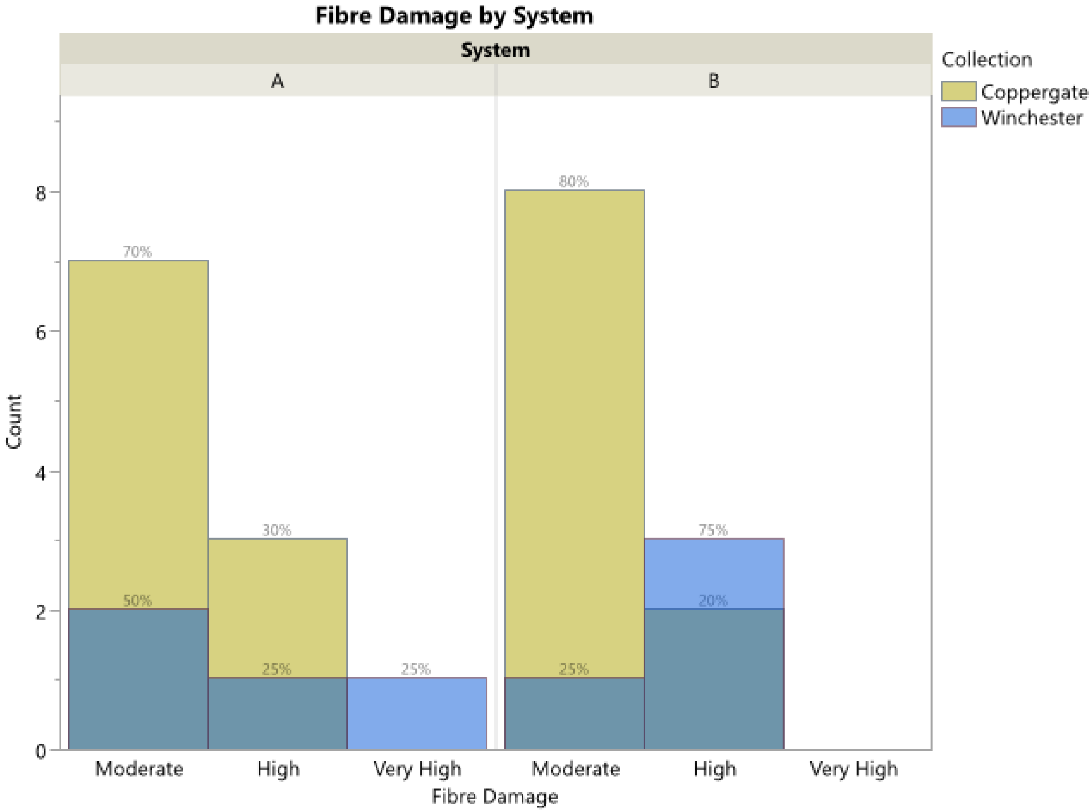
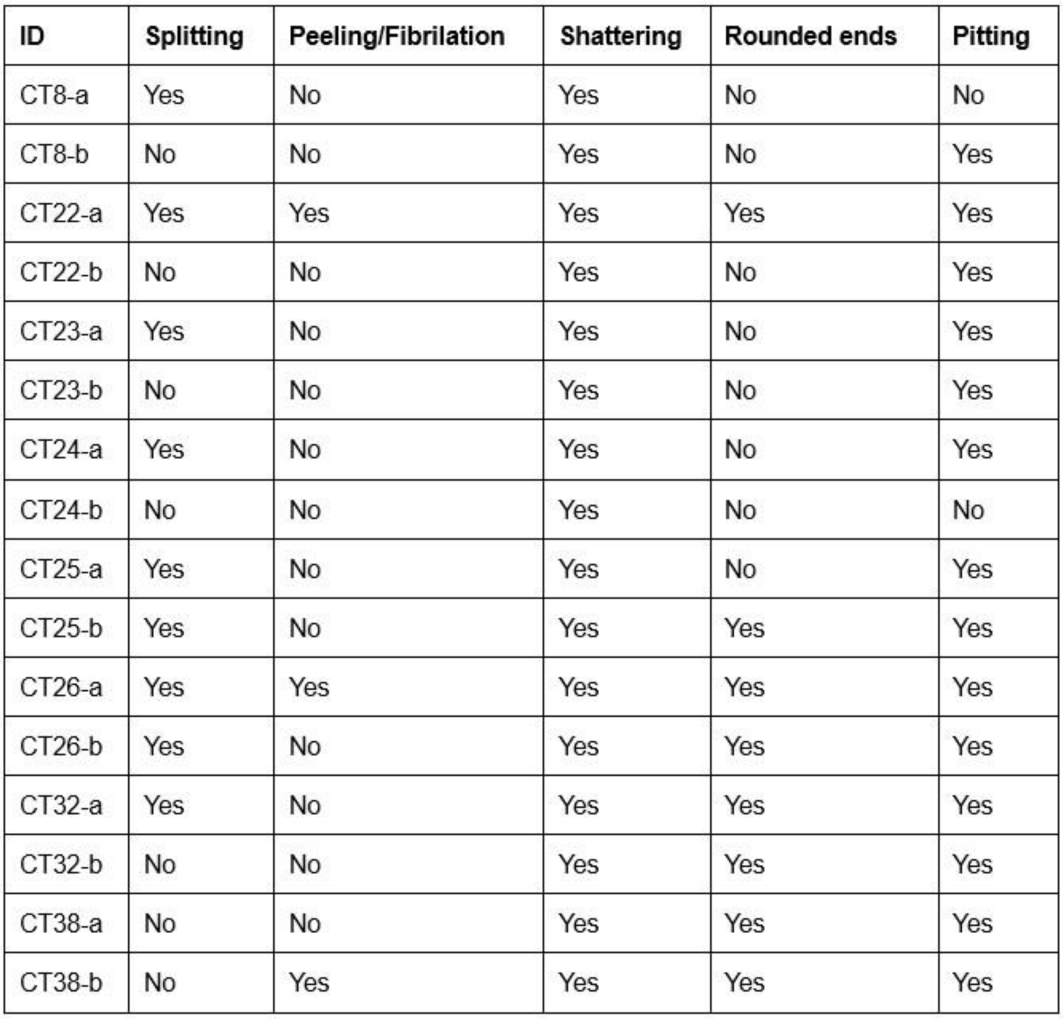


Figure 8.28: Levels of fibre damage observed in the archaeological silk fibres by thread system

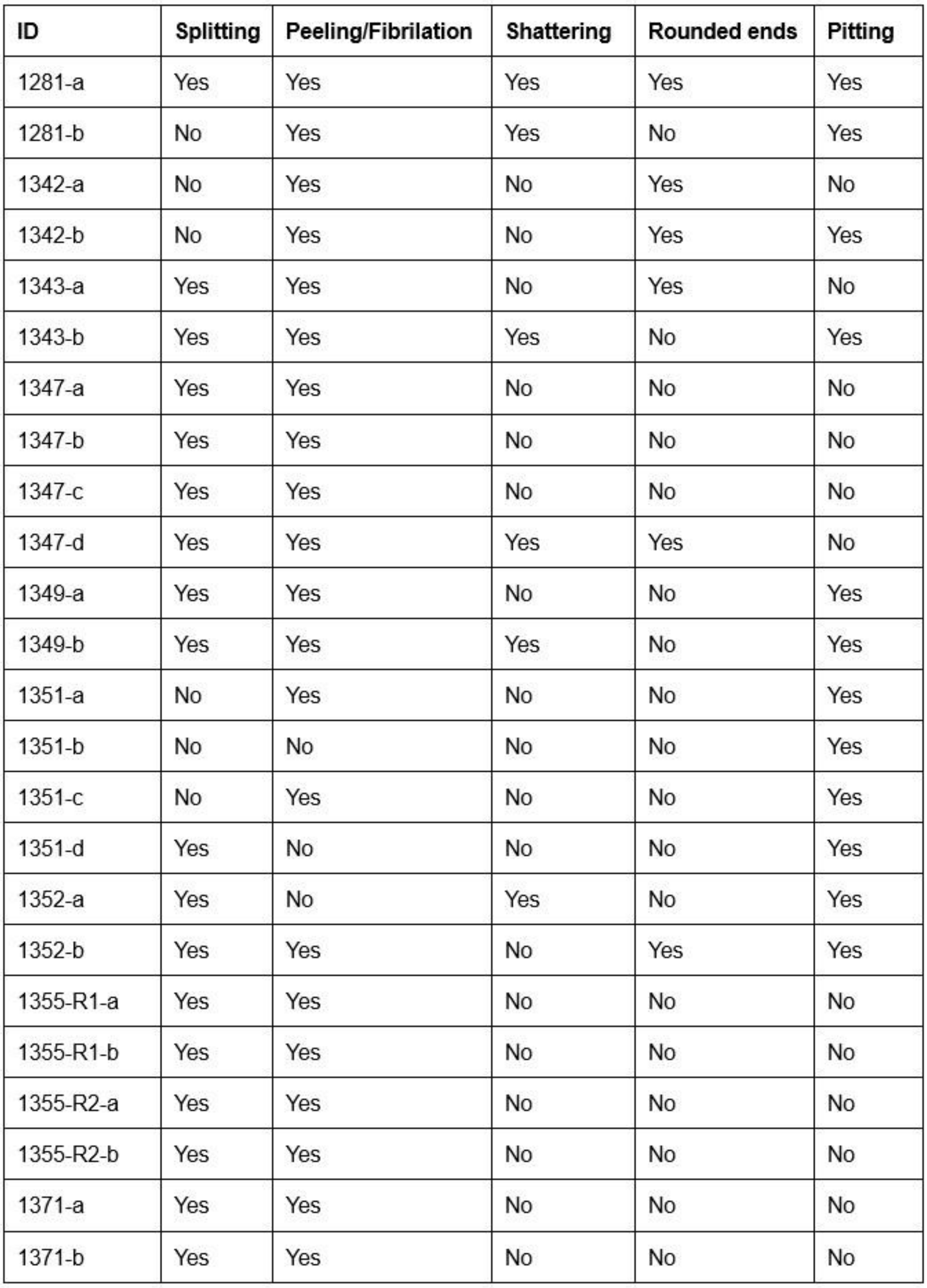
8.3.3.1 Different types of Fibre Damage

Multiple types of damage were observed across the different archaeological fibres (Table 8.1, Table 8.2).



ID	Splitting	Peeling/Fibrilation	Shattering	Rounded ends	Pitting
CT8-a	Yes	No	Yes	No	No
CT8-b	No	No	Yes	No	Yes
CT22-a	Yes	Yes	Yes	Yes	Yes
CT22-b	No	No	Yes	No	Yes
CT23-a	Yes	No	Yes	No	Yes
CT23-b	No	No	Yes	No	Yes
CT24-a	Yes	No	Yes	No	Yes
CT24-b	No	No	Yes	No	No
CT25-a	Yes	No	Yes	No	Yes
CT25-b	Yes	No	Yes	Yes	Yes
CT26-a	Yes	Yes	Yes	Yes	Yes
CT26-b	Yes	No	Yes	Yes	Yes
CT32-a	Yes	No	Yes	Yes	Yes
CT32-b	No	No	Yes	Yes	Yes
CT38-a	No	No	Yes	Yes	Yes
CT38-b	No	Yes	Yes	Yes	Yes

Table 8.1: Types of fibre damage observed in Winchester textiles



ID	Splitting	Peeling/Fibrilation	Shattering	Rounded ends	Pitting
1281-a	Yes	Yes	Yes	Yes	Yes
1281-b	No	Yes	Yes	No	Yes
1342-a	No	Yes	No	Yes	No
1342-b	No	Yes	No	Yes	Yes
1343-a	Yes	Yes	No	Yes	No
1343-b	Yes	Yes	Yes	No	Yes
1347-a	Yes	Yes	No	No	No
1347-b	Yes	Yes	No	No	No
1347-c	Yes	Yes	No	No	No
1347-d	Yes	Yes	Yes	Yes	No
1349-a	Yes	Yes	No	No	Yes
1349-b	Yes	Yes	Yes	No	Yes
1351-a	No	Yes	No	No	Yes
1351-b	No	No	No	No	Yes
1351-c	No	Yes	No	No	Yes
1351-d	Yes	No	No	No	Yes
1352-a	Yes	No	Yes	No	Yes
1352-b	Yes	Yes	No	Yes	Yes
1355-R1-a	Yes	Yes	No	No	No
1355-R1-b	Yes	Yes	No	No	No
1355-R2-a	Yes	Yes	No	No	No
1355-R2-b	Yes	Yes	No	No	No
1371-a	Yes	Yes	No	No	No
1371-b	Yes	Yes	No	No	No

Table 8.2: Types of fibre damage observed in Coppergate textiles

The appearance of damage can be indicative of how it was acquired. Mechanical or wear damage ranges from splitting(Figure 8.29) to fibrillation or peeling (Figure 8.30), both of which can be associated with tensile strain (Hearle, Lomas and Cooke 1998, 18). Brittle fracture or shattering (Figure 8.31) can be a result of tensile failure, but can also result from environmental damage such as photodegradation (Hearle, Lomas and Cooke 1998, 391). Pitting forming in distinct patterns (Figure 8.32) has also been observed, but it is unclear whether this is evidence of microbial attack or other environmental damage as it most closely matches images of “unspecified damage” from the *Atlas of Fibre Fracture and Damage to Textiles* (Hearle, Lomas and Cooke 1998, 381). Finally, larger, circular “bites” in certain samples (Figure 8.33) that may be evidence of pest activity.

Figure 8.29: Transmitted light micrograph of Coppergate 1349-a viewed at 400x magnification showing a split fibre

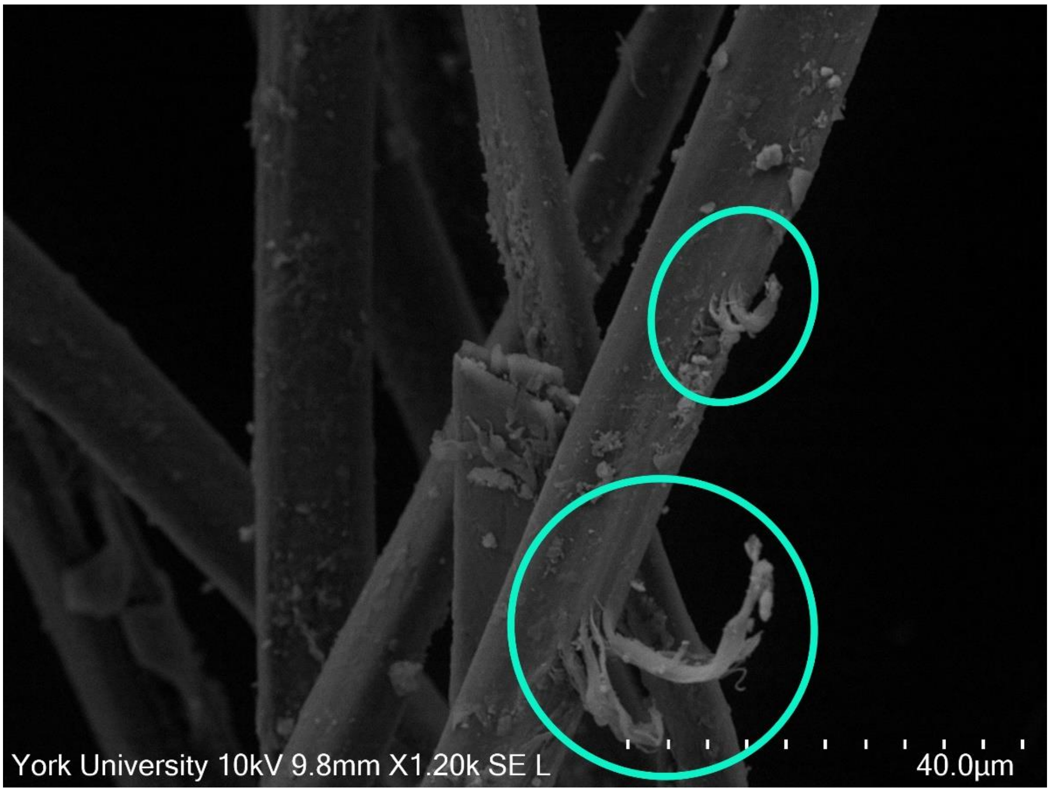


Figure 8.30: SEM micrograph of Coppergate 1342-b showing fibrillation

Figure 8.31: Transmitted light micrograph of Coppergate 1281-a viewed at 400x magnification showing a shattered fibre segment

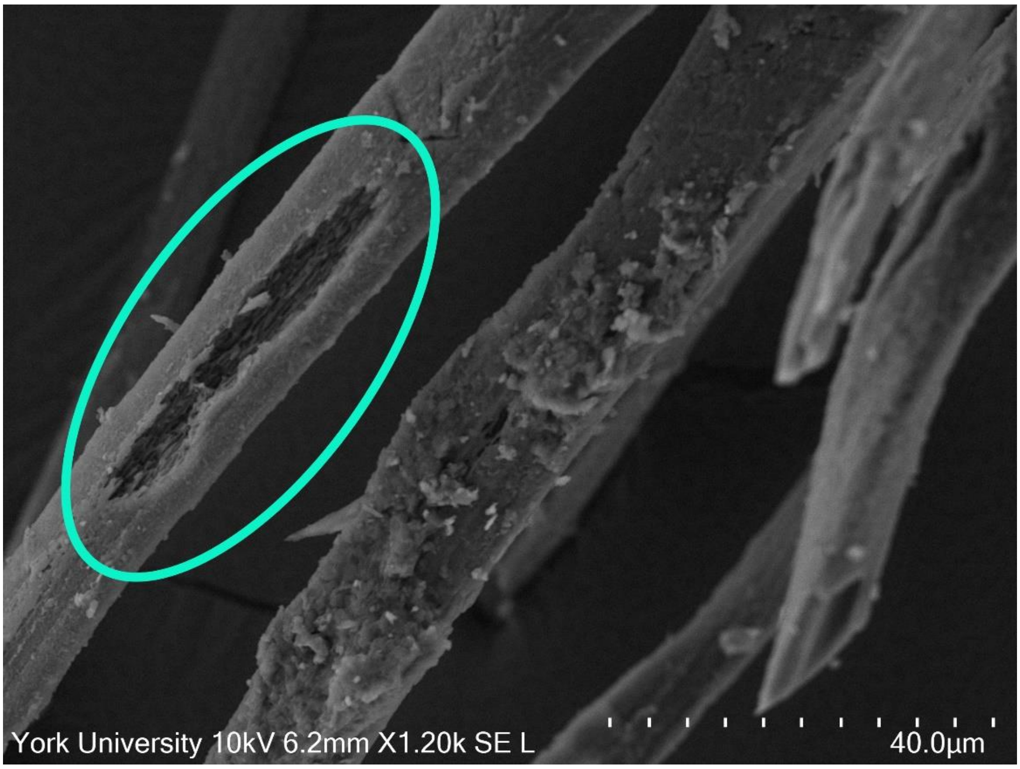


Figure 8.32: SEM micrograph of CT23-a showing pitting

Figure 8.33: Transmitted light micrograph of fibre from CT24-b viewed at 400x magnification showing a circular "bite" mark

8.3.4 Potential non-Bombyx mori inclusions

A select number of the samples analysed appeared to include fibres with distinct features from bombyx mori silk. Samples CT25-a, 1347-b&c and 1355-R2-b contained fibres with an elongated cross-sectional shape, larger diameter measurement (c. 15-28µm) and striations along the fibre length. These characteristics are more indicative of a wild silk variety such as the genus *Antheraea* (also called *Tussah* or *Tasar*) than *Bombyx mori*

(Figure 8.34;Figure 8.35).

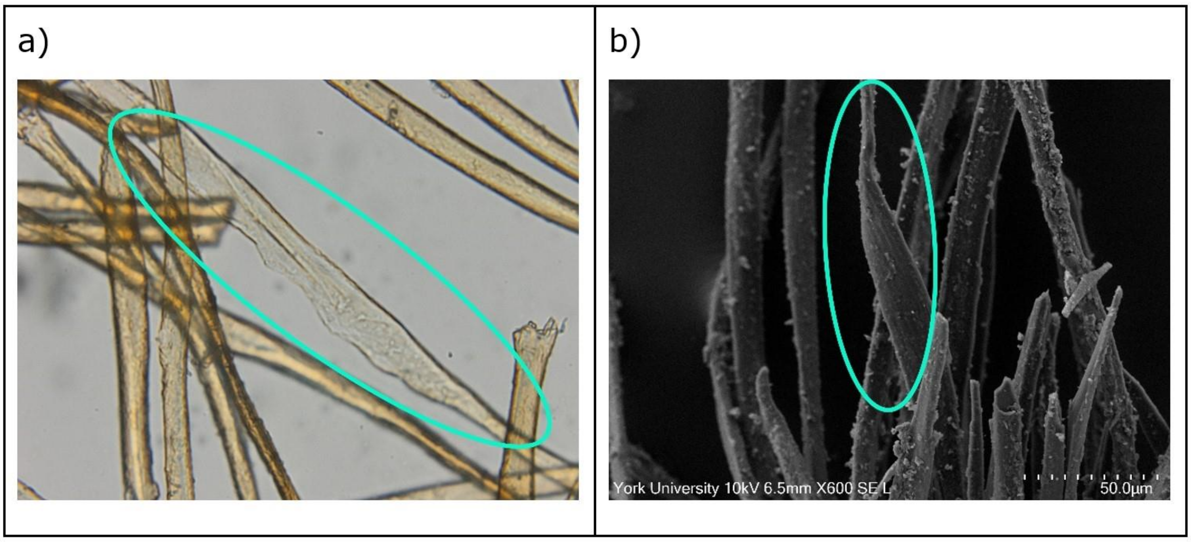


Figure 8.34: Transmitted light micrograph viewed at 400x magnification (a) and SEM micrograph (b) of Winchester CT25-a an irregularly shaped apparently silk fibre (a) and an unusually wide flat fibre (b)

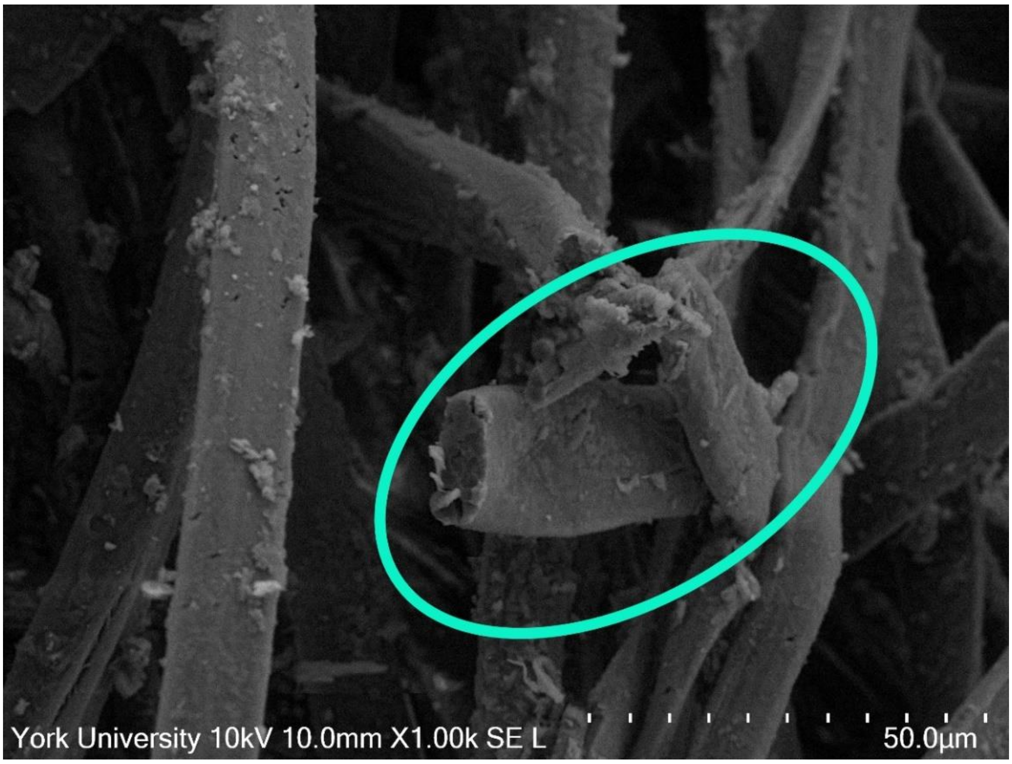


Figure 8.35: SEM micrograph of Coppergate 1352-b showing a flat fibre with elliptical cross-section

A small number of textiles also exhibited odd, cross-hatched markings on the surface of the fibres (Figure 8.36). Further cross comparison to a broader reference collection is necessary to determine if these markings are a form of mechanical damage (Hearle, Lomas and Cooke 1998, 18), or if they indicate a different fibre type.

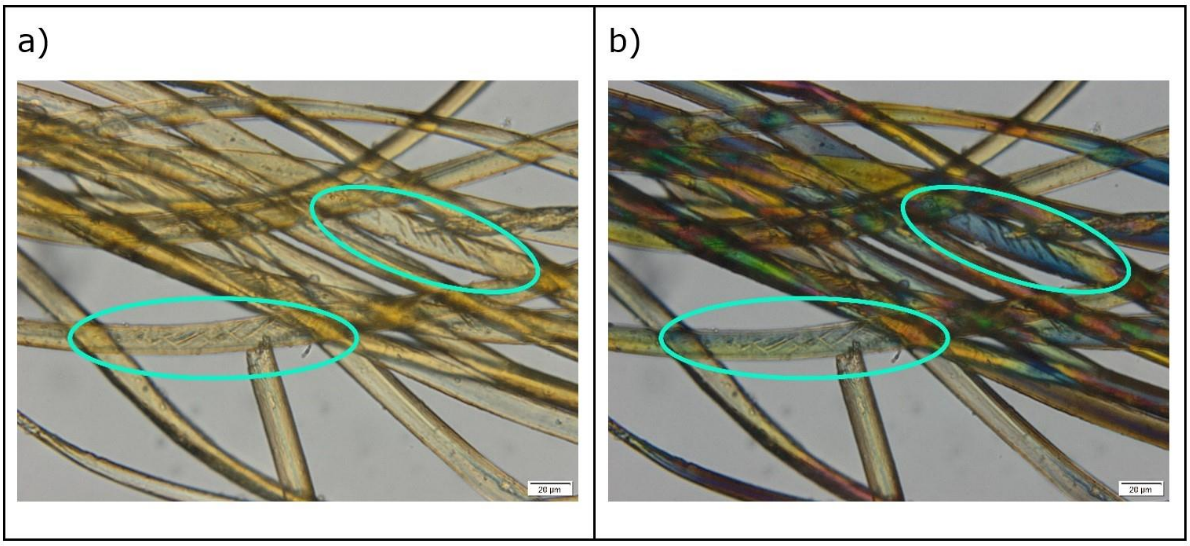


Figure 8.36: Crosshatch markings on fibres in sample from CT26-b, brightfield (a) and polarised (b) transmitted light micrographs of sample viewed at 400x magnification

Coppergate 1343-b includes some possible bast fibres, based on the vertical striations and crooked joints (Figure 8.37). It should be noted that this sample did include other plant material (Figure 8.38), so it is possible that these fibres are environmental inclusions rather than evidence of a mixed-fibre yarn.

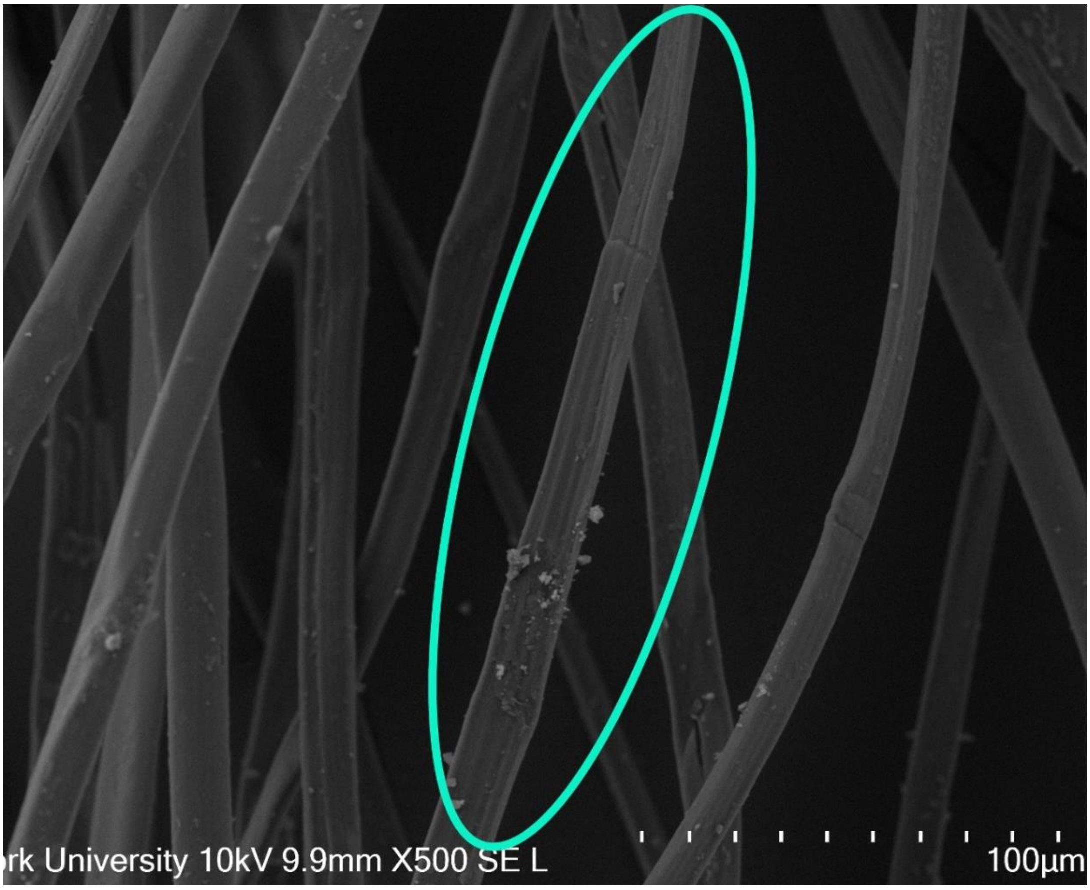


Figure 8.37: SEM micrographs showing possible bast fibres in Coppergate sample 1343-b

Figure 8.38: Plant material from Coppergate sample 1343-b

One final inclusion of interest is a flat fibre or filament coiled around some other fibres in Coppergate 1352-a (Figure 8.39) reminiscent of metal-wrapped thread. The hypothesis that this is a fragment of decorative metal-wrapped thread appeared to be further supported by a flat rectangular, opaque inclusion in the sample of 1352-a analysed with transmitted light (Figure 8.40).

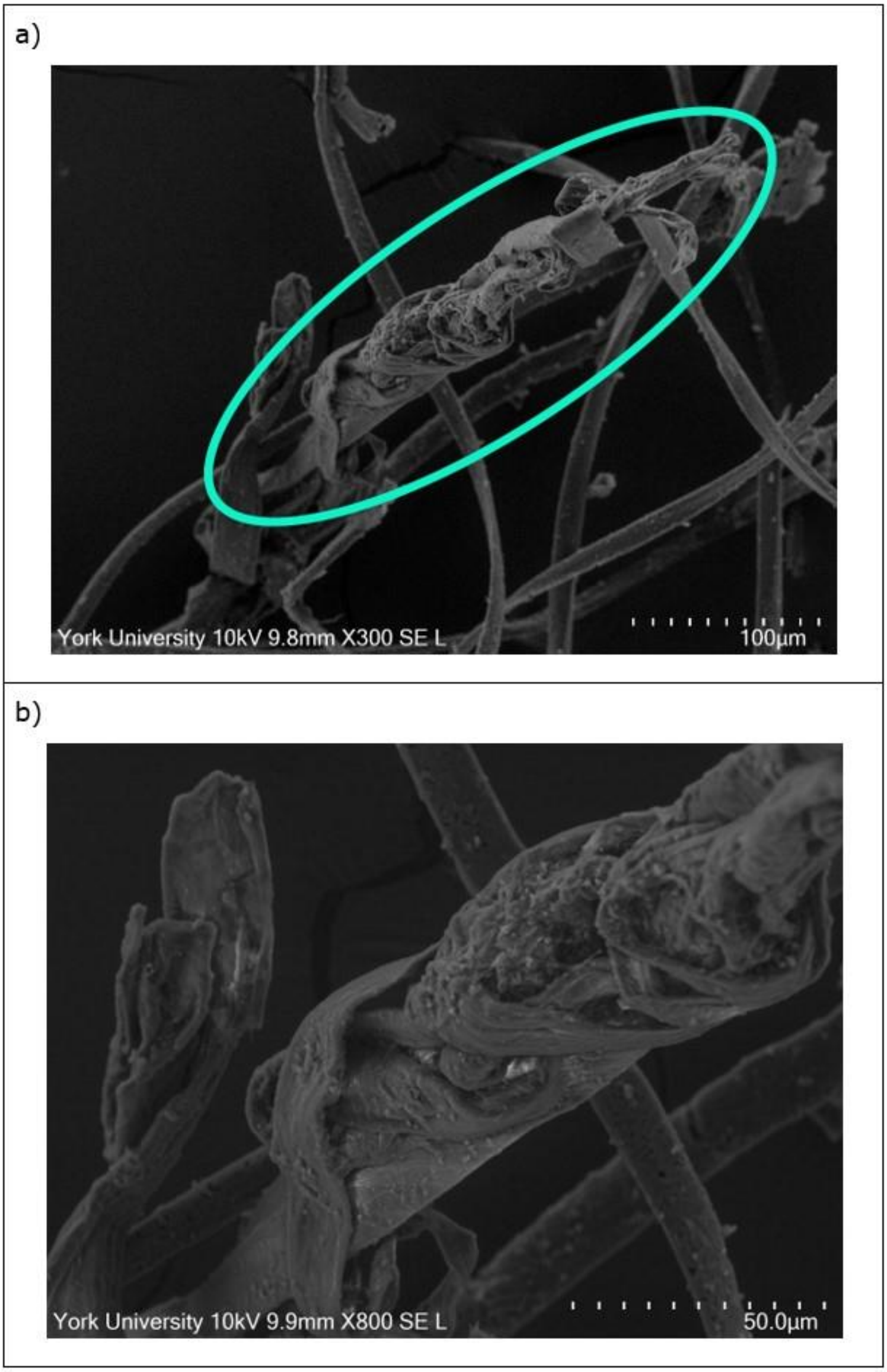


Figure 8.39: SEM micrographs of coiled flat element wrapped around fibres in Coppergate 1352-a

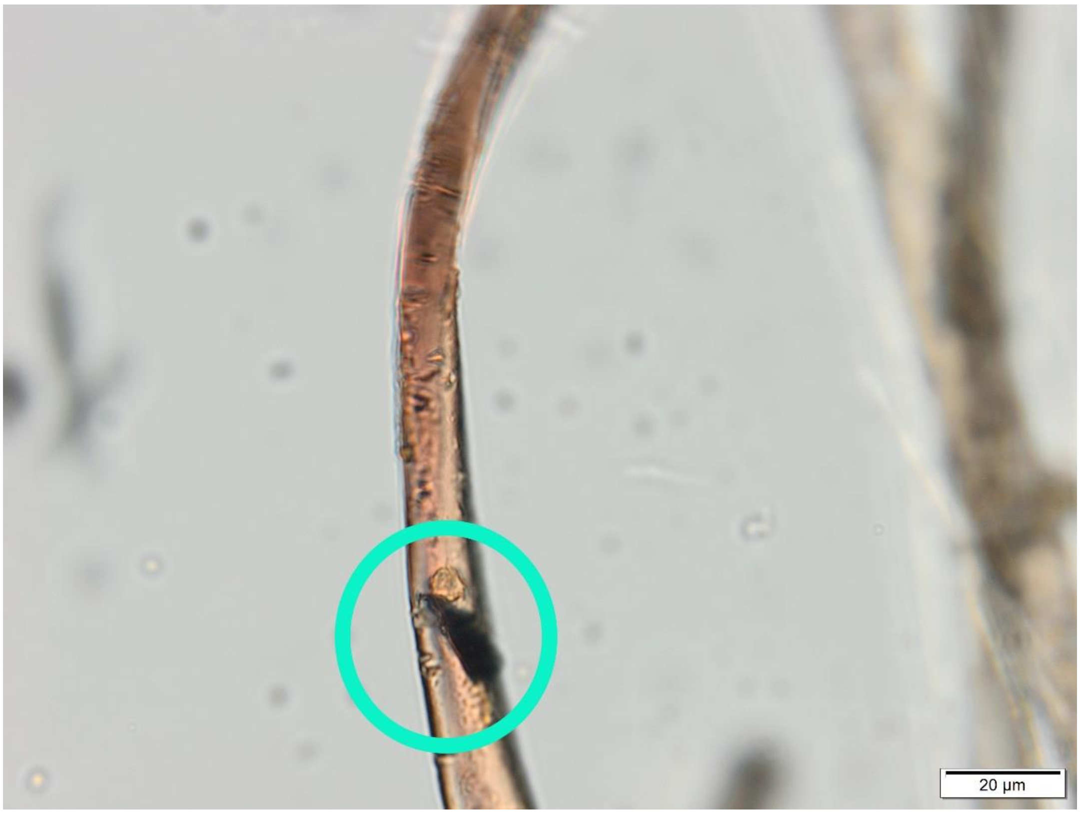


Figure 8.40: possible metal opaque inclusion in sample from Coppergate textile 1352-a viewed at 600x magnification

However, upon comparing the scale of the inclusion pictured in Figure 8.39 to measurements of other medieval and renaissance metal-wrapped threads it was concluded that the inclusion in Coppergate textile 1352 was too small to support this identification (Karatzani, Rehren and Zhiyong 2009, 102; Karatzani and Rehren 2006, 444–12; Vornicu, Bibire and Zaltariov 2021, 417). It is therefore uncertain what this inclusion is and this will merit further attention in future research.

One other possible fragment of metal-wrapped thread, which comprised primarily of a core was observed via stereomicroscope during the analysis of Coppergate 1355-R2 (Figure 8.41). This piece was intentionally left in situ, and no other traces were observed in the fibre samples extracted from this textile. Since chemical analysis was not part of this study, it could not be determined if the inclusion in question is a solid metal strip or a membrane composed of another material, possibly coated with metal leaf.

Figure 8.41: Reflected light micrograph of Coppergate Textile 1355-R2 showing possible core of metal-wrapped thread, viewed at 20x magnification

The above inclusions do not appear to be modern contaminants as they also exhibit signs of ageing and were well integrated within the samples in question. Although these fibres are scarce relative to the majority of *Bombyx mori* fibres observed in each sample, they may indicate intentional mixing of fibres, or could represent cross-contamination resulting from production in workshops where multiple types of cloth were manufactured.

8.4 Yarn Diameters in Archaeological Silk Textiles

The Winchester and Coppergate textile yarn diameters followed a similar trend to that of the fibre diameters. A comparison of the mean yarn diameters from Systems A and B in the Coppergate textiles revealed a wider range of diameters recorded (Figure 8.42) in contrast to the Winchester textiles.

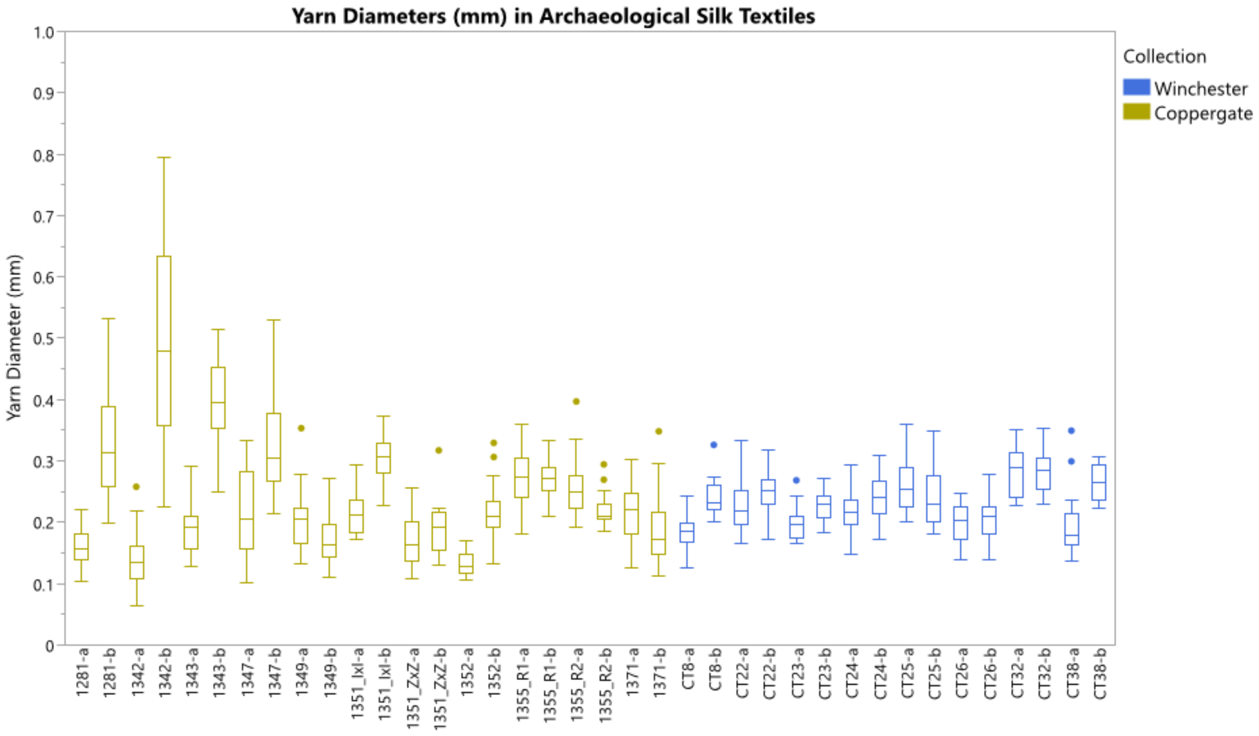


Figure 8.42: Box plots of yarn diameters from both systems of each textile from Coppergate and Winchester

Diameter ranges grouped by direction of twist revealed that most yarn samples without twist from Coppergate have both a larger diameter and more variable diameter measurements than all other yarn examples (Figure 8.43). The diameters of all S-twisted yarn from both Coppergate and Winchester fell within a similar range of measurements with moderate variation. Z-twisted yarn showed the smallest yarn diameters overall. More Z-twisted yarn was incorporated into textiles from Coppergate than Winchester, but the 2 Z-twisted yarn examples from Winchester showed a narrower range of smaller diameter measurements than the Z twist yarn examples from Coppergate. This difference is not extreme.

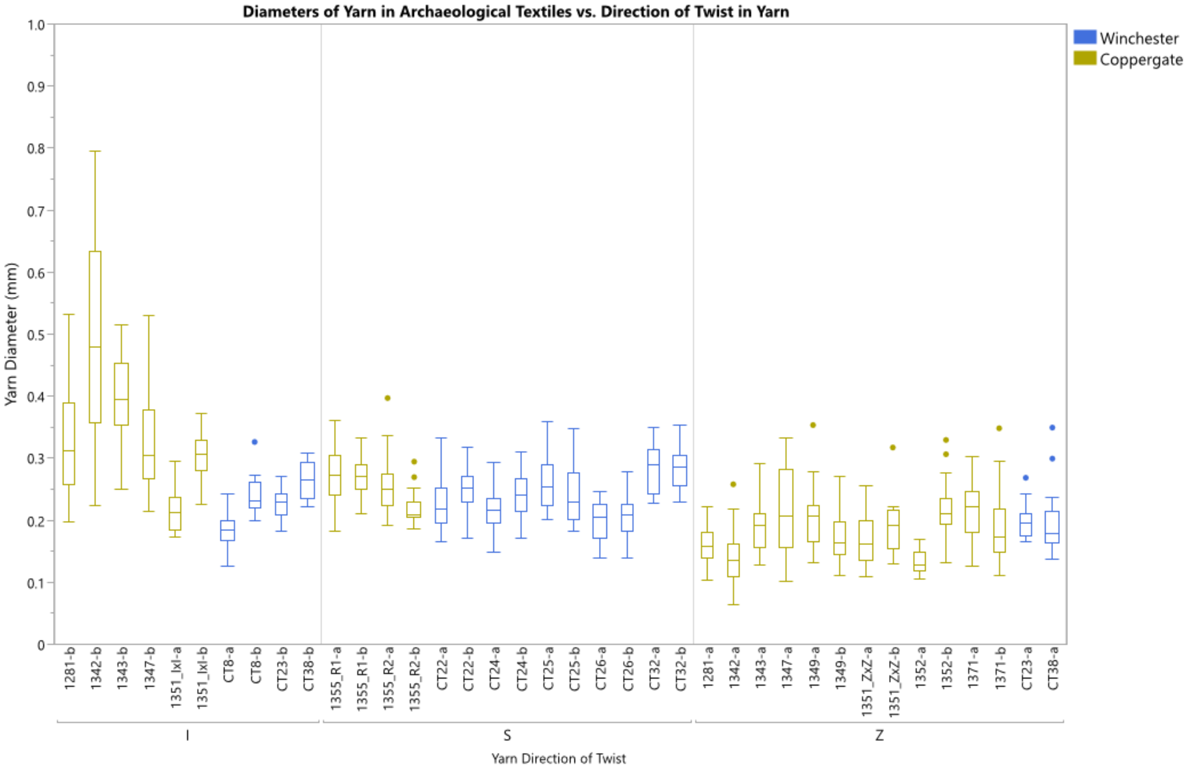


Figure 8.43:Box plots of yarn diameters in textiles from Coppergate and Winchester grouped by direction of twist.

Excluding the subset of textiles with arbitrarily assigned systems as described in Chapter 6.2.2.3, a comparison of the yarn in Systems A and B of each textile showed a trend of similar diameters in both systems of the Winchester textiles (Figure 8.44). The Coppergate textiles in contrast showed a trend of larger diameters in yarn from system B than system A.

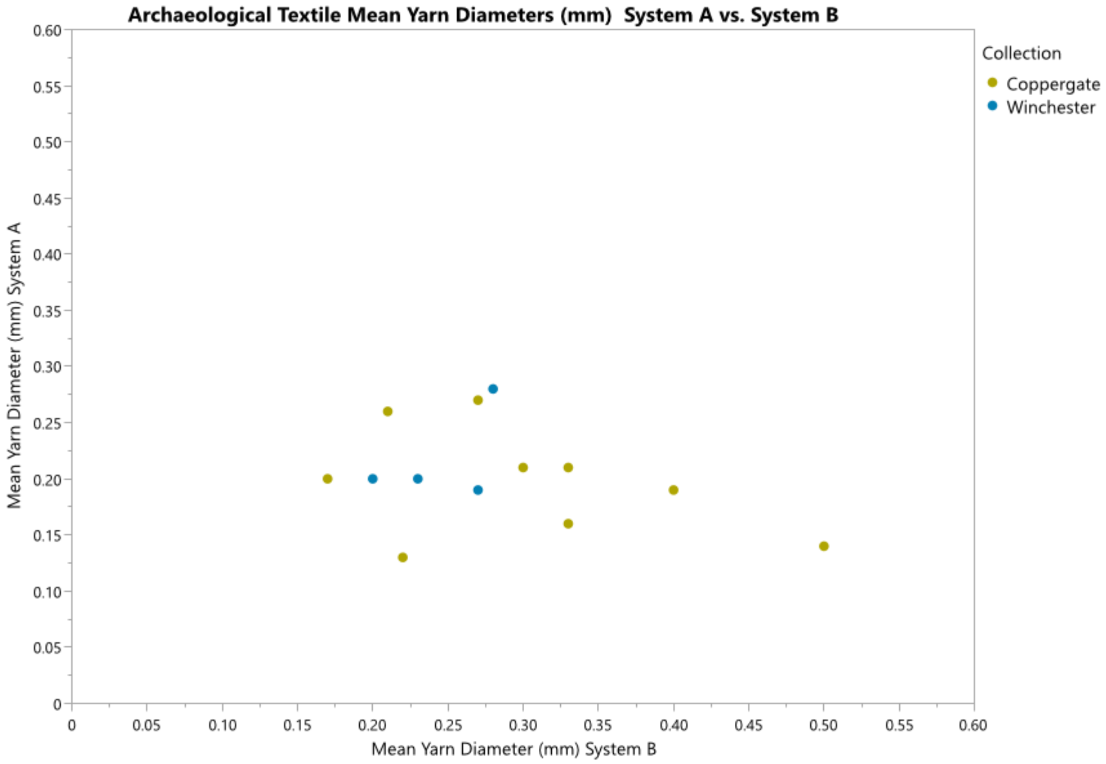


Figure 8.44: Scatter plot of mean yarn diameters from a subset of Coppergate and Winchester textiles with Confident identification of Systems A and B

8.5 Archaeological Silk Thread Counts and cover factors

All thread counts from the Winchester and Coppergate textiles have been summarised for comparison, apart from Coppergate 1352, which comprises several narrow strips of cut selvedge, and therefore did not give an accurate general thread count for the purposes of comparison.

As was the case with yarn diameters, the Winchester mean thread counts formed a closer grouping than the Coppergate thread counts (Figure 8.45), while the Coppergate textile thread counts showed more variation. The Winchester textiles also showed generally higher thread counts than the Coppergate textiles, while both collections showed a trend towards higher counts in System A than system B overall.

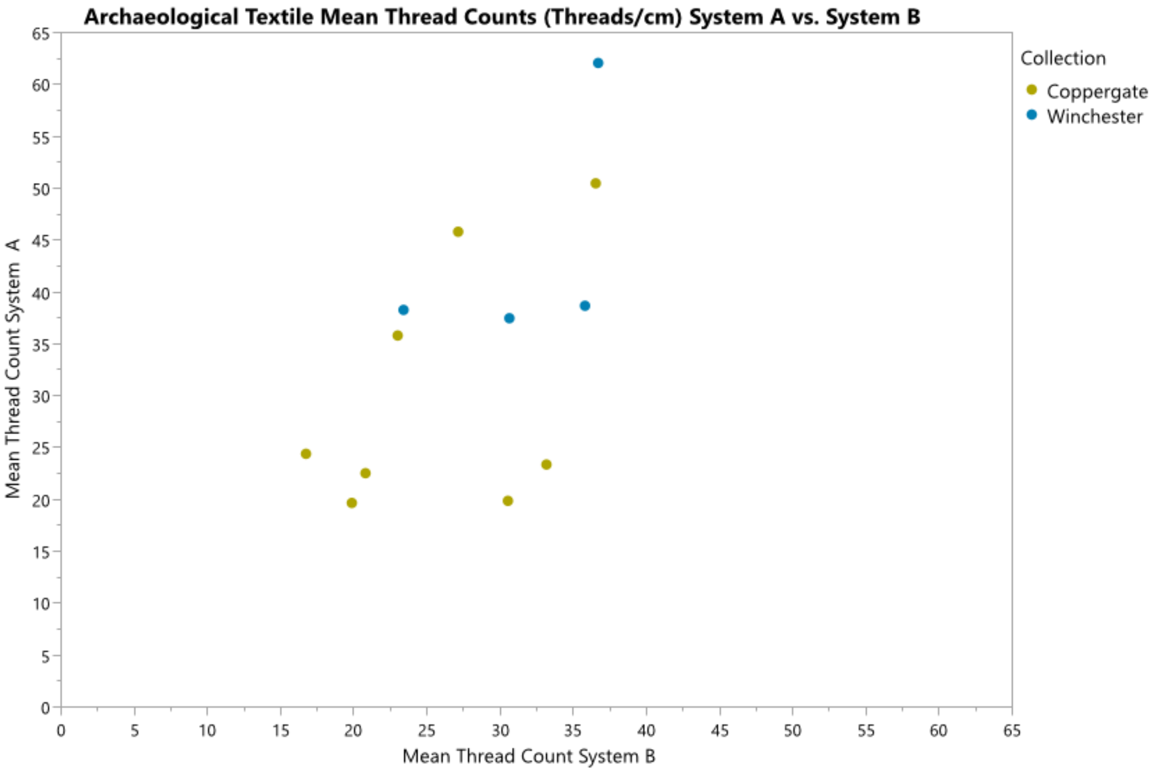


Figure 8.45: Scatterplot of confident subset of Winchester and Coppergate thread counts in System A and System B

When plotted by twist category (Figure 8.46), some trends in thread count were clarified. All SxS textiles showed a higher thread count in System A than system B. The Winchester SxS thread counts were closer to being balanced in both systems than the 2 ribbon fragments (1355) from Coppergate except for 1 textile (CT26), which had a very high system A thread count. The ZxI textiles from Coppergate had lower thread counts in system A than the Winchester textiles, while the system B thread counts in the Winchester ZxI textiles sat on the higher end of the Coppergate thread counts. There was also a trend in the ZxI Coppergate textiles towards higher thread counts in system B than system A, a characteristic not seen in other twist categories.

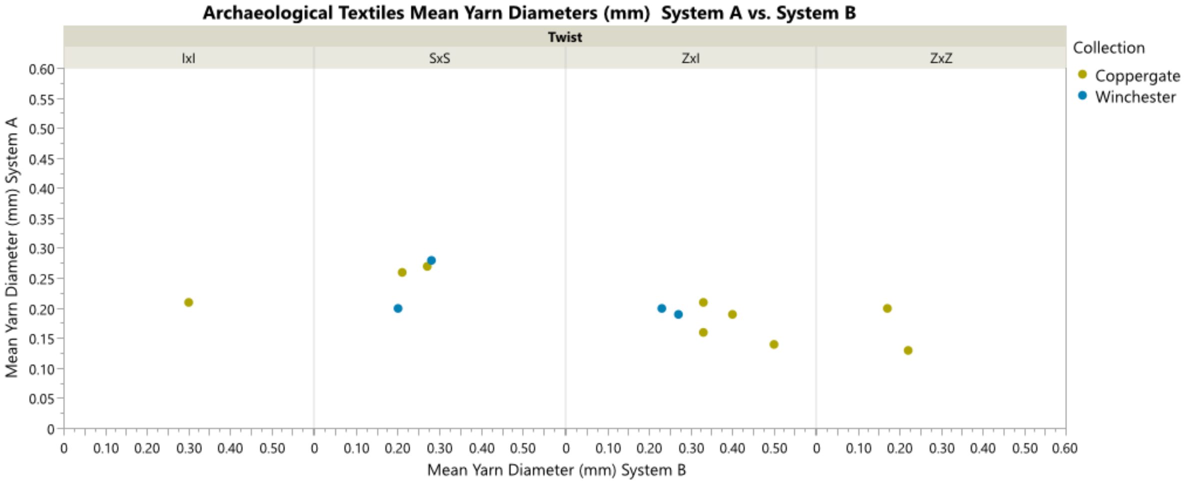


Figure 8.46: Archaeological textile median thread counts (Confident Subset) plotted by thread system and grouped by twist category

Translating the thread counts and yarn diameters of the textile into cover-factor calculations (ie. How much space within a square area of textile is taken by yarn) helped quantify the density of the textiles. The overall cover factor has indicated a higher overall textile density in the Winchester textiles (Figure 8.47). Cover factor by system indicated the Winchester textiles were relatively balanced across both systems, skewing slightly to higher system A density, except for CT8. The Coppergate textiles demonstrated higher density in system B than system A, except for the 1355 ribbons, which showed higher warp density, and the two 1351 textiles, which were more balanced overall.

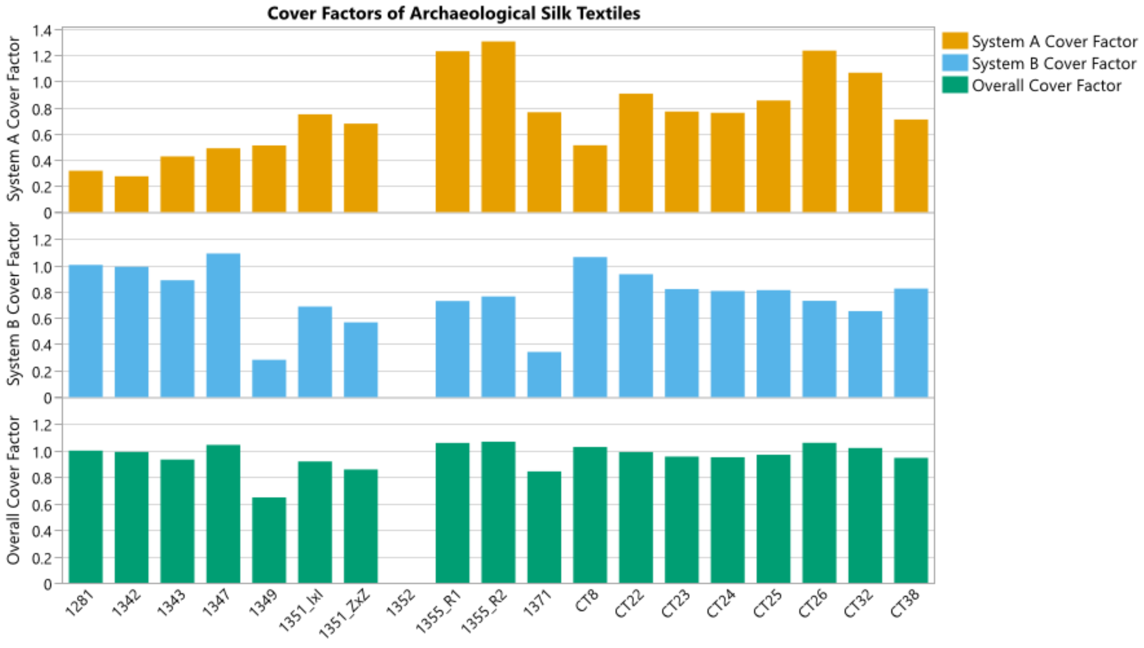


Figure 8.47: System A, System B, and overall cover factors of textiles from Coppergate and Winchester

8.6 Degree of Twist of Yarn in Archaeological Silk Textiles

As discussed in Chapter 6, an approach to measuring the angle of twist was adopted, which allowed both degree and direction of twist to be interpreted from the measured twist angles.

The fibre angles recorded from the Winchester (Table 27) and Coppergate (Table 28) silk textiles showed variation in the range of degree of twist, which was somewhat exaggerated due to the extreme difference in numerical angles reflecting direction of twist (Figure 8.48).

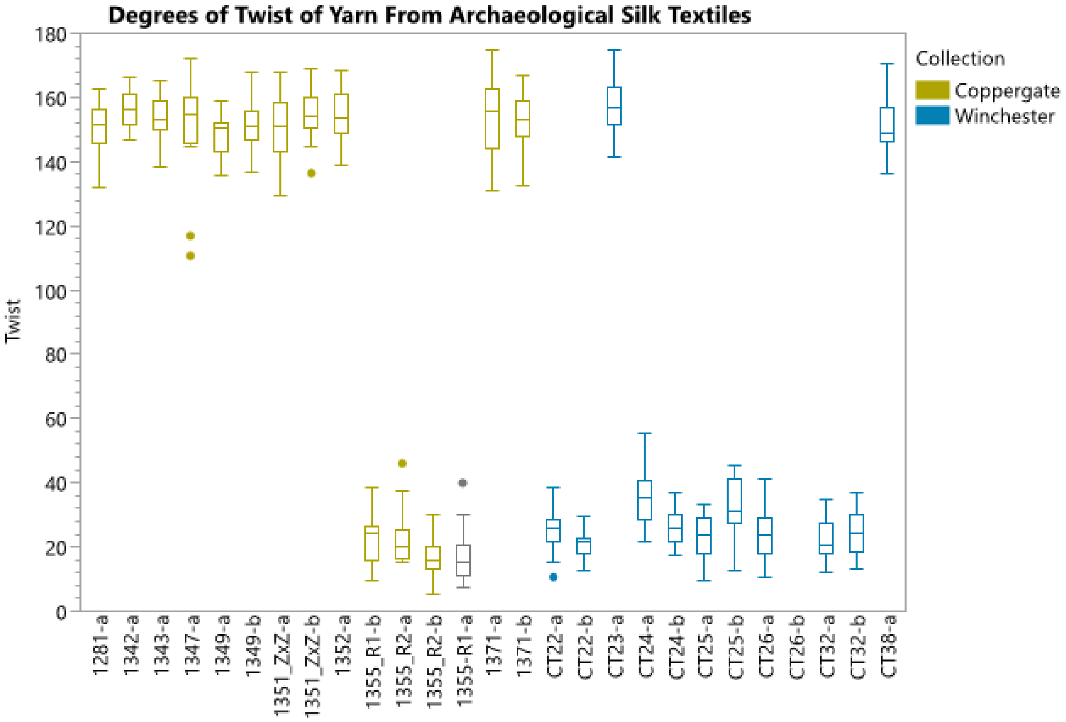


Figure 8.48: Box plots of twist measurements taken from the archaeological silk textiles

When separated by direction of twist, a higher degree of variation was observed in S-twisted yarn (Figure 8.49) from textiles in both collections in contrast to Z-twisted yarn (Figure 8.50).

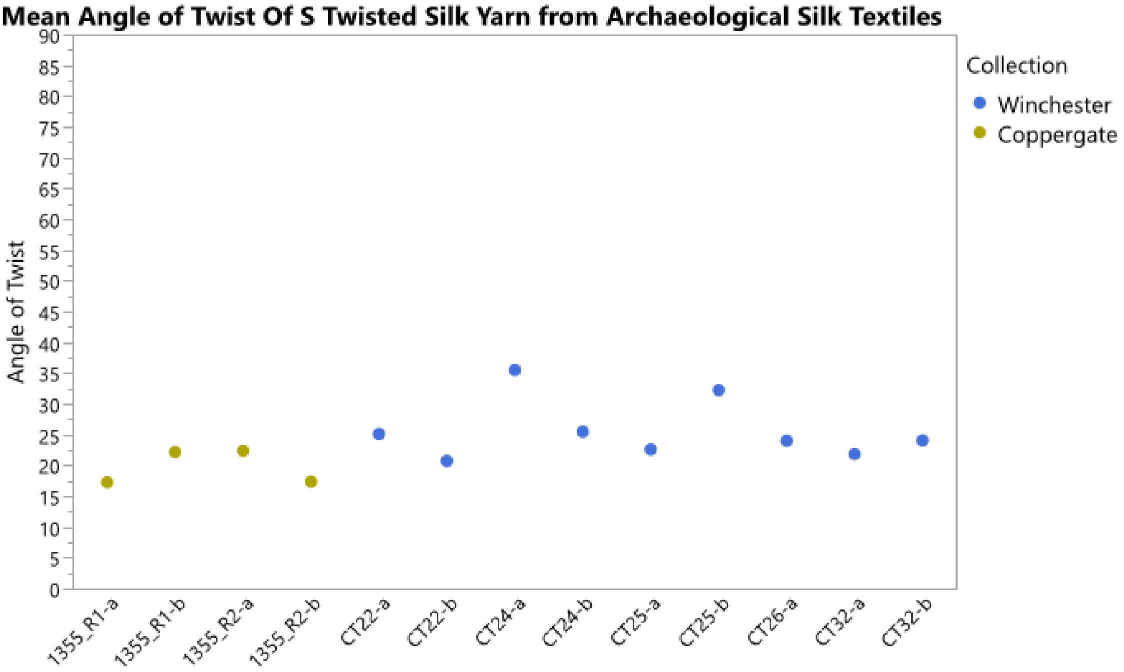


Figure 8.49: Scatterplot showing mean angles of twist of S-twisted yarn from Coppergate and Winchester

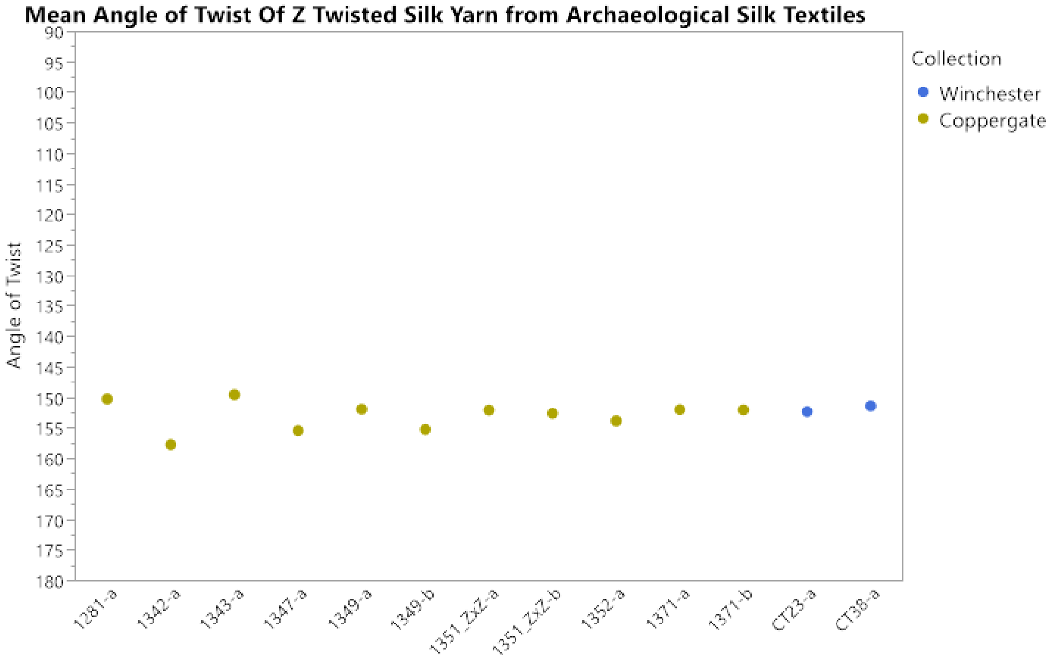
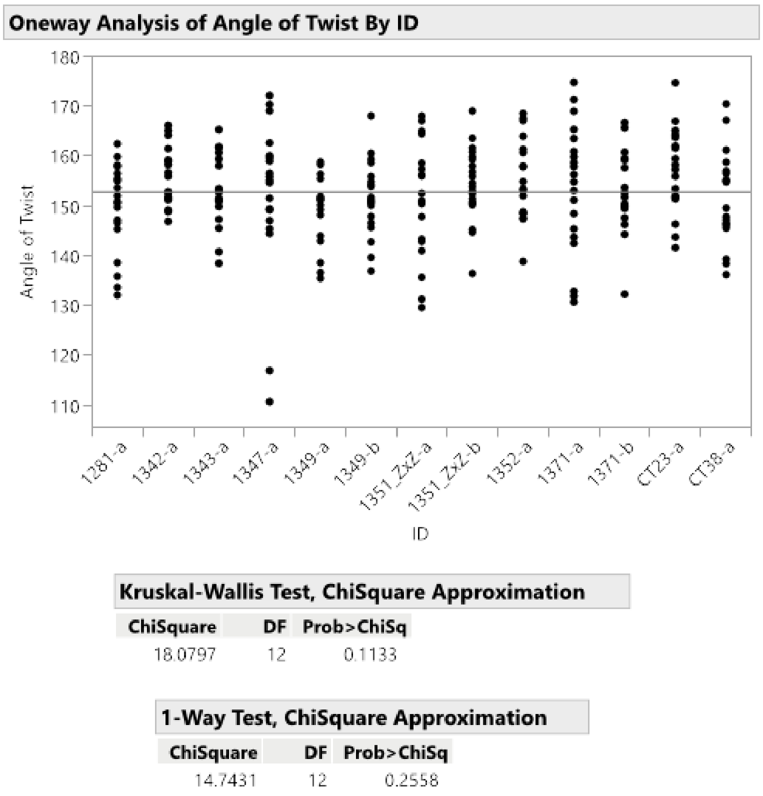


Figure 8.50: Scatterplot showing mean angles of twist of Z-twisted yarn from Coppergate and Winchester

The S-twisted yarn in the Winchester textiles showed an overall slightly higher degree of twist than those from Coppergate. In contrast, no clear trend was observed in the Z-twisted yarns apart from slightly more variation in the Coppergate samples.

The homogeneity of the angles of twist in the Z-twisted yarn from both collections was confirmed by a Kruskal-Wallis and Median Tests of Variance, which indicated that variations in the degree of twist in Z-twisted yarn were not statistically significant (Figure 8.51).



Oneway Analysis of Angle of Twist By ID

Kruskal-Wallis Test, ChiSquare Approximation

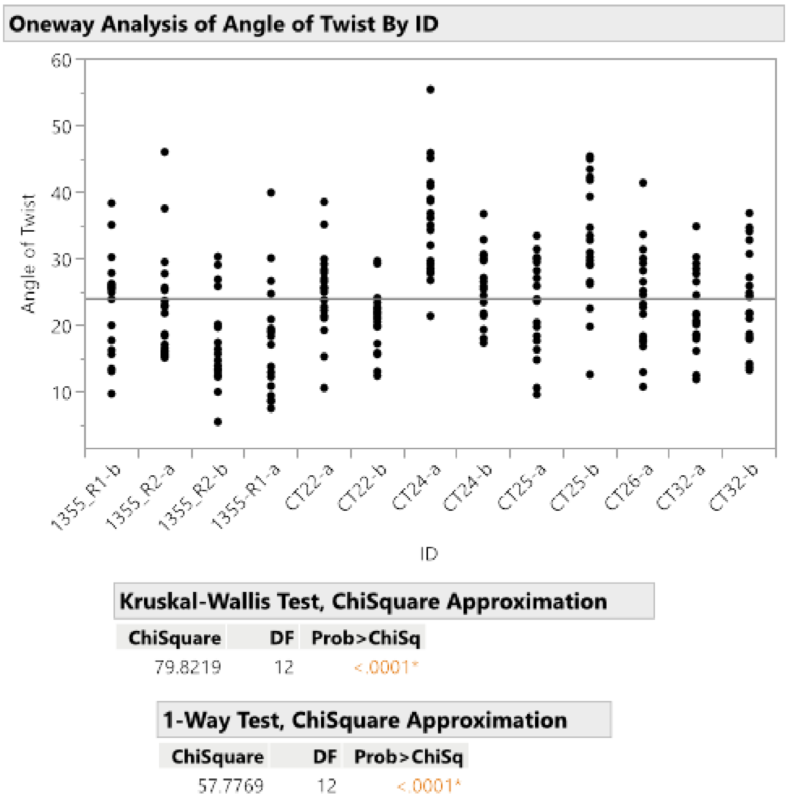
ChiSquare	DF	Prob>ChiSq
18.0797	12	0.1133

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
14.7431	12	0.2558

Figure 8.51: Results of Kruskal-Wallis and Median tests of Variance of the degree of twist of Z-twisted yarns

In contrast, the variation in the degree of twist of the S-twisted yarn was confirmed to be statistically significant (Figure 8.52). While the Z-twisted yarn samples measured within a narrow range of 148.45° to 156.45° (or a medium to high degree of twist according to the scale adapted from Emery (1980, 12)), the S-twisted yarn showed a slightly broader range of 17.34° to 35.59°(also a medium to high degree of twist). This raises an important question regarding the efficacy of assessing degree of yarn twist by measured angles alone. This topic will be explored further in relation to the visual analysis of the archaeological textiles.



Oneway Analysis of Angle of Twist By ID

Kruskal-Wallis Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
79.8219	12	<.0001*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
57.7769	12	<.0001*

Figure 8.52: Results of Kruskal-Wallis and Median Test Analyses of Variance of Degree of Twist of S-twisted yarn

The summarising tables of twist measurement include measurements taken from all twisted-yarn systems, except for CT26-b and Coppergate 1252-b, both of which could not be accurately measured due to the high degree of coverage from the warp system.

8.7 Visual Analysis of Archaeological Textile Characteristics

Visual analysis of the archaeological silk textiles provided a non-mathematical means of describing their physical characteristics. This analysis focussed particularly on the balance between thread systems, yarn movement, perceived cloth density, the perceived degree of twist in the yarn, and whether the yarn was plied. Another area of interest was flaws in the woven structure and their potential use in identifying warp direction.

8.7.1 Perceived Cloth Density

The appearance of the Coppergate textiles indicated more variation overall in cloth density than was observed in most Winchester textiles (Figure 8.53); the latter can be described as having a “balanced” density, where the weave is neither open nor are the threads crowded. The Coppergate ZxZ textiles (Figure 8.54) showed more variation in density, but some differences in density could also be observed in the ZxI Coppergate textiles, which ranged from open, to balanced, to variable even within the structure of a single textile. Although the Winchester textiles were more balanced overall, some variation could also be seen in the ZxI textiles (which varied from open to balanced), and the SxS textiles (which varied from balanced to dense).

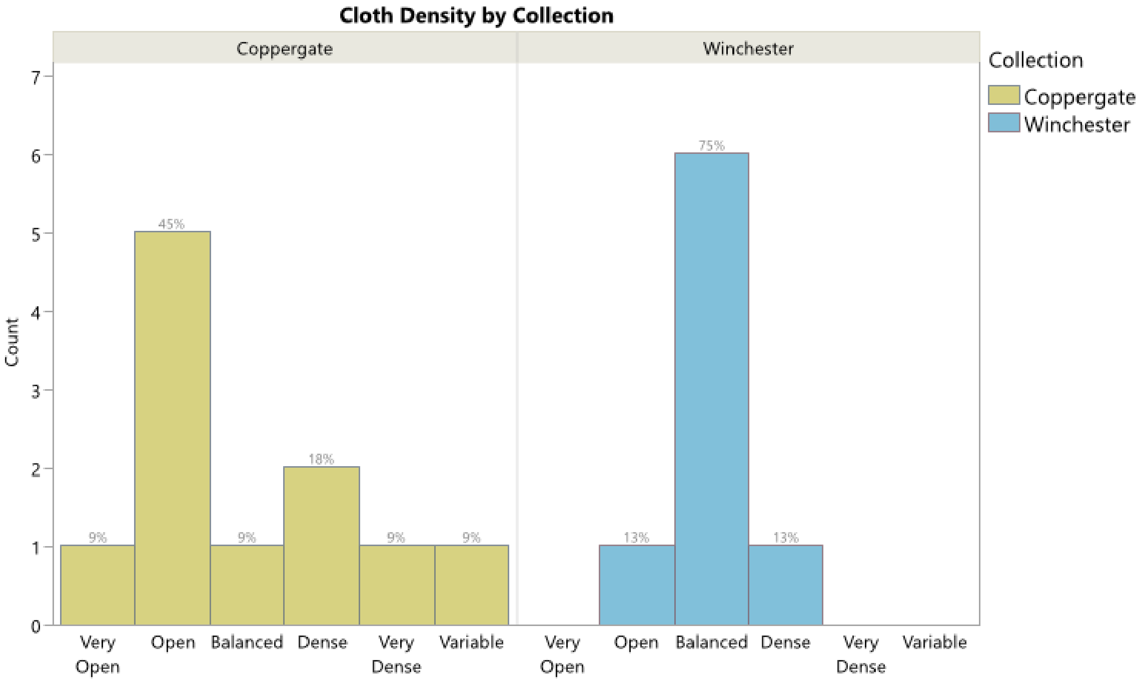


Figure 8.53: Archaeological textile density by collection

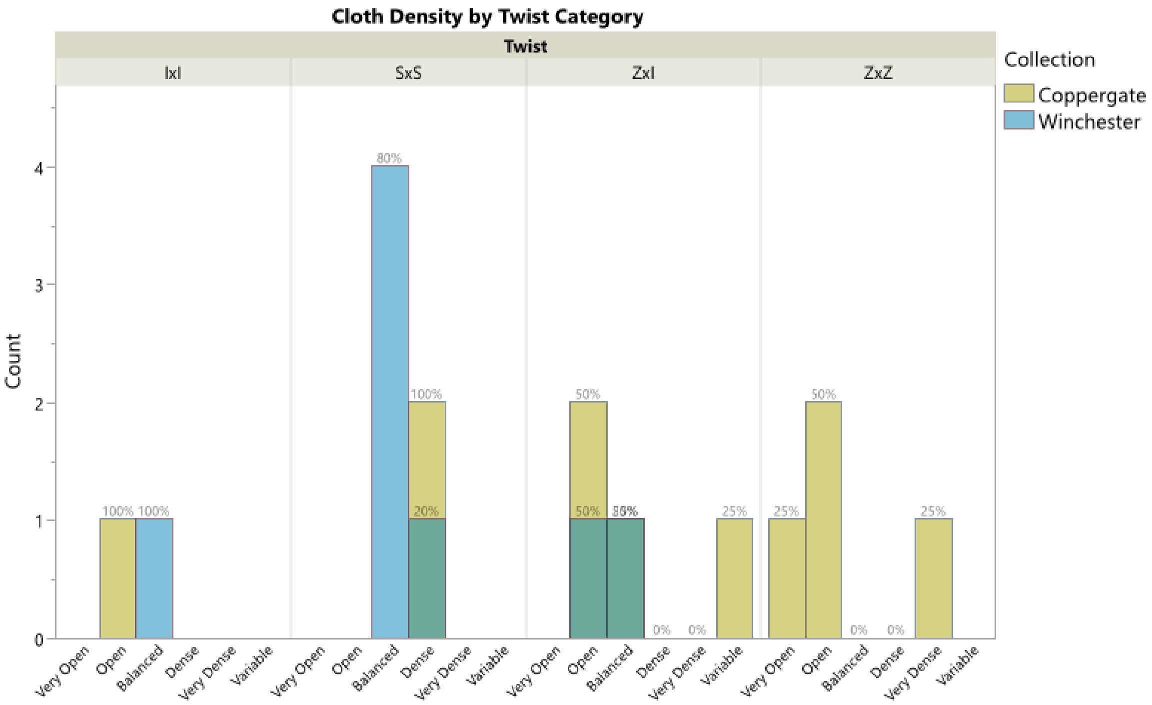


Figure 8.54: Archaeological textile density by twist category

The visual analysis of the textile density produced observations that correlated with the measured cover factors of the textiles (Figure 8.55).

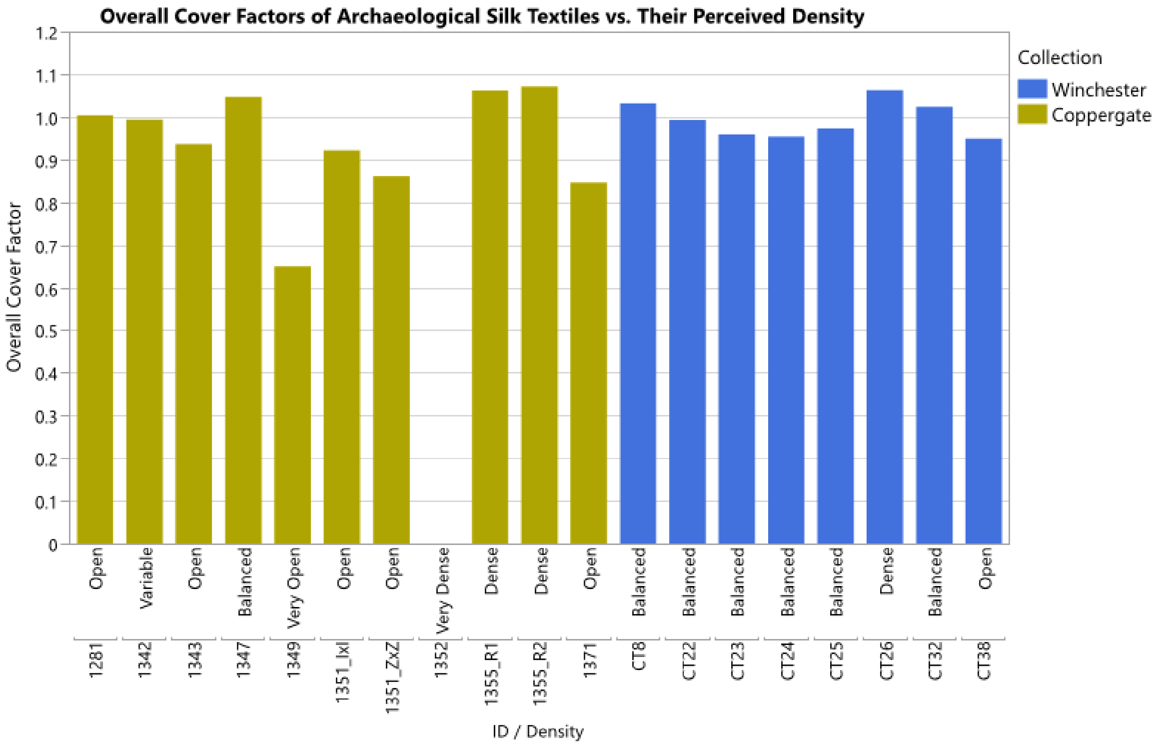


Figure 8.55: Overall cover factors of the archaeological textiles vs their perceived density

If Hammarlund's criteria developed for wool textiles (See chapters 2 & 6) were applied, all textiles but Coppergate 1349 would be categorised as medium-dense to very dense, while 1349 would be categorised as open rather than very open. A new set of density classifications for silk based on this analysis would shift the density parameters (Table 8.3), but it should be noted that the perceived density of all textiles does not perfectly fit within the newly devised parameters. This further emphasises the subjective nature of perceived density, while indicating that other factors might influence the visual perception of textile density.

Density	**Cover Factor**
Very Open	≤0.8
Open	0.81-0.94
Balanced	95-1.04
Dense	1.05-1.07
Very Dense	>1.08

Table 8.3: Reconfigured Textiles density descriptors based on the cover factors of silk tabby textiles

8.7.2 Yarn Movement

Yarn movement is a characteristic that is not easily quantified yet is relevant to the overall appearance of woven textiles. Yarn movement can be assessed in relation to cloth density (Figure 8.56) as more open cloth structure gives more room for yarn to shift.

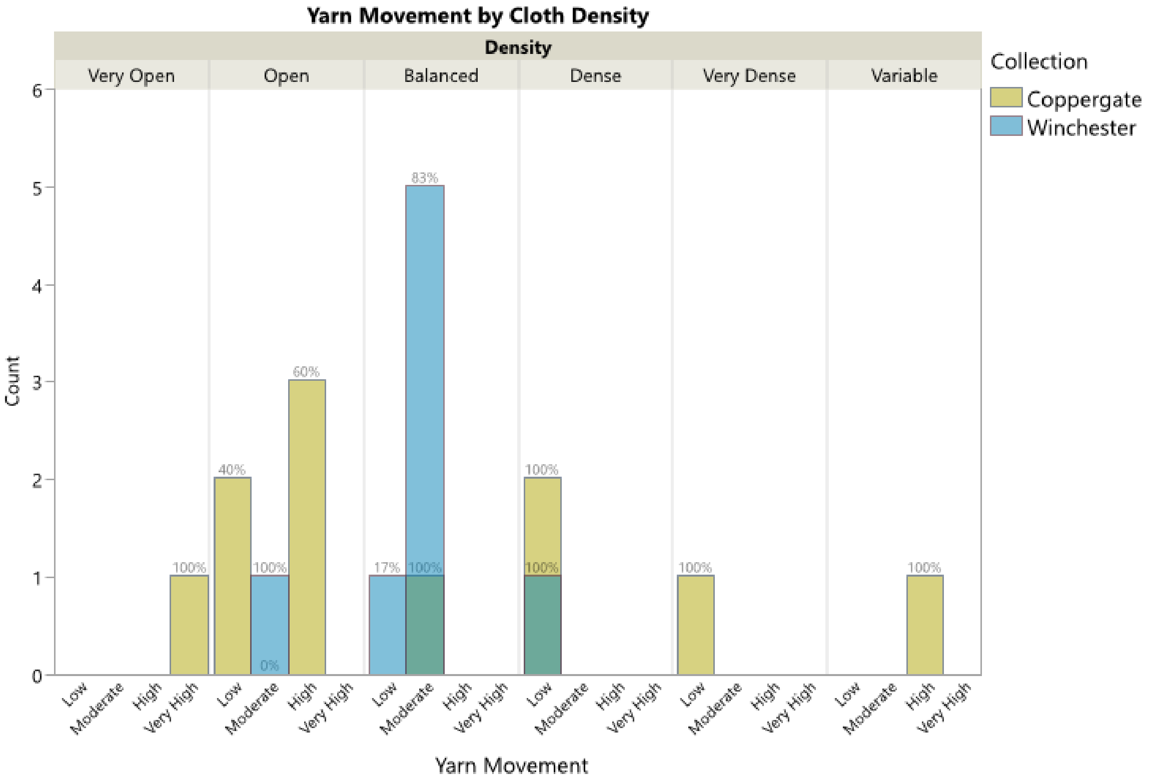


Figure 8.56: Extent of yarn movement in archaeological silk textiles by cloth density

Reflective of the variable cloth density, yarn movement was variable in the Coppergate silks, while the Winchester silks only showed low to moderate yarn movement (Figure 8.57). It should therefore be no surprise that the yarn movement in all SxS textiles was comparatively low, given the generally higher cloth density of this group (Figure 8.58)

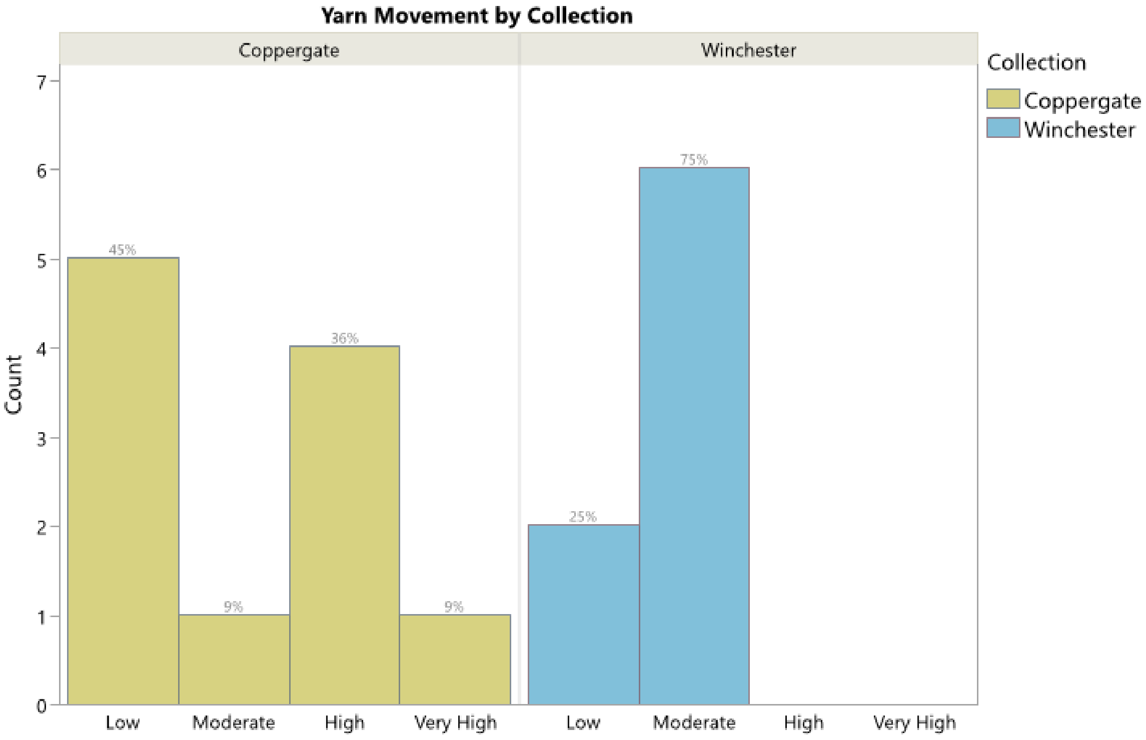


Figure 8.57: Extent of yarn movement in archaeological silk textiles by collection

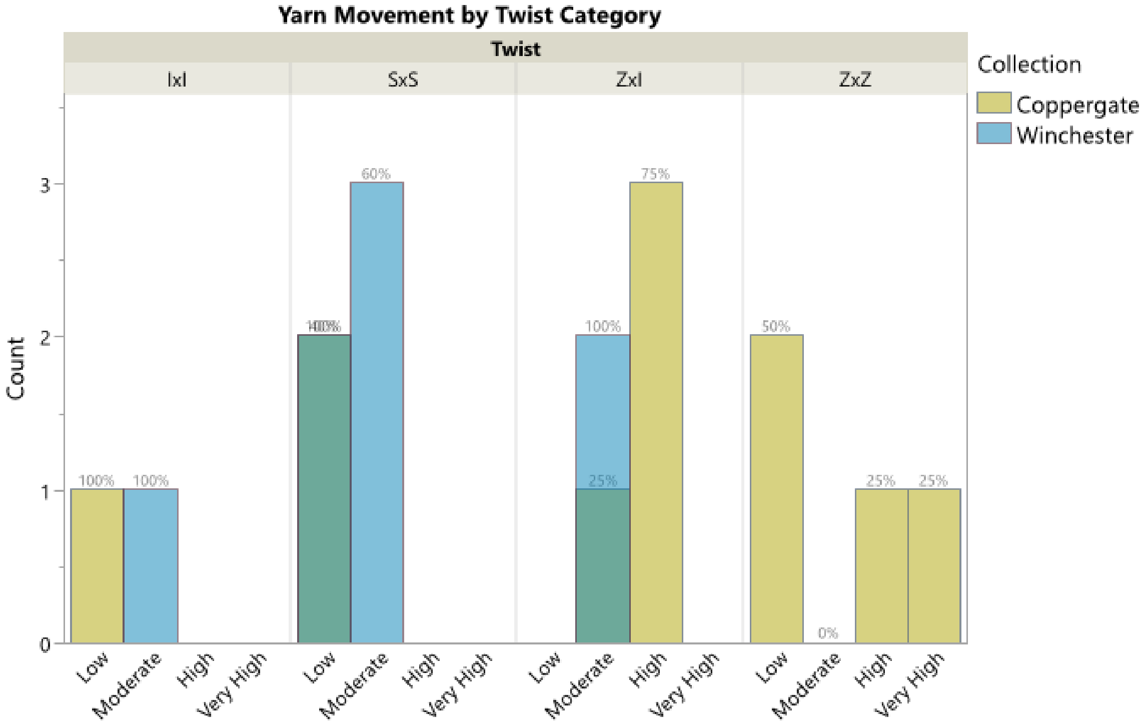


Figure 8.58: Extent of yarn movement in archaeological silk textiles by twist category

8.7.3 Perceived Degree of Twist

The comparison of measured twist angles indicated insignificant variation in the degree of twist in Z-twisted yarn from both collections, and a significant but low degree of twist variation in the S-twisted yarn. Using the twist categories adapted from Emery (See chapter 2), the measured twist results indicated that both S and Z-twisted yarns from both collections displayed a medium to high degree of twist. Visual analysis of the yarn returned very different results (Figure 8.59), which indicated more variation in the perceived angle of twist of the Z-twisted yarn than was reflected in the measured angles. The visual analysis also demonstrated a trend of lower perceived degree of twist in the S-twisted yarn than in the Z-twisted yarn, which was also not reflected in the measured angles.

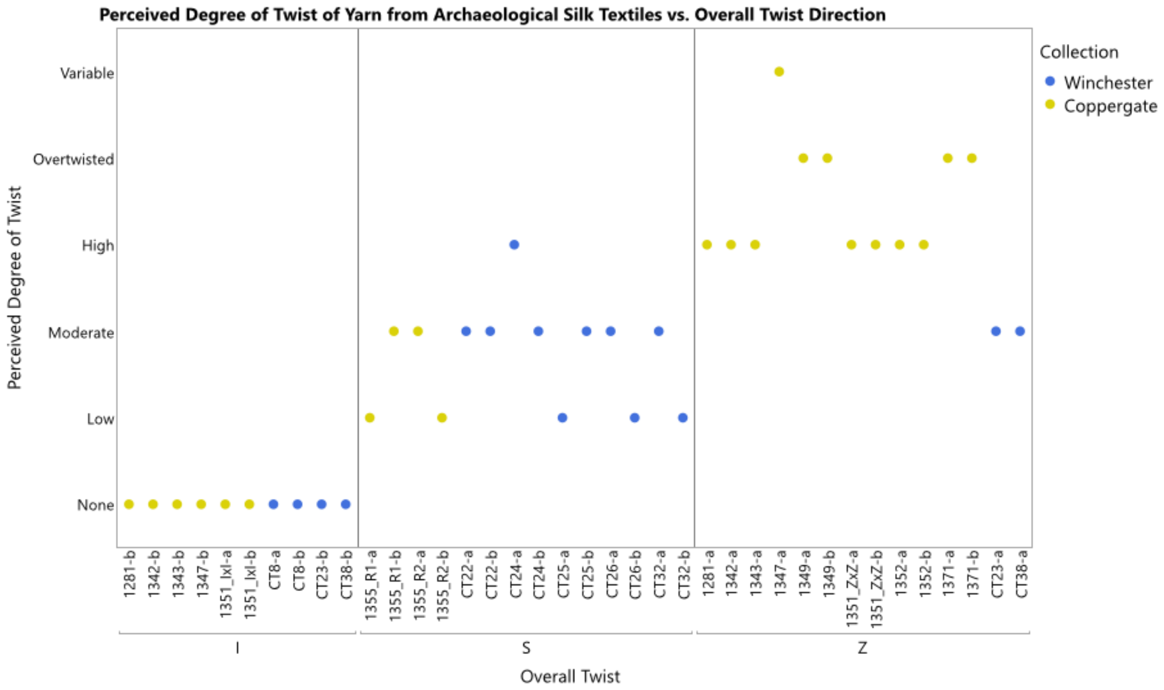


Figure 8.59: Scatter plot of the perceived angle of twist recorded for each yarn example from Coppergate and Winchester vs. Direction of twist

A comparison of yarn diameter and angle of twist in relation to perceived degree of twist suggests a tentative link between diameter, measured angle of twist, and the resulting perceived degree of twist; S-twisted yarn from system A of CT32 was perceived to have a moderate degree of twist, despite having a slightly lower angle of twist than the S-twisted yarn from system A of CT25, which had a perceived low degree of twist (Figure 8.60).

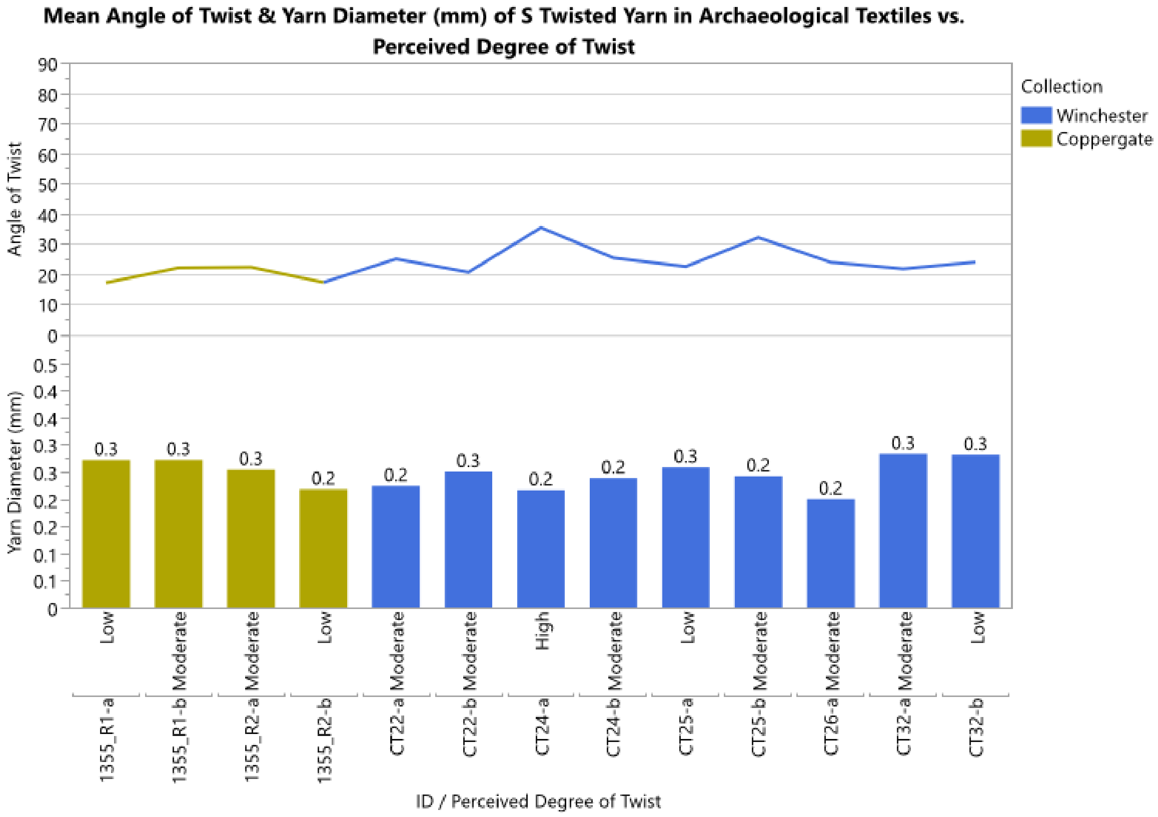


Figure 8.60: Chart comparing measured angle of twist to perceived degree of twist and diameters (mm) of S-twisted yarn from Coppergate and Winchester textiles

These discrepancies were more pronounced in the Z-twisted yarn, which varied from moderate levels of twist to overtwisted, despite little variation in the measured angles of twist (Figure 8.61).

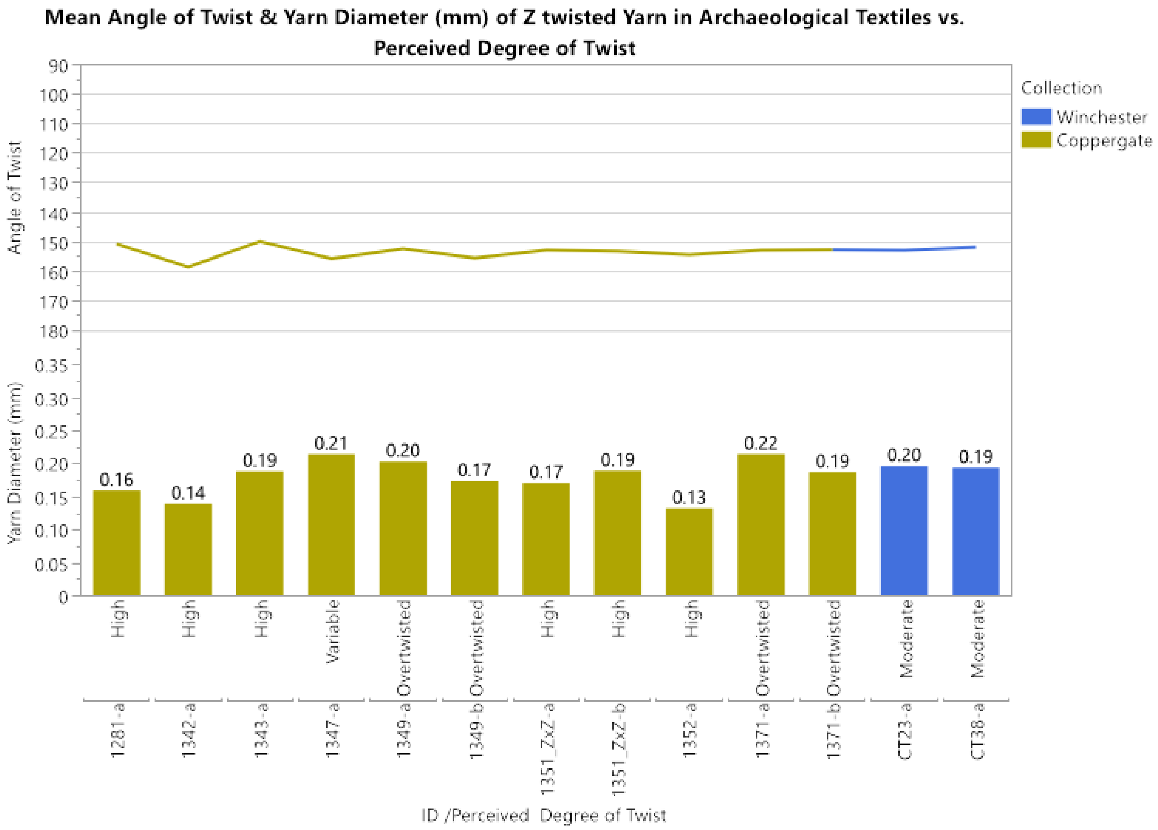
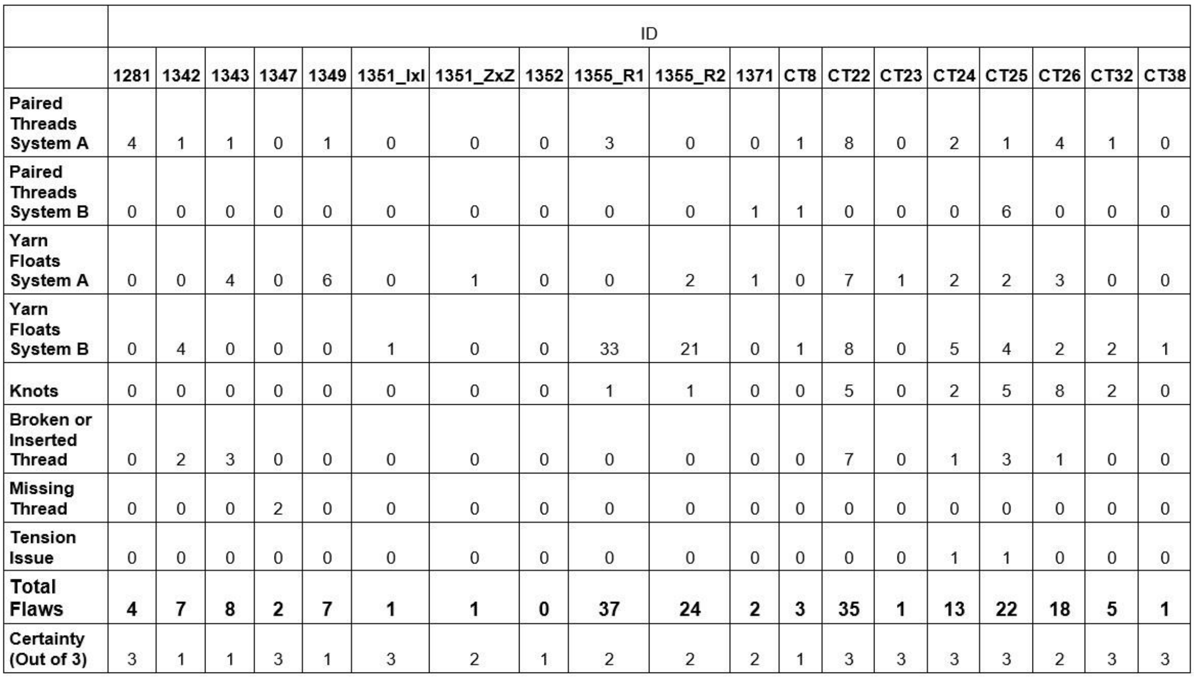


Figure 8.61: Chart comparing measured angle of twist to perceived degree of twist and diameters (mm) of Z-twisted yarn from Coppergate and Winchester textiles

This suggests that other factors must influence the perceived degree of twist. There were differences in the diameter of yarn, but no clear correlation between yarn diameter, angle of twist and perceived degree of twist could be found. Regardless, this comparison demonstrates that, while still a potentially useful measure, angle of twist alone is insufficient for characterising degree of twist, and it does not seem to be an accurate predictor of the overall appearance or behaviour of silk yarn in a woven textile.

8.8 Analysis of Weaving Flaws

Analysis of the physical properties of the archaeological textiles led to the identification of flaws that are likely to be the result of errors made during the weaving process. The total number of flaws and the number of each type of flaw per textile were recorded for both the Winchester and Coppergate textiles (Table 8.4). Identification of flaws in cloth structure have the potential to be obscured by deteriorated threads, so a conscious effort was made to record only confidently identified flaws. In some cases, identifications were made with less certainty, particularly during the analysis of the Coppergate textiles, as the digital photographs showing the entirety of the textile were not of a high enough resolution to support flaw analysis with the level of accuracy made possible by the scans of the Winchester textiles. This meant a more piecemeal approach was taken for the Coppergate material, using stereomicrographs of sections of textile, and leaving more room for omitted sections of textile. The overall certainty of the flaw identifications has been indicated with a certainty score, with the number 1 denoting a low level of certainty, and 3 indicating a high degree of certainty.



	ID																		
	1281	**1342**	**1343**	**1347**	**1349**	**1351_IxI**	**1351_ZxZ**	**1352**	**1355_R1**	**1355_R2**	**1371**	**CT8**	**CT22**	**CT23**	**CT24**	**CT25**	**CT26**	**CT32**	**CT38**
Paired Threads System A	4	1	1	0	1	0	0	0	3	0	0	1	8	0	2	1	4	1	0
Paired Threads System B	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	6	0	0	0
Yarn Floats System A	0	0	4	0	6	0	1	0	0	2	1	0	7	1	2	2	3	0	0
Yarn Floats System B	0	4	0	0	0	1	0	0	33	21	0	1	8	0	5	4	2	2	1
Knots	0	0	0	0	0	0	0	0	1	1	0	0	5	0	2	5	8	2	0
Broken or Inserted Thread	0	2	3	0	0	0	0	0	0	0	0	0	7	0	1	3	1	0	0
Missing Thread	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tension Issue	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Total Flaws	**4**	**7**	**8**	**2**	**7**	**1**	**1**	**0**	**37**	**24**	**2**	**3**	**35**	**1**	**13**	**22**	**18**	**5**	**1**
Certainty (Out of 3)	3	1	1	3	1	3	2	1	2	2	2	1	3	3	3	3	2	3	3

Table 8.4: Flaws recorded in the Coppergate and Winchester textiles by type, with level of certainty marked out of 3

When considered in relation to twist categories (Figure 8.62), the highest numbers of weaving flaws were observed in the SxS textiles. In the ZxI category, the Coppergate textiles were found to have higher numbers of weaving flaws than the Winchester textiles, although this data is skewed due to the lower number of ZxI textiles from Winchester. The Winchester IxI textile showed a higher number of flaws than the

Coppergate IxI textile, but this may also be skewed by the larger size of the Winchester IxI textile.

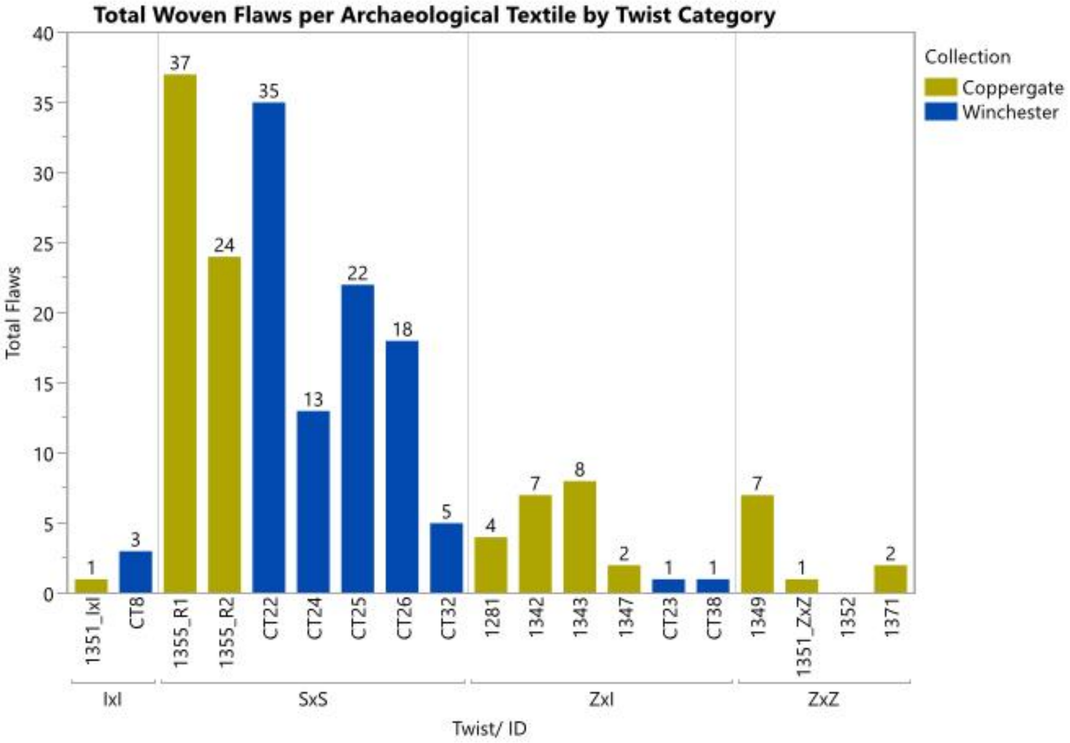


Figure 8.62: Total weaving flaws per textile grouped by twist category

In the SxS twist category, Coppergate 1355-R1 displayed a higher number of weft floats than any other textile, particularly at the turned edge (Figure 8.63). This does not appear to be the result of warp threads wearing away, as a solid web is visible under these weft floats, and the weft appears to enter this lower layer. This contrasts with other areas of the same ribbon where the warp threads have worn and created a hole in the textile (Figure 8.64). These floats have been interpreted as errors that occurred during the weaving process, but the number is surprisingly high, which could suggest tension problems during the weaving process.

Figure 8.63: Reflected light micrograph of Coppergate 1355-R1 showing weft floats

Figure 8.64: Reflected light micrograph of Coppergate 1355-R1 showing hole created by deteriorated yarn

The weaving flaws observed in the archaeological textiles could have implications related to the production of these textiles and the priorities of the weavers who made them. This will be discussed in greater detail in chapter 9.

8.8.1 Woven Flaws by System

Of the textiles with preserved selvedges that exhibited paired threads (aside from those intentionally included in a selvedge), these thread pairings were only observed in the warp system. Within this group of textiles, where it was possible to determine the orientation of knots, these knots appeared to be joining warp threads. The same trend of paired threads exclusively observed in System A was also observed in ZxI textiles, regardless of selvedge preservation. Based on this pattern, it may be possible to identify warp direction in remaining textiles that exhibit paired warp threads.

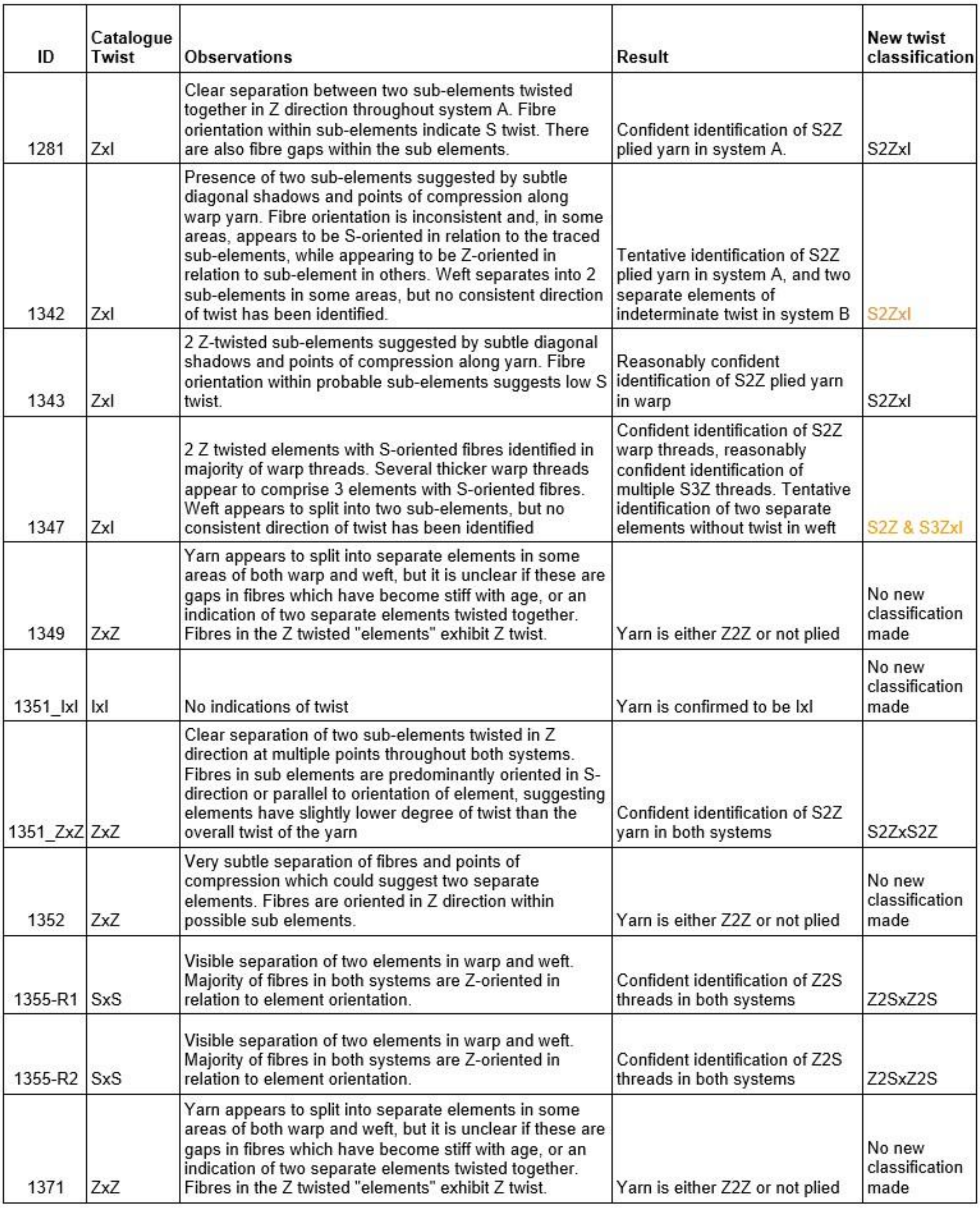
One precaution must be made regarding confusing a paired thread for an inserted thread. For the purposes of this identification, paired threads were labelled as such if the thread remained paired throughout the entire fragment, while paired threads appearing briefly in the matrix of the cloth were identified as either the tail ends of a knot where one was visible, or as an inserted thread, which could be the result of broken thread repair, or the joining of a new weft thread, depending on weaving direction.

Based solely on frequency and direction of paired threads, Warp direction of Coppergate 1371 could be tentatively identified in the direction of designated system B. System A of CT23 could be more confidently identified as the warp direction, while System B of CT25 could be reasonably confidently identified as the warp direction. Further supporting the identification of the warp direction of CT22 was the identification of a number of inserted threads, which appear to be woven-in gussets (Figure 8.65) in the direction of System B of the type intended to correct tension issues (Walton and Eastwood 1988, 12). The observation of this weaving technique not only strongly indicates warp and weft direction, but also demonstrates a decision to correct tension issues on the part of the weaver. This could indicate the use of a loom prone to uneven warp tension, or problems with warping technique resulting in tension problems, but either way is a concrete reflection of a technical choice made during the weaving process.

Figure 8.65: Cropped image of Winchester textile CT22 with 2 woven-in gussets indicated (modified from original image provided by ASLab)

8.9 Identification of Plied Yarns in Coppergate Silk Textiles

Traced ply analysis was conducted to determine if previously unidentified plied yarn had been incorporated in the Coppergate textiles. This analysis led to the identification of many plied threads, with varying degrees of confidence (Table 8.5).



ID	Catalogue Twist	Observations	Result	New twist classification
1281	ZxI	Clear separation between two sub-elements twisted together in Z direction throughout system A. Fibre orientation within sub-elements indicate S twist. There are also fibre gaps within the sub elements.	Confident identification of S2Z plied yarn in system A.	S2ZxI
1342	ZxI	Presence of two sub-elements suggested by subtle diagonal shadows and points of compression along warp yarn. Fibre orientation is inconsistent and, in some areas, appears to be S-oriented in relation to the traced sub-elements, while appearing to be Z-oriented in relation to sub-element in others. Weft separates into 2 sub-elements in some areas, but no consistent direction of twist has been identified.	Tentative identification of S2Z plied yarn in system A, and two separate elements of indeterminate twist in system B	S2ZxI
1343	ZxI	2 Z-twisted sub-elements suggested by subtle diagonal shadows and points of compression along yarn. Fibre orientation within probable sub-elements suggests low S twist.	Reasonably confident identification of S2Z plied yarn in warp	S2ZxI
1347	ZxI	2 Z twisted elements with S-oriented fibres identified in majority of warp threads. Several thicker warp threads appear to comprise 3 elements with S-oriented fibres. Weft appears to split into two sub-elements, but no consistent direction of twist has been identified	Confident identification of S2Z warp threads, reasonably confident identification of multiple S3Z threads. Tentative identification of two separate elements without twist in weft	S2Z & S3ZxI
1349	ZxZ	Yarn appears to split into separate elements in some areas of both warp and weft, but it is unclear if these are gaps in fibres which have become stiff with age, or an indication of two separate elements twisted together. Fibres in the Z twisted "elements" exhibit Z twist.	Yarn is either Z2Z or not plied	No new classification made
1351_IxI	IxI	No indications of twist	Yarn is confirmed to be IxI	No new classification made
1351_ZxZ	ZxZ	Clear separation of two sub-elements twisted in Z direction at multiple points throughout both systems. Fibres in sub elements are predominantly oriented in S-direction or parallel to orientation of element, suggesting elements have slightly lower degree of twist than the overall twist of the yarn	Confident identification of S2Z yarn in both systems	S2ZxS2Z
1352	ZxZ	Very subtle separation of fibres and points of compression which could suggest two separate elements. Fibres are oriented in Z direction within possible sub elements.	Yarn is either Z2Z or not plied	No new classification made
1355-R1	SxS	Visible separation of two elements in warp and weft. Majority of fibres in both systems are Z-oriented in relation to element orientation.	Confident identification of Z2S threads in both systems	Z2SxZ2S
1355-R2	SxS	Visible separation of two elements in warp and weft. Majority of fibres in both systems are Z-oriented in relation to element orientation.	Confident identification of Z2S threads in both systems	Z2SxZ2S
1371	ZxZ	Yarn appears to split into separate elements in some areas of both warp and weft, but it is unclear if these are gaps in fibres which have become stiff with age, or an indication of two separate elements twisted together. Fibres in the Z twisted "elements" exhibit Z twist.	Yarn is either Z2Z or not plied	No new classification made

Table 8.5: Results of ply analysis with observations that led to each conclusion. New classifications colour coded orange show tentative results.

Of the ZxI tabby silks, 1281 (Figure 8.66a,b) and 1343 (Figure 8.66e,f) have been confidently identified as having S2Z threads in System A, while the classification of the threads in 1342 (Figure 8.66c,d) as S2Z is more tentative. Textiles 1342 and 1347 (Figure 8.67) also showed subtle evidence of 2 sub- elements in system B, but no direction of twist was identified, so these yarn examples were not classified as having been plied.

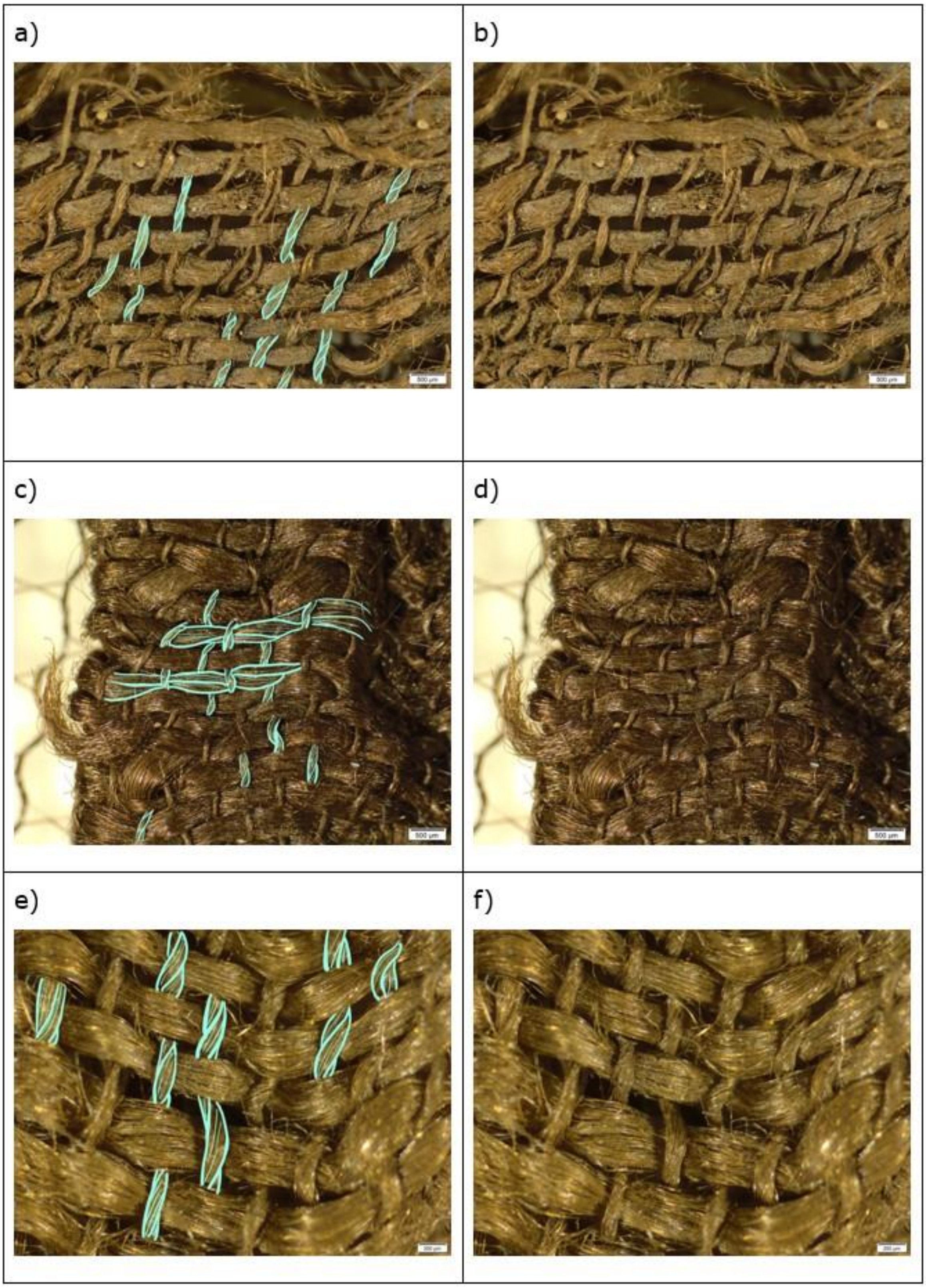


Figure 8.66: Coppergate textiles 1281 (a,b); 1342 (c,d); 1343 (e,f) showing traced indications of S2Z yarn in the warp/system A(a,c,e)

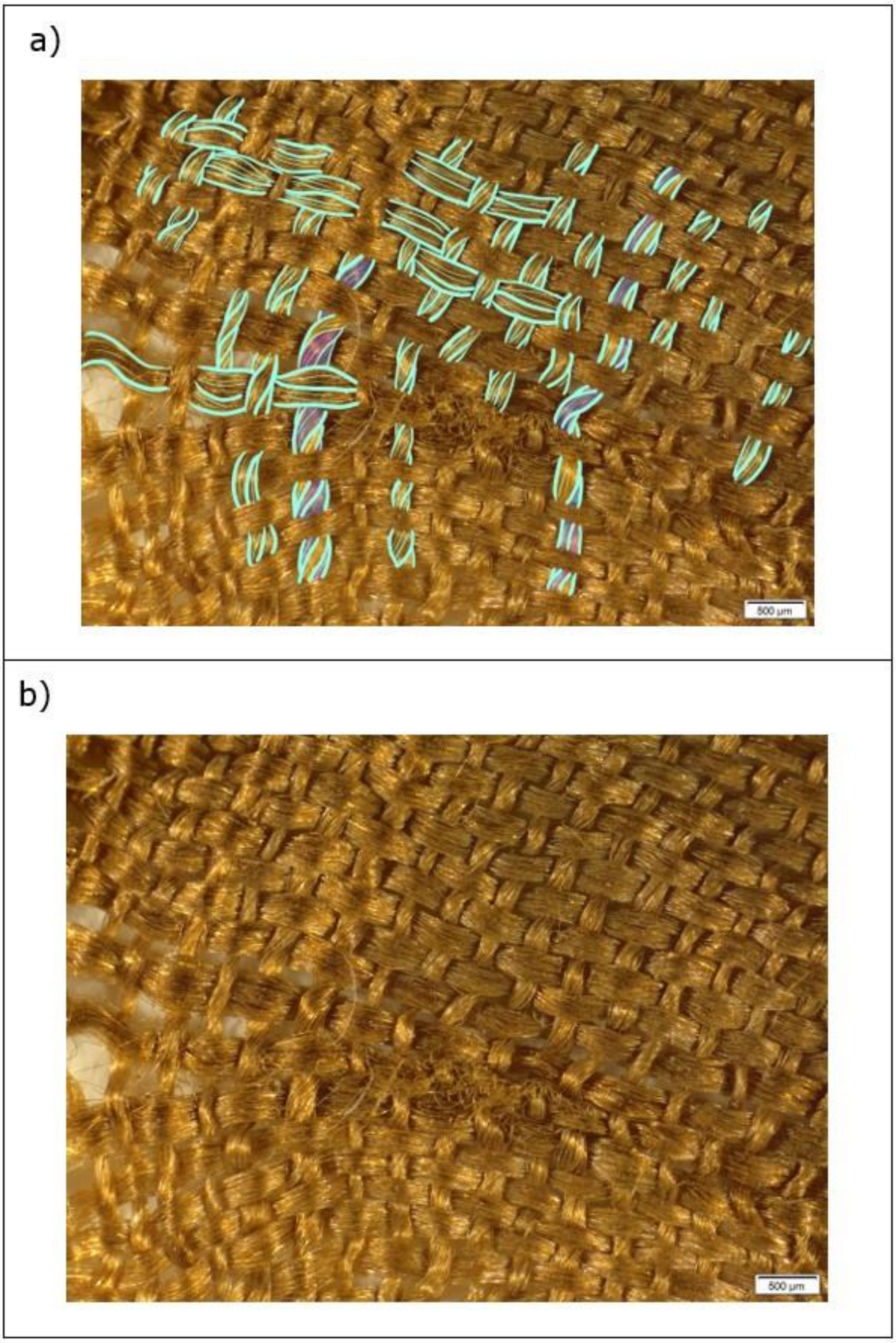


Figure 8.67: Coppergate Textile 1347, with traced indications of S2Z and S3Z-plied Yarn in warp system (a). The 3 separate elements visible in 2 of the warp threads in this image have been indicated with a 3-colour overlay

Coppergate 1347 is particularly interesting as it exhibited strong characteristics of plied yarn throughout the warp system. Most of the warp threads appeared to be S2Z, but there were indications of more than 2 elements being twisted together in some warp threads that appeared at intervals throughout the textile, suggesting that these particular threads were S3Z. These threads were typically thicker, and/or exhibited a higher degree of twist than the threads that appeared to be plied S2Z. These new observations would reclassify the twist of 1347 as S2Z&S3ZxI putting it in its own twist category.

Most textiles in the ZxZ category (Figure 8.68) have not been reclassified as any suggestions of ply were too subtle to support confident identification. The exception is 1351_ZxZ, which exhibited strong indications of an S2Z-plied yarn in both systems (Figure 8.69).

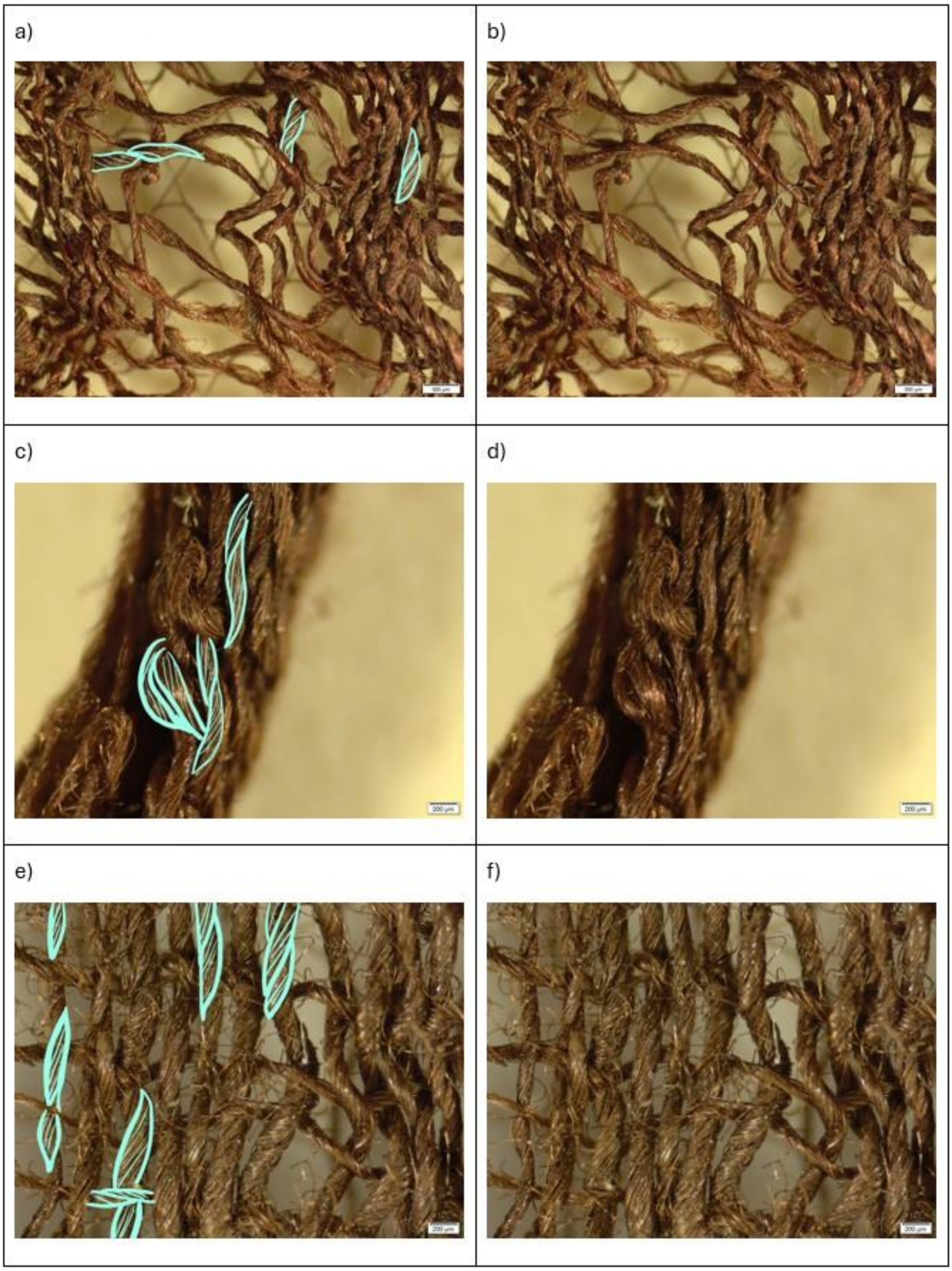


Figure 8.68: Coppergate textiles 1349 (a,b); 1352(c,d); 1371(e,f) showing traced areas that could indicate 2 separate elements in the threads (a,c,e)

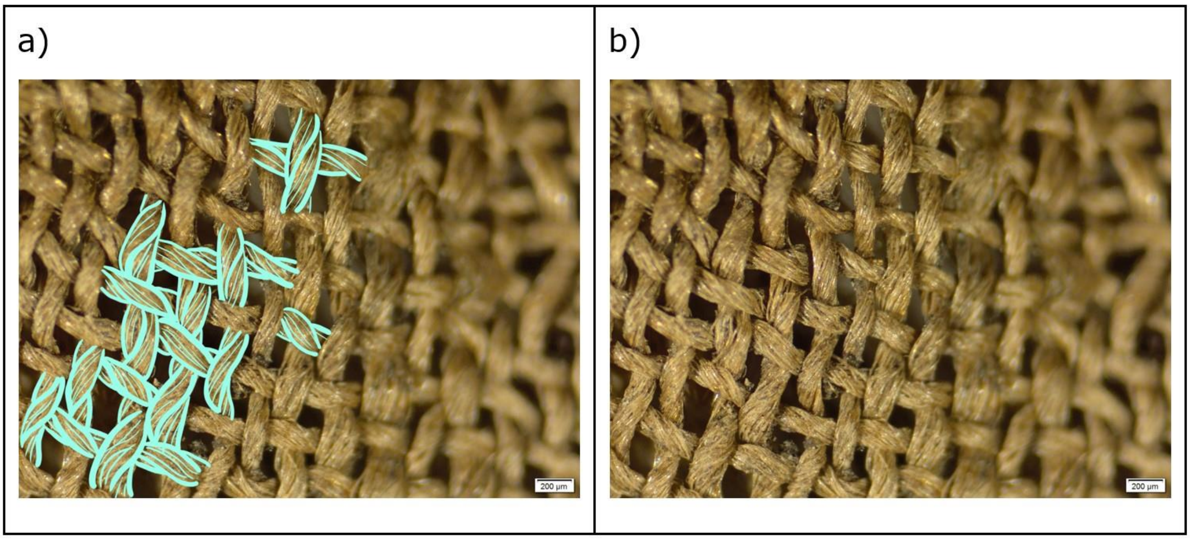


Figure 8.69: Coppergate textile 1351_ZxZ with traced indications of S2Z yarn in both systems (a)

The stitched-together pieces of silk ribbon which form Coppergate textile 1355 (Figure 8.70) showed clear indications of Z2S-plied yarn in the warp and weft systems. The indications of this have been made more subtle by close thread spacing and worn fibres, particularly in 1355-R2.

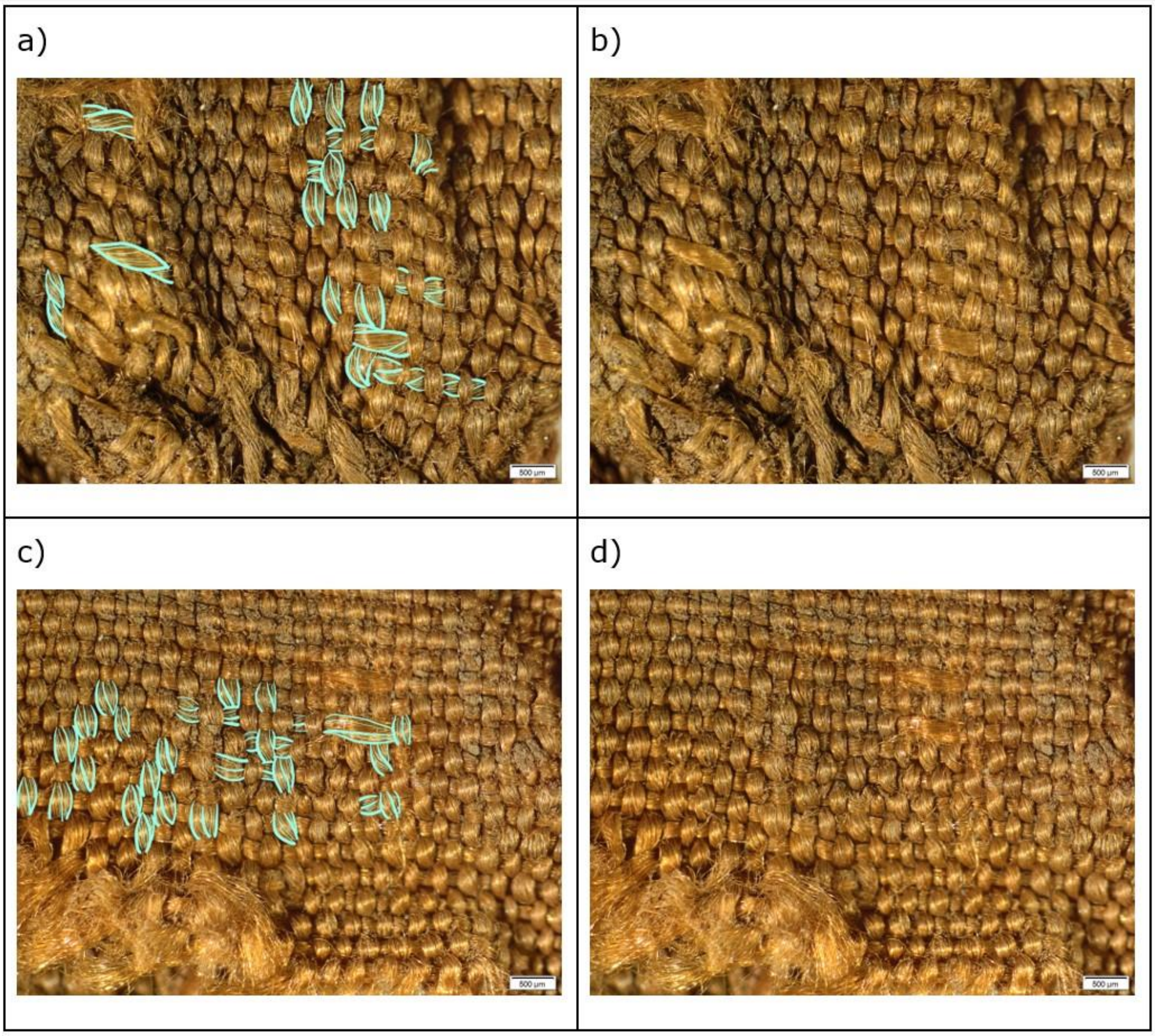


Figure 8.70:Coppergate 1355_R1 (a, b) and 1355_R2 (c, d) with traced indications of Z2S yarn in warp and weft (a, c)

The classification for 1351_IxI (Figure 8.71) has not changed, as there were no indications of twist or ply in either system.

Figure 8.71: Coppergate textile 1352_IxI, which shows no indications of ply or twist

These analyses have identified indications of plied yarn in at least one system of most of the textiles analysed, which created additional twist categories for the tabby-silk textiles from Coppergate (Figure 8.72). That said these new classifications were only suggested for fragments where the evidence for plied yarn has supported a confident identification.

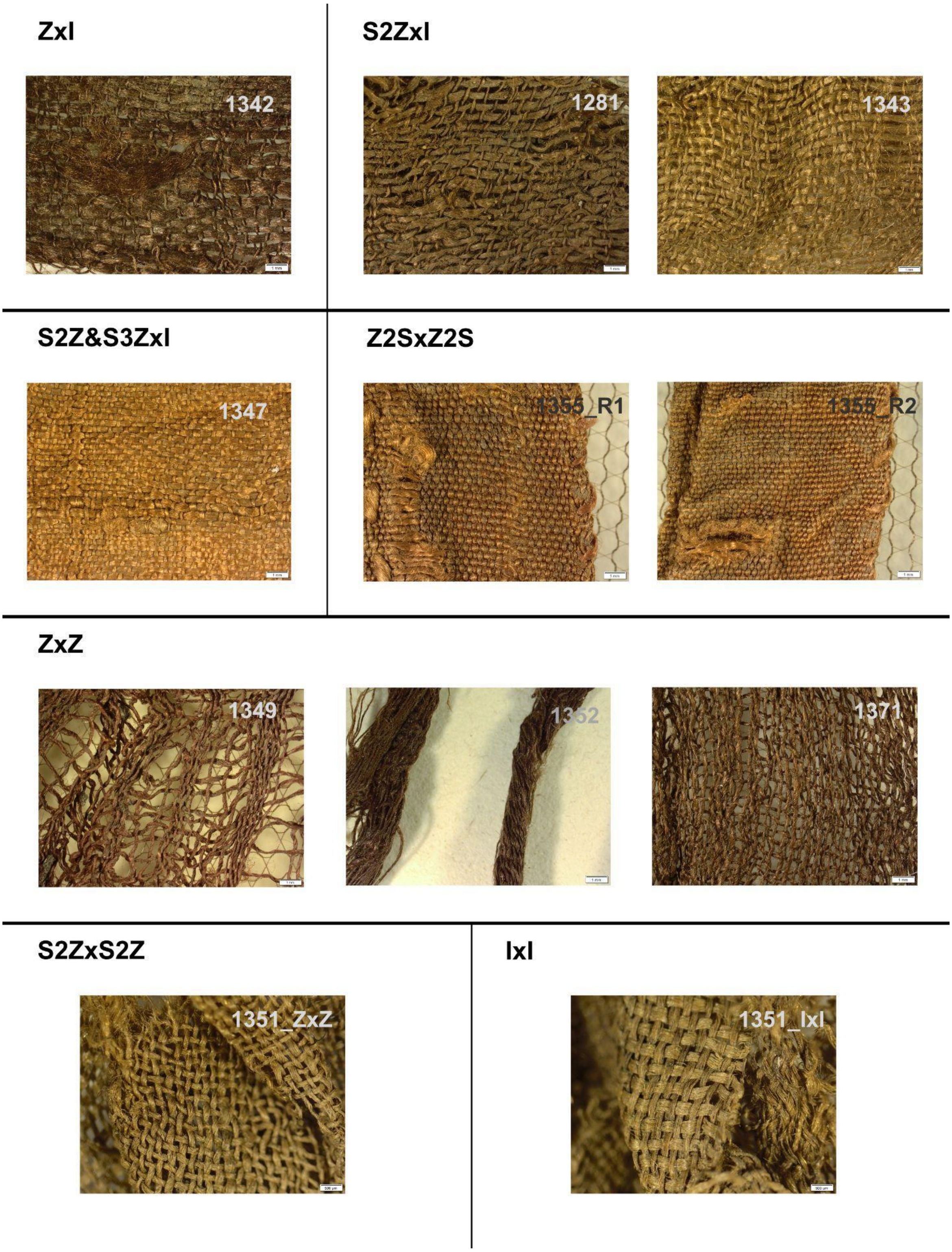


Figure 8.72:The Coppergate silk textiles sorted into new proposed twist categories based on the confident identifications indicated in Table 29

While the ply analysis carried out on the selected Coppergate silk textiles has complicated the twist categories, until a more comprehensive investigation of indications of plied yarn can be carried out on the remaining silk tabbies from Coppergate, Winchester and other comparable sites and collections, I argue that the textile twist groupings as previously written remain a useful shorthand for referring to tabby-silk textiles with these shared characteristics if treated as an overarching category for ease of reference, with ply details treated as a sub category within a larger group: a sort of theoretical taxonomic order of silk textiles (Figure 8.73) to which yet unobserved twist combinations could also be appended.

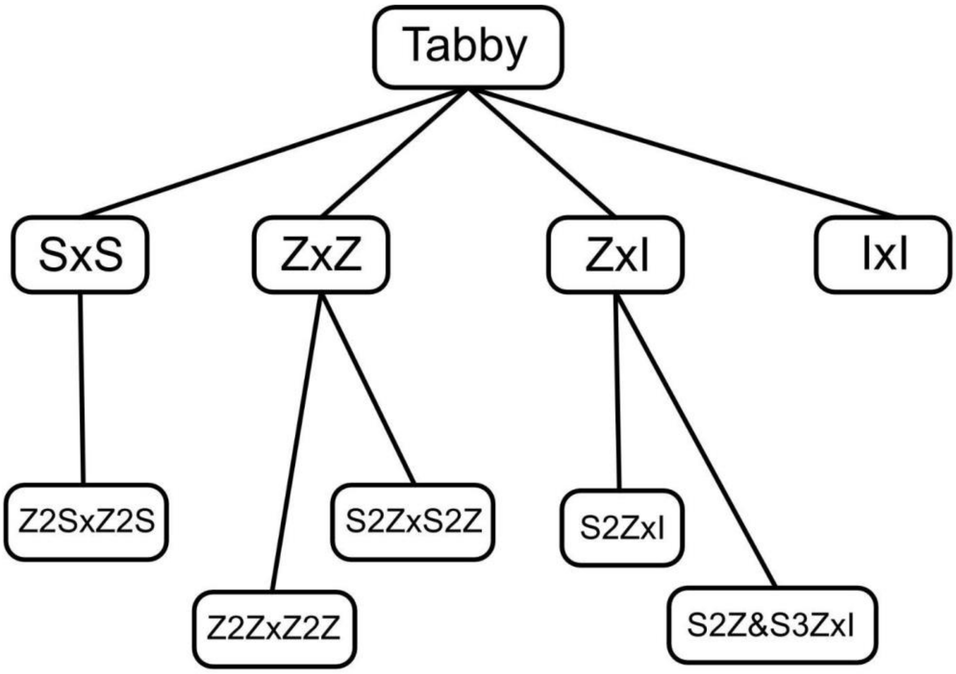


Figure 8.73:Diagram of how tabby cloth structures with plied yarns can be categorised as part of overall twist categories

8.9.1 Ply in relation to perception of twist

Revisiting the degree of twist of the textiles with the new ply identifications has yielded further useful results. Whether or not a yarn is plied appears to influence the perception of degree of twist relative to yarn twist angle. This is particularly clear when examining the Z-twisted samples, as most samples identified as plied were labelled as exhibiting a high degree of twist, while the samples identified as not being plied were almost entirely labelled as overtwisted (Figure 8.74).

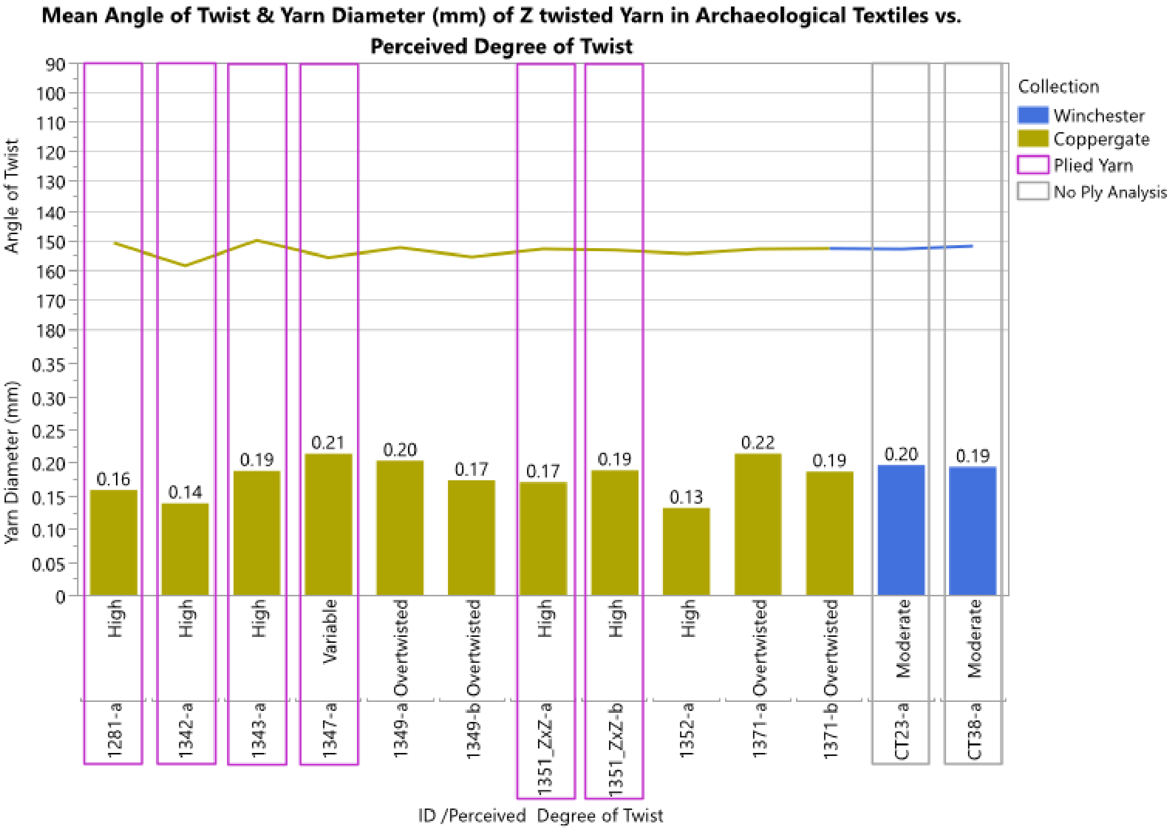


Figure 8.74: Mean angle of Twist of Z-twisted yarn vs. perceived degree of twist with plied yarns highlighted

This suggests that despite measured angle of twist, plied yarn tends to be perceived as exhibiting a lower degree of twist than single yarn with a comparable measured angle of twist. This can partly be attributed to the tendency of yarn that has been tightly twisted but has not been plied to kink or twist back upon itself.

This relationship is more difficult to assess in relation to the S-twisted yarn samples (Figure 8.75), as only 4 of the samples underwent ply analysis and all were identified as plied (Z2S). The plied samples in question were categorised as showing low to moderate twist, but without conducting a ply analysis of the Winchester textiles, further comparison cannot be made.

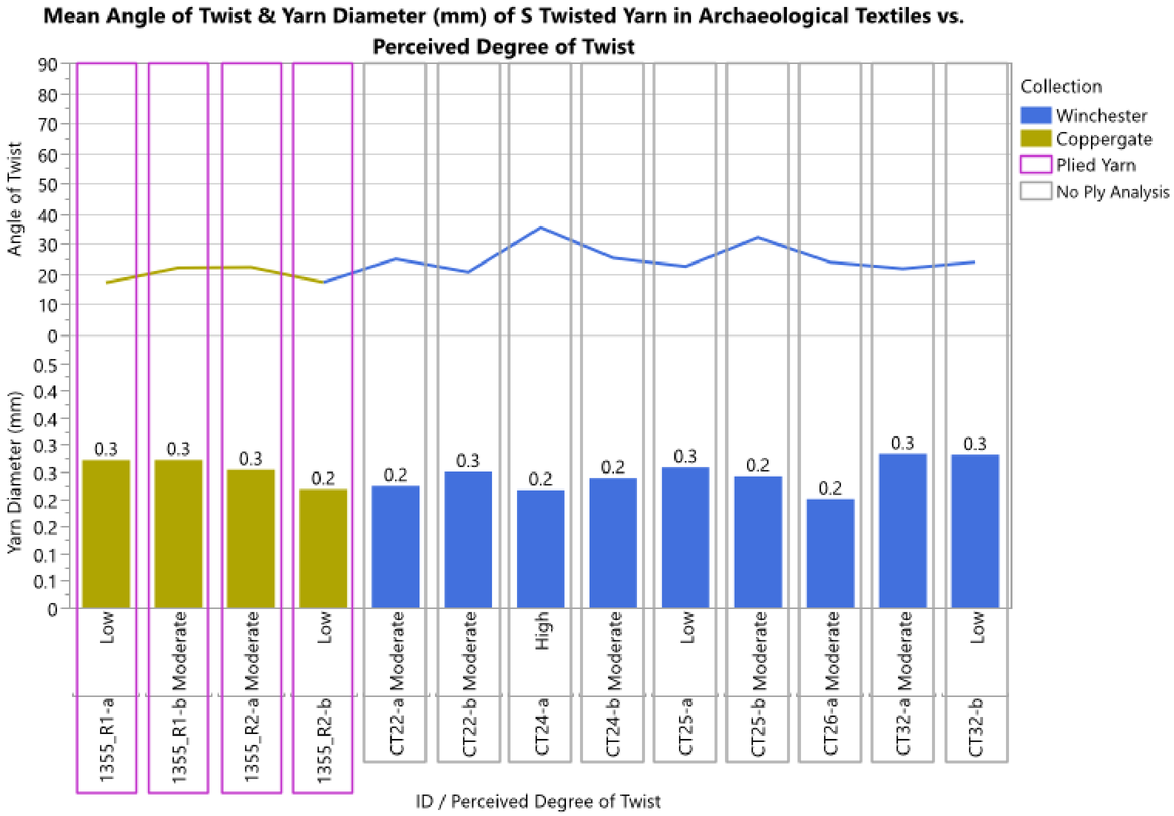


Figure 8.75:Mean angle of Twist of S-twisted yarn vs. perceived degree of twist with plied yarns highlighted

8.10 Analysis of thick threads in warp and weft systems of Coppergate textile 1347

Coppergate textile 1347 stands out visually in contrast with the other ZxI textiles. 1347 is more closely woven, with an overall more lustrous appearance than the other textiles in this group, and as has already been discussed appears to incorporate a number of threads in its warp system that are plied from 3 separate elements. Also of interest are 2 pairs of thicker weft threads visible in the upper third of the fragment. When mapped out in contrasting colours (Figure 8.76) the thicker threads give the impression of an irregular checked pattern, which appears to be a unique design feature not found in the other textiles analysed.

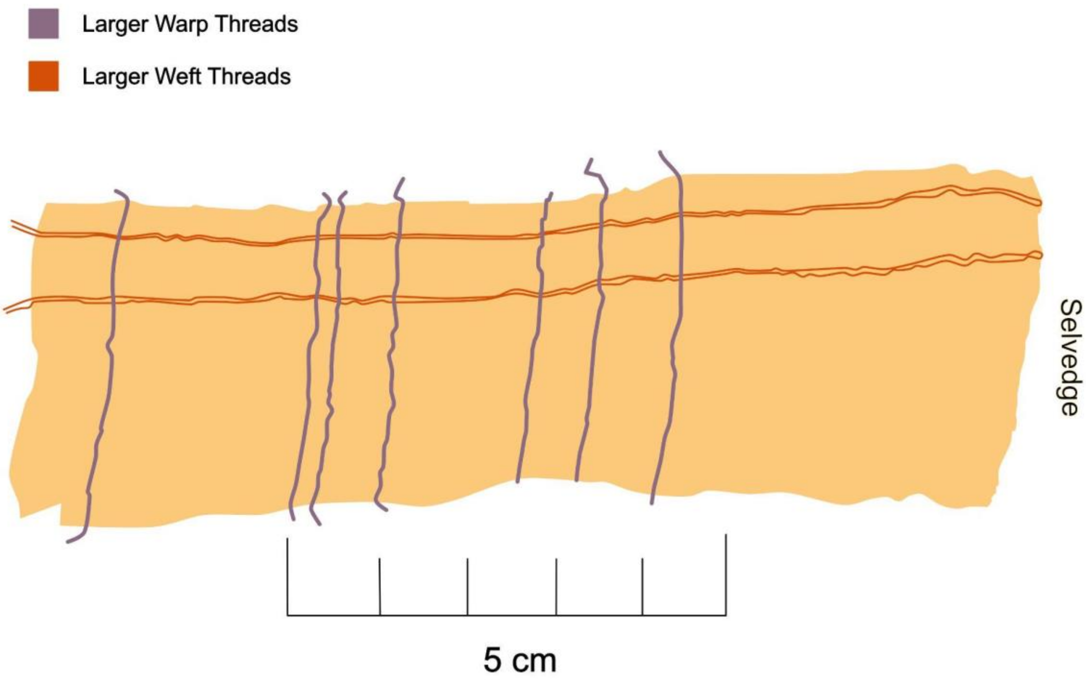


Figure 8.76: Illustration tracing the thicker warp and weft threads in Coppergate textile 1347

8.11 Reconfiguring Yarn and Textile Categories

While grouping the silk textiles by direction of twist in each system has indicated some trends in technical characteristics such as thread count and yarn diameter, this approach can obscure the ways in which the archaeological textiles may be grouped according to visual similarity. There is also a risk of losing sight of the various production stages involved in the manufacture of these textiles: an important consideration given that technical choices made during the production of silk textiles are likely to provide the strongest link to the location of manufacture, or at the very least the cultural tradition being followed. The qualitative categories established during the visual analysis of the textiles provide clues to how the yarn was manufactured, while highlighting visual and textural cloth characteristics that indicate technical choices made during the weaving process. Descriptive categories of the identified production methods and technical characteristics can expand upon the previously established textiles groupings, which primarily emphasise direction of twist. These re-imagined cloth and yarn categories highlight technical characteristics at multiple stages of production from yarn manufacture to finished cloth.

Across the Coppergate and Winchester textiles, 11 distinct types of yarn were observed when factoring in direction of twist, whether the yarn was plied, and whether the yarn was degummed:

1) Yarn without twist (I), Raw
2) Yarn without twist (I), Partially degummed
3) Yarn without twist (I), Degummed
4) Yarn with overall Z twist, Partially degummed
5) Yarn with overall Z twist, Degummed
6) Plied yarn (S2Z), Degummed
7) Plied yarn (S3Z), Degummed
8) Yarn with overall S twist, Raw
9) Yarn with overall S twist, Partially degummed
10) Yarn with overall S twist, Degummed
11) Plied yarn (Z2S), Degummed

When considering overall cloth characteristics, 7 distinct types of tabby cloth were observed based on thread density and balance, and type of selvedge:

1) Open crepe Tabby
    a. No preserved selvedge
    b. With preserved paired warp selvedge
2) Weft-dominant tabby
    a. No preserved selvedge
    b. With preserved paired warp selvedge
3) Textured tabby with mixed yarn diameters, preserved paired-warp selvedge
4) Dense tabby with 1 system dominant, No preserved selvedge
5) Balanced tabby with closely spaced threads, no preserved threads
6) Balanced tabby with open thread spacing
    a. No preserved selvedge
    b. Preserved plain selvedge
7) Warp-dominant tabby ribbon with plain selvedge

It should be noted that cloth of an overall type with a selvedge was not considered to be a separate category from cloth of the same type without a preserved selvedge. Were the selvedges of all textiles preserved, it is possible even more distinct categories would have been established.

When the production stages of each textile are illustrated (Figure 8.77) a tangled network of possible production sites can be visualised.

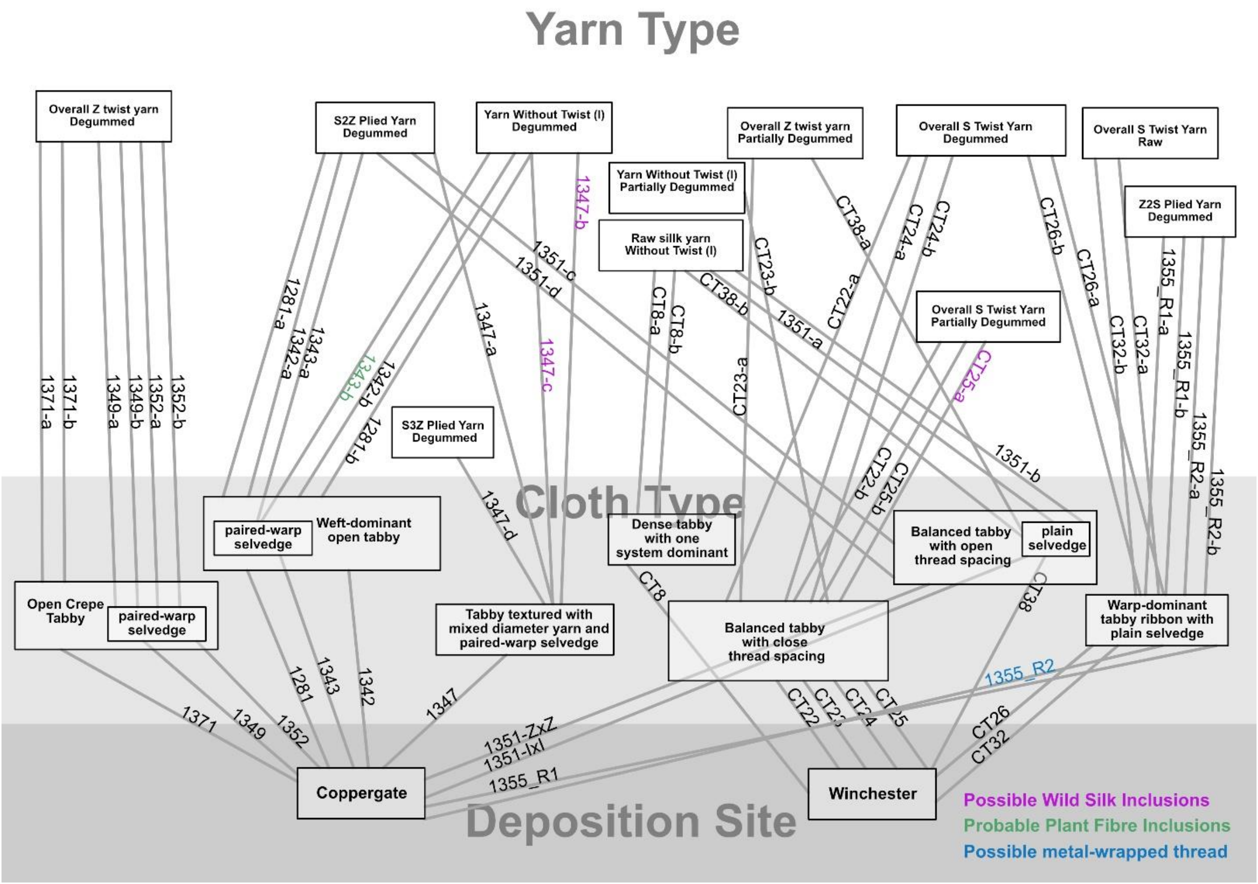
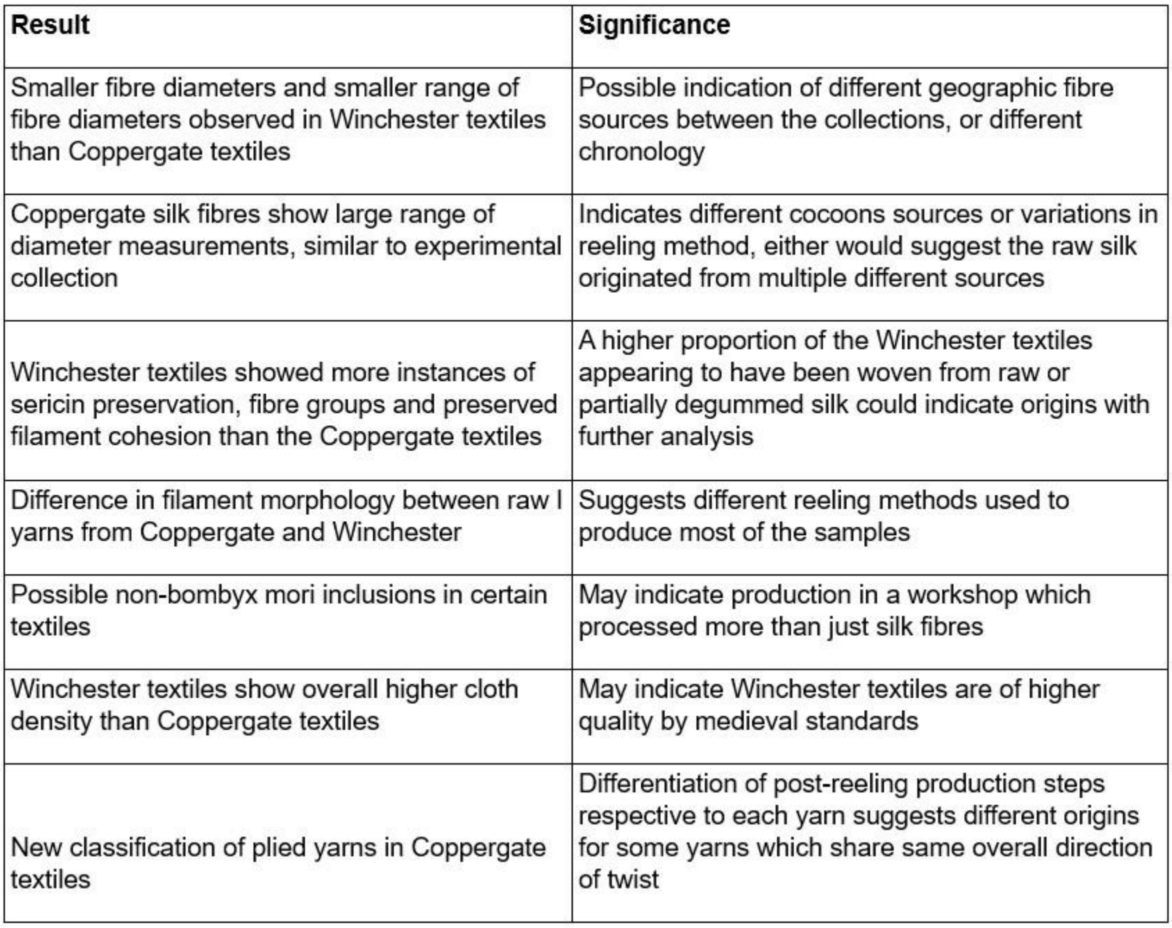


Figure 8.77: Theoretical Network Diagram Illustrating the technical features of the silk textiles and their component yarn from Coppergate and Winchester

Although theoretical, this diagram provides a useful reminder of the entangled silk production networks indicated by medieval sources. This visualisation also emphasises the potential for shared origins of particular yarn types. For example, all Coppergate textiles that can be described as “Open crepe tabby” are woven from the same type of yarn, suggesting that these cloth fragments could share an origin, and that their yarn may also all come from the same source. The warp-dominant ribbons in contrast, although sharing similar woven characteristics, show differences in their yarn; the 2 examples from Coppergate share yarn characteristics, while the 2 ribbons from Winchester show different levels of degumming from each other. Ply analysis of the Winchester textiles would aid in determining whether the yarn from CT26 shared the same production steps as the yarn from the Coppergate ribbons as they have both been degummed. Beyond the yarn and cloth categories depicted in figure Figure 8.77, the key findings of this research (Table 8.6) have also highlighted several fibre characteristics that may provide further indication of locations for each stage of production. The data generated here can be considered a first step in the direction of more comprehensive analysis.



Result	Significance
Smaller fibre diameters and smaller range of fibre diameters observed in Winchester textiles than Coppergate textiles	Possible indication of different geographic fibre sources between the collections, or different chronology
Coppergate silk fibres show large range of diameter measurements, similar to experimental collection	Indicates different cocoons sources or variations in reeling method, either would suggest the raw silk originated from multiple different sources
Winchester textiles showed more instances of sericin preservation, fibre groups and preserved filament cohesion than the Coppergate textiles	A higher proportion of the Winchester textiles appearing to have been woven from raw or partially degummed silk could indicate origins with further analysis
Difference in filament morphology between raw I yarns from Coppergate and Winchester	Suggests different reeling methods used to produce most of the samples
Possible non-bombyx mori inclusions in certain textiles	May indicate production in a workshop which processed more than just silk fibres
Winchester textiles show overall higher cloth density than Coppergate textiles	May indicate Winchester textiles are of higher quality by medieval standards
New classification of plied yarns in Coppergate textiles	Differentiation of post-reeling production steps respective to each yarn suggests different origins for some yarns which share same overall direction of twist

Table 8.6: summary of key results of the archaeological textile analysis and their significance

8.12 Summary

The results presented in this chapter introduce multiple pathways of exploration. The comparison of **fibre diameters** has introduced new questions regarding the variables that impact fibre diameter and how they may be used to better understand the production and origins of surviving mediaeval silk textiles. **Visual analysis of silk fibres** has presented the possibility of identifying production methods in surviving fibres, while also demonstrating the limitations of this approach depending on the types of processes applied to the silk, and the level of deterioration in the case of archaeological textiles. Contrasting visual analysis results with quantitative measurements have also highlighted the potential for discrepancies between measured values and the appearance of archaeological textiles, emphasising the value of a multi-faceted analytical approach.

The **visual analysis of the archaeological textiles** has introduced a wealth of new data to consider. The reconfigured textile descriptors provide another dimension to the silk tabby textiles focussed on their sub-elements, while demonstrating the degree of visual variation between the samples studied. This analytical approach has highlighted some trends in the appearance of the silk textiles, particularly amongst the established twist categories.

The comparison of different textile characteristics highlights similarities that may indicate shared processing methods and/or origins, while in-depth analysis of specific features such as plied yarn have opened a new avenue of inquiry regarding the production stages of medieval textiles. In Chapter 9 the implications of these results will be explored in relation to the context of medieval silk production and trade.

9 Discussion

The aim of this thesis was to determine whether the origins of archaeological silk textiles could be determined through technical analysis of yarn and fibres. The broader implications are that the results of this analysis can be used to expand our understanding of medieval trade connections. As will be discussed in this chapter, the technical analysis of the archaeological silk textiles expanded beyond yarn and fibre characterisation to examine how these elements form a simple cloth structure. Tabby silk textile characteristics have become an important part of this research and will be discussed in greater depth. The silk-processing experiments and textile analysis have yielded a significant quantity of data, providing new information on the identification of silk-processing methods. These results have complicated topics such as the identification of plied silk. Given that this research has employed a broad spectrum of analytical methods, this chapter first discusses the analytical approach taken and the reliability of the results of the experiments and analysis carried out. This will then lead into a key consideration: how the results may be used to infer potential production sites, before addressing the core question, "Can the origins of Archaeological silk textiles be determined through technical analysis?". The chapter will conclude by contextualising the Coppergate and Winchester Textiles, and considering the potential for further research.

9.1 Benefits of a Multi-Method Approach to Textile Analysis

This research was designed with an understanding that there are many different accepted approaches to archaeological textile analysis. The combination of an experimental approach with multiple analytical methods has helped to reduce the number of unknown variables informing the analysis and has provided insight into how a combination of approaches can make use of the strengths of each method while offsetting the weaknesses.

The combination of different types of microscopy and experimental archaeology has produced a novel study that provides detailed insight into the many variables connected to medieval silk production:

1. Transmitted light microscopy allowed for the observation of fibre shape, behaviour, texture, and easy distinction between fibre and sericin. The limitations of this method, however, are in the increasingly shallow depth of focus at higher levels of magnification, which limits the ability to accurately view a single fibre in its entirety above 100x magnification, and occasionally limits the ability to view an entire filament in focus above 50x magnification.

2. Scanning electron microscopy supported detailed capture of micrographs above 400x and easily up to 2000x magnification, while still showing fibres and filaments in relatively clear focus. The drawback of this method is that electron microscopy, not relying on the transmission of light, does not allow for differentiation between colours and levels of transparency in a sample. This means that, particularly in the case of raw silk fibres, it can be difficult or even impossible to differentiate between sericin and fibre. This emphasises the importance of using combinations of methods to properly characterise physical characteristics, particularly in relation to shape and texture.

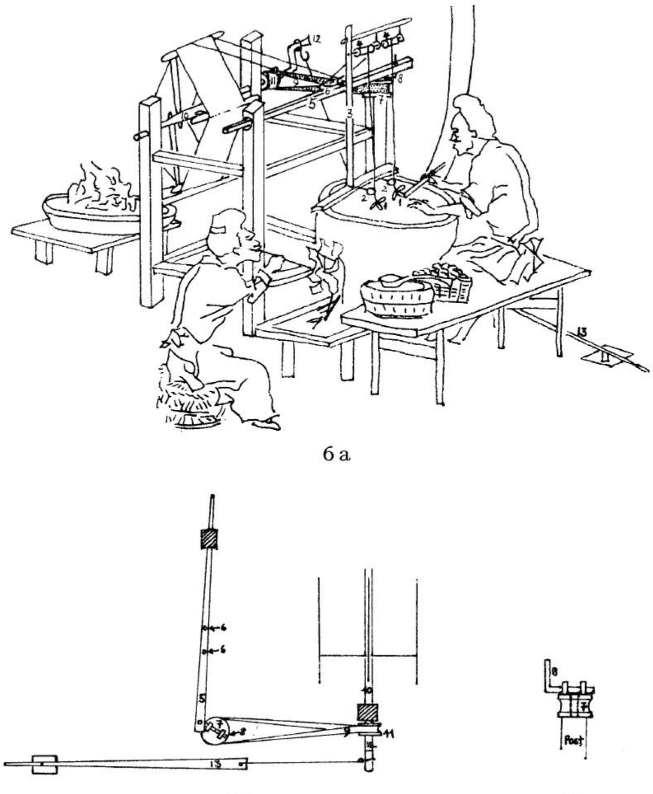
3. The combination of microscopic analysis with experimental archaeology has allowed for the observation of physical textile characteristics indicative of specific production methods. This has allowed for the creation of several new silk textile analytical frameworks including ply identification, and the distinction between raw, partially degummed, and fully degummed silk fibres. The assessment of archaeological silk fibres in contrast with experimentally generated silk fibres has also allowed for the assessment of silk fibre deterioration under different conditions.

In future, the combination of microscopic analysis with various methods of chemical and compositional analysis has the highest potential to yield a full picture of each production stage of a medieval silk textile. Collaboration across the fields of archaeology, chemistry and biology are most likely to produce more comprehensive results in future silk analysis endeavours.

9.1.1 Visual analysis of images: Successful transmissions or lost in translation?

Producing line drawings of silk-reeling device archetypes (as seen in Figure 3.1 & Figure 3.2) created an opportunity for further visual analysis of the catalogue images. This process highlighted many, sometimes subtle differences between mechanisms depicted in the catalogue while highlighting overarching similarities. Some of these observations have been addressed in relation to chronology. Other examples may seem extraneous but are worth noting, such as the evident differences in carpentry methods employed to construct these mechanisms. This manifests in the flat, blade-like shapes of the reel cross-pieces in European examples, in contrast with the more rounded Chinese examples and the frequently squared, with rounded edge shape of the Japanese examples. The construction of the reeling-frame in Figure 3.14 from an English source appears to use dowel joints to hold the frame parts in place, while the often-invisible joins of the Asian examples, and the Italian example in Figure 3.10 may indicate a more subtle method of mortise-and-tenon joinery or similar: another possible indication of a more direct connection between the 16th-century Italian reeling-frame and the style of reeling-frame depicted in 13th-century China.

The importance of close study of historical artwork may be further emphasised by the disparity in technical details between Figure 3.6 and a reinterpretation of Liang Kai’s early 13th-century depiction of a silk-reeling device (Figure 9.1). This illustration from c. 1981 has been used in multiple publications by Dieter Kuhn (1981, 1988).



6 a

6 b

6 c

Figure 9.1: Redrawing of reeling-frame depicted in Liang Kai's handscroll from Kuhn (1981, 73)

The redrawing aimed to clarify and correct some apparent mechanical inconsistencies in the original 13th-century image. Kuhn (1988, 358) claimed that Liang, the 13th-century artist, produced an incorrect depiction of the ramping-board, which he stated was depicted along the wrong axis of the reeling-frame. It was, however, suggested by Penelope Walton Rogers (2020b) during the initial compilation of this catalogue, that Kuhn interpreted Liang’s painting incorrectly, and that the ramping-board in the original appears to be depicted accurately if at an odd angle. Closer examination of the 2 illustrations confirmed Walton Rogers’ observation and revealed that Kuhn’s reinterpretation not only may have been unnecessary, but also took some of its own interpretive liberties, including depicting the rotating cam that drives the ramping-board on the opposite side of the reeling-frame to the original image. The line drawing produced for the diagrams in this summary have endeavoured to follow Liang’s illustration more closely.

Finally, while a visual investigation of Historical silk-reeling equipment provides many valuable insights, it cannot fill one persistent gap in knowledge; the fact that depictions of European silk-reeling devices appear to crop up suddenly no earlier than the 16th century means that it is frustratingly difficult to interpret the transmission and evolution of earlier European devices. The continuity of form, in particular the striking similarities between Arcimboldo’s depiction of a reeling device and Kai Liang’s demonstrates a clear connection between Chinese reeling devices and those used in early modern Europe. An unfortunate gap in understanding this transmission of technology is an apparent dearth of depictions of silk-reeling equipment from Central Asia and the Middle East in particular, despite written evidence that sericulture was practiced in these regions.

9.1.2 The Importance of Experimental Archaeology to Understanding Medieval Silk Production

The study of artefacts has generated innumerable theoretical debates regarding the how and why of making. In a sea of theory, the practical and tactile aspects of craft can be easily washed away. In a frustrated critique of what he observed to be a theoretical fixation on the concept of materiality divorced from actual materials, Tim Ingold asked, “Might we not learn more about the material composition of the inhabited world by engaging quite directly with the stuff we want to understand: by sawing logs, building a wall, knapping a stone or rowing a boat?”(Ingold 2007, 3). Susanna Harris (Harris 2019, 12–13) has also emphasised the value of experimental archaeology in exploring the sensory qualities of textiles. Engaging with silk as a material has been at the core of this research, and while the experimental design took a scientific approach with the aim of conducting controlled, repeatable experiments, the experiential aspect of this process has also provided further insight into the aspects of silk-reeling that are rarely articulated in writing. In this case, enacting the tactile processes of silk production led to observations resulting from the experimenter's own sensory experiences, which allowed the discussion of key tactile and physical aspects of silk-reeling. As Millson cautions, these experiences cannot be used to infer the emotions and motivations of silk reelers of the past (Millson, Theoretical Archaeology Group and ebrary, Inc 2010, 3), but the experiences are nonetheless valuable and highlight the range of information that can be gleaned by designing experiments that may serve as a springboard for experiences.

9.1.3 Tacit Knowledge and Apprenticeship

The experimental research conducted has underscored the importance of tacit knowledge in relation to craft production, while providing the opportunity to reflect on the role of apprenticeship in relation to this topic (Chapter 5.4.5). The physical process of reeling and working with silk has helped to highlight the importance of tacit knowledge when working with such a precious and specialised material, which calls to mind Ingold's frustrated call to arms. The process of carrying out multiple, and repeated silk-processing experiments certainly led to a better understanding of production methods than could be achieved through the analysis of archaeological textiles alone.

As has already been alluded to, the importance of tactile, visual, and mechanical understanding of silk-reeling has implications for how knowledge of silk-production methods is transferred. This also needs to be considered in relation to the various contexts of silk production previously discussed, from rural sericultural operations to large-scale imperial workshops. The natural variation of practice in these different contexts will partially account for varying qualities of raw silk noted in the historical record. This is important given that, as discussed in chapter 2, variations in quality of silk from the archaeological record are often attributed to differing sericultural practices resulting in varying qualities of cocoons in different regions. While cocoon quality should not be dismissed as an influencing factor (as it seems likely that qualities such as fibre diameter are at least partly influenced by the cocoon formation process), fibre analysis results from the experimental reference collection indicate that reeling methods are likely to have some impact on the silk fibres themselves, and certainly impact the shape, cohesion, and sericin integrity of raw silk filaments. This clearly demonstrates that the methods applied to reeling and, by extension skill and knowledge of the process, have a measurable impact on silk quality.

Finally while there is a strong theoretical movement towards exploring the interconnections between material and social engagement in archaeological theory, as emphasised by researchers such as Dobres (Dobres 2000, 128), a more dualistic framing of the technical and theoretical aspects of production can be found in discussions of textile production (Harris 2019; Bunn 2022).

The positioning of considerations such as *chaîne opératoire* in opposition to engagement with theories of apprenticeship and knowledge acquisition in relation to habitus, tactile learning and so on misses the opportunity to explore what can be learned from each approach. I find it more helpful to view them as distinct approaches suited to answering different questions. Bunn has rightly argued that the concept of *chaîne opératoire* is not equipped to address phenomena like tacit knowledge, or how craft skills are acquired (Bunn 2022, 68–69), but that is not a problem if the researcher’s concern is with the origin of materials and the “how” of production. This is worth keeping in mind as, while the modes of knowledge transmission relevant to medieval textile production are an important and fascinating concept, there are limitations to the degree to which one may understand the thought-process and physical experiences of a medieval silk worker. In the absence of written first-hand accounts, traces of frustration and carelessness in the form of structural flaws preserved in surviving textiles provide a window into the experiences of the medieval silk weaver. On the other hand, as would be the case when peering into the window of a stranger’s house, one may gain insight into what that person is doing but this does not necessarily enable the voyeur to understand the full complexity of “why” a person is doing something. Peering through a window is not the equivalent to mind-reading; this is why a combination of approaches is beneficial, as it allows the researcher to explore craft activities at different scales, as it were.

9.2 Significance of the Methods Tested

The broad scatter of analytical methods tested during this research has been covered in Chapter 6, and as was made clear in chapters 7 and 8, a large volume of data was generated. The silk processing experiments demonstrated that both reeling technique and the equipment used influence the shape, diameter, appearance, and texture of the silk in a way that is (to a variable degree) perceptible without microscopic analysis. Other characteristics influenced by these variables such as filament cohesion and sericin integrity, while not always obvious without microscopic analysis, could have implications for the strength and resistance to friction of the reeled silk, which may have the potential to be related to previously mentioned descriptions of high- or low-quality silk in medieval documents.

The key finding of the experiments is that variation in (1) the types of equipment and (2) production methods affect the morphology and behaviour of reeled silk in a manner that can be observed. These observations support the idea that regional and chronological differences in processing methods and equipment throughout the Middle Ages would have had a measurable impact on the silk produced, and in many cases the impact of these variations would have been perceptible even without the use of modern scientific equipment. One would assume this would particularly be the case for craftworkers, and traders who made a living from medieval silk industries and worked closely with silk in its various forms.

9.2.1 Fibre Deterioration: Mechanical, Environmental, or Bacterial?

The assessment of fibre deterioration has been important to assessing the validity of the fibre-analysis results. The analysis results indicated different levels of deterioration between textiles, as well as different trends in the overall deterioration at the fibre and textile level between the 2 collections. The Winchester silks showed an overall higher level of fibre deterioration, with more instances of pitting than the Coppergate textiles, while the Coppergate textiles showed more overall yarn deterioration at a macro level. To understand the causes of this deterioration, it is important to look at the types of damage recorded as well as considering the textiles within their deposition context.

The Coppergate and Winchester silks show multiple types of deterioration including shattering (brittle fracture), splitting and fibrillation, and pitting, forming in 2 distinct patterns. A few traces of insect damage were also observed, but this type of deterioration was rare overall.

Both Coppergate 1355_R1 and 1355_R2 show brittle fracture in the warp systems that is similar to damage observed in one of the Alexander series tapestries from Hampton Court Palace, and described by Hearle et al (1998, 390) as creating a “pile” effect in the dominant system (the weft in the case of the tapestries). In the case of the tapestries, the damage was attributed to a probable iron mordant in combination with photodegradation, and this may provide cause to investigate the possible mordants used in these textiles, which have already been determined to have been dyed with Kermes (Walton 1989, 367–368). Because the Coppergate and Winchester silk textiles predate the common 19th-century practice of using tin and other metals to “weight silk”, this can be ruled out as the cause of any brittle fracture observed (Hearle, Lomas and Cooke 1998, 391). Splitting and fibrillation can be attributed to mechanical damage through abrasion (Hearle, Lomas and Cooke 1998, 382) and since this form of damage was observed at a higher rate in the Coppergate silk textiles, this could indicate more frequent use and wear of the garments or accessories with which these samples were associated.

Other studies on historic and archaeological silk deterioration have determined that silk fibroin is less vulnerable to fungal attack but is still at risk of bacterial damage (Luxford 2009, 26), which may be the cause of the higher concentrations of pitting observed in the Winchester textiles. In contrast, the overall excellent preservation of the Coppergate textiles was first explained by Walton Rogers, who in addition to noting the previously made point about the relative resistance of silk to fungal damage, pointed out that in soil rich in tannins and humic acids bacterial deterioration is also less likely to take place (Walton 1989, 300). It is possible therefore, that if some of the pitted damage observed in the Coppergate silks is the result of bacterial damage, this could have occurred in the time between initial conservation and analysis and this recent analysis.

The findings from this research also call into question the assertion that sericin is unlikely to be preserved outside of arid conditions (See Chapter 2), although it is worth asking whether the higher number of Winchester samples with preserved sericin relates to technical choices, or the fact that their preservation conditions were different from the high-humidity conditions of the Coppergate silk textiles. That said, were the soil conditions at Coppergate to play a large part in the deterioration of sericin, it might be expected that more uniform elimination of sericin would have been observed. Given the fact that both clearly degummed and probably raw samples were identified in both collections, it seems likely that at least some degree of variation in the production choices made is responsible, but it is possible that at least some sericin preservation has been lost due to environmental conditions.

9.2.2 Impact of the Degumming Process on the Plausibility of Interpreting Reeling Methods from Archaeological Fibres

When silk is degummed, the sericin coating the fibres and adhering them together is either partially or completely removed. This naturally means that a key challenge to identifying reeling methods in archaeological silk textiles is that the obvious visual evidence of specific reeling methods is eradicated by the degumming process. This means that archaeological silk fibres with higher amounts of sericin preservation are more likely to support the identification of reeling methods, while archaeological silk fibres with little to no sericin integrity are less likely to allow for this identification. Conversely, lower degrees of sericin preservation may still provide insight regarding the degumming processes used, and a good deal may still be interpreted from degummed yarn regarding throwing methods.

The preservation of sericin in some of the archaeological textiles analysed supported the identification of parallels between the IxI textile fibres and specific experimental samples. This led to suggestions of which reeling techniques might have been used, though no such parallels could be reliably made with the remaining samples, which showed less sericin preservation and/or were more difficult to interpret while in situ in twisted yarn.

While the suggested reeling methods are plausible, and could be used in combination with other textile characteristics to determine the potential production place(s) of the IxI textiles, the possibility of other factors influencing the preservation and appearance of the fibres must be acknowledged, as well as current gaps in information regarding the technical details of comparable textiles associated with other sites.

9.2.2.1 Interpreting the Efficacy of Degumming Methods

The degumming methods trialled proved to be highly effective at stripping sericin from the fibres in alkaline solutions of at least a pH of 8.

Degumming processes using a solution with a pH of 7 proved ineffective at dissolving sericin, regardless of temperature, but did reduce the cohesion of the reeled filaments, with increasing efficacy proportional to the amount of time simmered. The results were partially degummed silk that was softer to the touch but without the same texture and sheen as fully degummed samples.

The degumming experiments identified water pH as a key factor in the degumming process. This variable could be explored further to assess the point at which sericin begins to dissolve. Further experimentation with pH variation could produce samples with further varying levels of sericin preservation.

These experiments highlighted the fact that Sericin is resilient, with traces surviving even following thorough degumming processes meaning that accidental degumming is unlikely to occur except in environments with extremely high pH. It is possible to visually distinguish between raw, partially, and wholly degummed silk fibres to a certain extent, but this becomes complicated in the case of raw silk with low filament cohesion. This means that it may not be possible to distinguish between raw silk that has been reeled at lower temperatures or from small cocoon quantities resulting in low cohesion, and silk that has been partially degummed. This is particularly true if other distinguishing characteristics such as the crystalline inclusions observed in the partially degummed experimental samples are unlikely to survive deposition and aging in an archaeological context.

9.3 Indications of Different Production Sites

The aim of identifying indicators of the origins of silk textiles through technical analysis has been central to this thesis. A key assumption in the study of archaeological textiles is that variations in production method between textiles are indicative of different production locales, be they workshops, communities, or broader regions. In a study of Late Horizon

(1400-1532 CE) Andean textiles, Bongers et al. propose that "materials with apparent, consistent techniques across multiple phases of production correspond to preferences that marked distinct communities of weavers." (Bongers, O'Shea and Farahani 2018, 223). This integrates with the previously discussed concept of the prevalence of social and cultural influence on craft processes and technological development, specifically the interdependence of social influence and technology (Dobres 2000). Lemonnier (2004, 3) argues that any techniques should be considered a "physical rendering of mental schemas learned through tradition and concerned with how things work,". This principle is also supported by Desrosiers' (Desrosiers 2004, 184) suggestion that a homogeneity of technique will indicate a silk textile's origins.

There is arguably further room for exploration of technical variation in textile production as an indicator of origin; the idea that differences in technical choices are influenced by the artisan's social context is foundational to any interpretations we can make on a theoretical trade and production network of medieval silk textiles. Within the context of this thesis, a broad scatter of analytical methods was trialled with the aim of determining the extent to which measurements such as thread count, yarn diameter and angle of twist, and fibre and filament diameter are reflective of specific processing methods. This has been further expanded through the visual analysis of textiles resulting in a theoretical network of differing production origins. The link between differences in technique and different production sites is further bolstered by historical descriptions of silk textiles.

While a significant amount of information on the technical aspects of silk production has been lost to time, we are fortunate to have an impressive number of written records related to the types of silk traded during the c. 300-year period before, during, and after the 10th century, which in some cases indicates continuity of textile types extending both earlier and later than this time-period. While these written records provide fascinating (sometimes contradictory) insights into which regions produced desirable silk at a given time, and what types of silk were most desirable, it can be difficult if not impossible, to link many of the terms used to a specific type of silk product, presumably because the writers of the time assumed that these terms would be understood without explanation. Nonetheless, thanks to the work of several dedicated scholars, some clues can be gleaned from these historical texts.

From translations of documents from the Cairo Genizah (c. 950-1230 CE), and Dunhuang and Turfan (Zhao and Wang 2013), Byzantine texts such as the aforementioned Book of the Eparch, and a number of Arabic texts (Serjeant 1972) terms for particular types of silk crop up that provide some indication of the common types of silk produced. For example, the documents from Dunhuang and Turfan, contain a general word for plain weave silk (*Juan*), and specific terms for raw (*Sheng Juan*) and degummed (*Lian*) plain weave silk, and even coarse tabby woven from spun silk (*Gua*) (Zhao and Wang 2013, 351, 353). The Arabic term *Attabi* referring to tabby/plain weave cloth (Serjeant 1972, 243) is certainly applicable, but not exclusive to silk.

9.3.1 Fibre and Filament Diameters

Analysis of the experimental silk fibres has confirmed that relative position within the cocoon influences fibre diameter, while complicating how this can be interpreted in relation to archaeological silk fibres in situ in a woven textile. Experimental fibre diameters were compared in relation to water temperature, type of reeling-frame and crossing method, and some indication that water temperature and to a lesser extent crossing method could influence fibre diameter was observed. This result could indicate that silk fibres are sufficiently malleable when being reeled in very hot water that the varying degrees of pressure exerted by different crossing methods result in some degree of fibre compression. This is an intriguing possibility, but a great deal more experimentation and analysis would be necessary to confirm this.

The similarities between the Coppergate fibre-diameter range and the experimental silk-diameter range have been discussed as a potential indication that the Coppergate textiles may be reflective of a reeling method that incorporates new cocoons throughout the reeling process. It is uncertain if incorporating new cocoons was a less common practice in some regions. If so, the smaller range of Winchester diameters could be considered an indication that the reeling of these silks was carried out in such a place.

Interpreting the stage of reeling as a proxy for the position of the fibres within the cocoon partially supports other evidence that the position of a fibre segment within the cocoon influences fibre diameter. The slightly larger diameters from the beginning of the reeling stage suggest larger diameters in fibres from the exterior of the cocoon, while the generally lower fibre diameters from the end stage of reeling suggest smaller diameters from the interior fibres. That said, both the wider range and higher average of diameter measurements from the middle reeling stage disrupt the theorised pattern of diameter measurements, and demonstrate that fibre diameter cannot be considered an accurate predictor of where the fibre was located within the cocoon.

One final but important consideration is how frequently fresh cocoons are added during the reeling process, and by extension the accuracy of using fibres from the middle reeling stage as a proxy for fibres from the middle of the cocoon when gathering samples. Subtle variation in cocoon size and wall thickness result in silk cocoons completely unravelling at different rates, which is why descriptions of the reeling process emphasise the importance of a designated, experienced individual minding the cocoons and introducing fresh ones as they run out or break away (Desrosiers 2019, para.6). The silk-reeling experiments incorporated the introduction of new, soaked cocoons as older ones fell away to reflect historical reeling processes more accurately and marginally extend the output of silk. This is an important consideration as, while the majority of the fibres from a sample representing the middle of the reeling process are likely to be from the middle of the silk cocoon, these middle-of-reeling samples are likely to comprise some fibres from closer to the interior of the cocoon as well as fibres from the exterior, which would result in a much wider range of fibre diameters within a sample. Middle-of-reeling samples that generated fibre diameter measurements within a narrower range/smaller standard deviation may represent a middle stage of reeling during which no cocoons have run out, and no fresh cocoons have been added. It is therefore possible that such samples more accurately reflect the diameters of fibres from the middle of the cocoon.

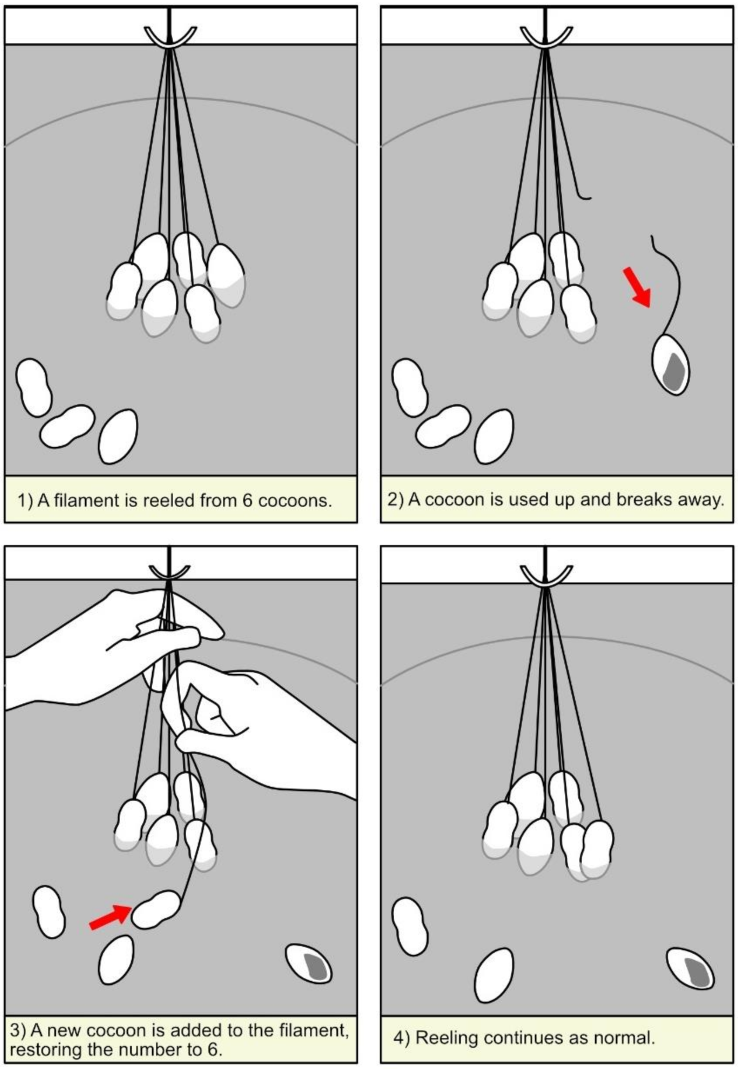


Figure 9.2: Steps for incorporating a new cocoon into the filament during reeling (Illustration by Gwendoline Pepper)

The results of this analysis have demonstrated that fibre-diameter measurements in isolation cannot be considered an accurate predictor of position of the fibre within the cocoon (Chapter 7.6.1.). The collected data do, however, indicate that fibre samples with a wider range of diameters are more likely to have been produced during the middle stage of reeling. It could therefore be argued that range of measurements and average diameter in a fibre sample could be used to interpret the stage of reeling during which the sample was produced, if other variables are also taken into consideration.

Difference in the origin of the cocoons is unlikely to have impacted the experimental fibre diameters, as the cocoons were all procured from the same source. That said, it was not possible to control for factors like potential variation in silkworm nutrition or rearing conditions during the growing season, so these remain unmeasured potential variables.

Given that both position of fibre within the cocoon and origins of modern silk cocoons have already been demonstrated to influence fibre diameter (See Chapter 2), if fibre-diameter range and mean can be confidently linked to stage of reeling, rather than cocoon quality or silkworm origin, this would have important implications for interpreting reeling methods through technical analysis of fibres.

Analysis of the filament diameters indicated strong relationships between crossing method and filament diameter, which in some cases appeared to supersede the obvious relationship between filament diameter and the number of cocoons reeled. The basic principle that wrapping silk around a roller results in generally smaller filament diameters, with still smaller resulting diameters when the silk is crossed around itself, is useful in the analysis of silk yarn. This is particularly important as –at least as far as raw silk yarn is concerned – the experiments have demonstrated that the number of cocoons that make up a yarn fragment cannot be accurately estimated without accounting for potential crossing or wrapping methods.

The process of adding cocoons throughout the reeling process is also relevant to filament diameter. As discussed, the addition of cocoons at different stages and with different levels of frequency by experiment resulted in the combination of exterior, interior, and middle cocoon fibres during the middle-stage of reeling, which explains the degree of diameter variation in the middle-of-reeling fibres analysed. In contrast the filament diameters showed less variation in the middle-of-reeling stage than the fibre diameters did. This can be attributed to the averaging out of overall diameters (whether the filament section is made from all middle cocoon sections, or a mixture, of thicker exterior, thinner middle, and thinnest, interior fibres), as thinning cocoons dropped off and new ones were added in. What this means is that, while an analysis of the fibre diameters of the interior, exterior, and middle sections from single cocoons may yield the predicted results, this was not the case overall when analysing the fibres which made up silk samples from the middle of the reeling process, regardless of technique. The significance of this point is that while the fibre diameters in the main part of the reeled silk filament may be inconsistent, this does not translate to the filament diameter, and by extension does not negatively impact the quality of the reeled filament. This is worth taking into consideration as higher degrees of variation in cross-sectional area have been used as evidence for inferior qualities of silk, and used to argue fibre origin (Zhao 2021, 100–101). The experimental results do not disprove this theory but do indicate the possibility that a higher degree of variation may simply indicate whether silk came from the beginning, middle, or end, of the reeling process. This does not mean that other variables such as silkworm origin and nutrition have no impact on fibre diameter, but these observations do highlight the importance of taking production methods into consideration alongside these other potential variables.

9.3.2 Other Physical Characteristics of Fibres and Filaments

The experimental silk analysis has successfully identified several physical characteristics that may allow for the identification of specific reeling methods through the microscopic analysis of raw silk filaments. What can be explored further is how these characteristics may influence the durability, strength, and overall appearance of the yarn and finished textiles manufactured from the different types of raw silk filament. Some predictions may be made on this subject. For example, the tendency for wide-spread fibres with low filament cohesion in silk reeled at lower temperatures and with no crossing method is likely to mean that the silk filaments are less abrasion-resistant and could be more vulnerable to breaking and fraying during subsequent production stages. This may also result in less durable cloth. The inverse would be expected of silk that has been reeled at a temperature of at least 80° and has been crossed in some manner, resulting in more densely packed fibres and high filament cohesion. The potential impact of the "looped" fibre effect in silk reeled in boiling water is harder to predict, but it could result in increased wear on the section of fibre that loops away from the otherwise cohesive filament, resulting in a slightly "hairy" yarn. This would have important implications for linking water temperature, physical characteristics and region of production if considered in relation to Galliker's observation that silk yarn in textiles confidently attributed to the mediterranean were notably hairy in appearance (see chapter 2.3.5.3).

These predictions are plausible but unproven and made to emphasise the point that the effects of reeling methods may influence the quality of the silk at each subsequent stage. The full implications of the effect of silk-reeling processes on the quality and appearance of finished silk products cannot be determined without further experimentation and analysis. This is an important consideration, as the archaeological silk textiles analysed vary widely in texture, appearance, and preservation. Additionally, linking fibre and filament characteristics to strength and durability may allow for connections to be drawn to medieval concepts of quality. For example, the c. 11th-century term "*Jiz*", which apparently refers to silk reeled from the cocoon, is described as very high quality. This demonstrates a clear understanding of the distinction between reeled silk and spun silk in the medieval mediterranean while suggesting that reeled silk held a higher value than spun silk (Goitein 1967a, 455). *Khazz* is described in the *Mahasin al Tidjara* as another high-quality silk based on the strength of the warp yarn(Serjeant 1972, 201). This indicates the value placed on yarn strength, which underscores the importance of understanding the relationship between yarn and fibre characteristics and strength.

The influence of crossing methods on filament cohesion, fibre spacing, and filament shape also clearly correlate to the influence of crossing methods on filament diameter. It could therefore be argued that crossing methods used during reeling influence the overall shape, fibre spacing, and level of cohesion within a filament, which have a carry-over effect of influencing both filament-diameter mean and variation of diameters within the filament.

The visual analysis of the experimental silks also identified characteristics that can be tied to specific processing variables. Rippled fibres in an otherwise highly cohesive raw-silk filament can indicate that the silk was reeled using boiling water, while the inclusion of cubic crystalline structures in association with mostly preserved sericin, may indicate partial degumming carried out using an alkaline additive.

The variation in filament morphology, shape and fibre spacing has been noted. Another result of varying filament morphology is a difficulty in counting the number of fibres (brins), or fibre pairs (baves) in a single filament when in whole-mount. The number of cocoons per filament was a known quantity, as they were counted during the reeling process, but it was observed that fibre overlap in the filament samples resulted in imprecise counting of fibres, and often meant that the number of fibres visible were not reflective of the actual number of fibres present, particularly in filaments with a rounded shape and/or close fibre spacing. The same difficulty was encountered during the analysis of degummed silk samples. This difficulty in accurately quantifying the number of cocoons used to produce a particular raw filament or yarn sample is important given that estimates regarding the number of cocoons used to produce archaeological yarn samples are occasionally provided in reports, often with little to no explanation of how this number was determined. The most straightforward means of accurately counting fibres would be through mounting a yarn fragment in cross-section, but this does not necessarily account for fibre deterioration throughout the yarn fragment, which may confound an accurate fibre count. It may be that further work on silk-textile analysis could expand on the data from this thesis regarding cocoon numbers and filament diameter, to create a reference guide for generating more accurate estimates for the number of cocoons used to produce archaeological silk textiles. An exploration of the relationship between yarn diameter, number of filaments and number of cocoons would need to take reeling methods, degumming processes, degree of twist, and fibre diameter variation into account, but could generate informative results.

When considered in combination, the results of the silk-processing experiments and the analysis of the experimental silks paint a clearer picture of the potential incentives for using different combinations of method. For example, the use of a crossing method that wraps the silk multiple times is more likely to produce a round filament with high cohesion. This method used in combination with boiling water could speed the reeling process but might risk lowering the sericin integrity. In contrast, the use of no crossing method on a simple reel may speed the efficiency of reeling and offset any slow start to the process if reeling with water at a lower temperature. This in turn may result in higher sericin integrity, though is also more likely to produce a flat filament, with wide fibre spacing.

The visual comparison of the silk fibres from the Coppergate and Winchester IxI textiles has provided the opportunity to draw parallels in appearance between the archaeological fibres and the raw experimental samples, resulting in the identification of reeling variables that may have produced the archaeological fibres in question. This comparison has also identified visual similarities in some fibre samples across the 2 textiles, while highlighting some clear differences.

9.3.3 Yarn Diameters and Cloth Density

Rather than providing clear clues to a particular production site, the yarn diameters and cloth density of the archaeological textiles have the potential to provide insight regarding how their quality might have been judged during the Middle Ages. While medieval descriptions of high- or low-quality silk do not always provide qualifiers, some descriptions from Arabic sources do indicate overall trends. For example, the finest quality *Ibrism* silk is described in the 12th-century *Mahasin al Tidjara* as being "pure and lovely-coloured in kind, free of all variations (in colour and texture) and stains which confuse some of its threads. The thread should be of one shape and not some coarse and some fine, nor bulging." He continues, "Good quality is recognised by the heaviness in weight and whenever I have seen a web (*luhma*) of a heavy weight, it is better." (Serjeant 1972, 201). Regarding higher-density silk textiles as being of higher quality seems to be a trend, confirmed by the 9th-century writer *Al-Sakati*, who indicates that cloth of a lighter weight with lower thread count is of poor quality (Serjeant 1972, 200). Based on this evidence, one could argue that the relative quality of the Coppergate and Winchester textiles can be interpreted, at least in the context of a medieval Mediterranean framework.

The Coppergate ZxI textiles are overall more open in their woven structure with finer system A threads, resulting in a more noticeable visual difference between the yarn diameter of System A and System B. The exception is textile 1347, which is denser in woven structure, with more balance between the systems. In contrast, the 2 Winchester ZxI fragments, while not significantly finer in their Z system, are woven with finer thread in the I system, resulting in a significantly more balanced cloth structure that is also more closely woven than most Coppergate ZxI textiles. The visual difference between the textiles from the 2 collections is stark (Figure 9.3) and it could be argued that the ZxI Winchester textiles would have been considered higher quality than the majority of the ZxI Coppergate textiles.

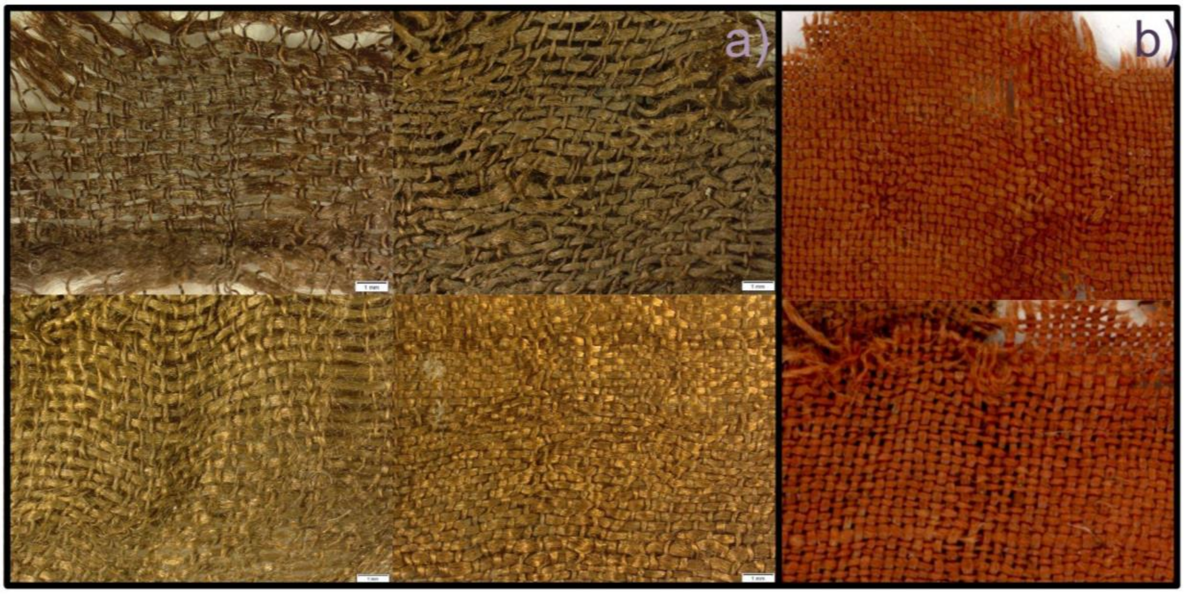


Figure 9.3: The ZxI tabby silks from Coppergate (a), and Winchester (b) (Images of Winchester textiles courtesy of ASLab)

Across the 2 collections, the SxS textiles all exhibit a higher cloth density and are perhaps the most visually similar across the 2 collections. The conjoined ribbon fragments from Coppergate are densely woven and warp dominant. They show only slightly thicker warp and weft threads than most of the Winchester SxS textiles, except for Ribbon CT26, which exhibits both finer warp threads and a denser warp count than any of the other textiles. In terms of yarn diameter, Ribbons CT32 and 1355_R1 are closest in both warp and weft diameter, but Ribbon CT32 has a notably lower warp count than either of the 1355 ribbons, which links it more strongly to the other non-ribbon Winchester SxS textiles. CT26, in contrast, is more similar in visual density to the Coppergate ribbons (Figure 9.4). It is unclear whether the differences in density and balance of woven structure should be considered evidence for different weaving traditions, as the ribbons in particular share the same selvedge treatment and overall yarn twist. That said, a ply analysis of the Winchester SxS tabbies could shed further light on this.

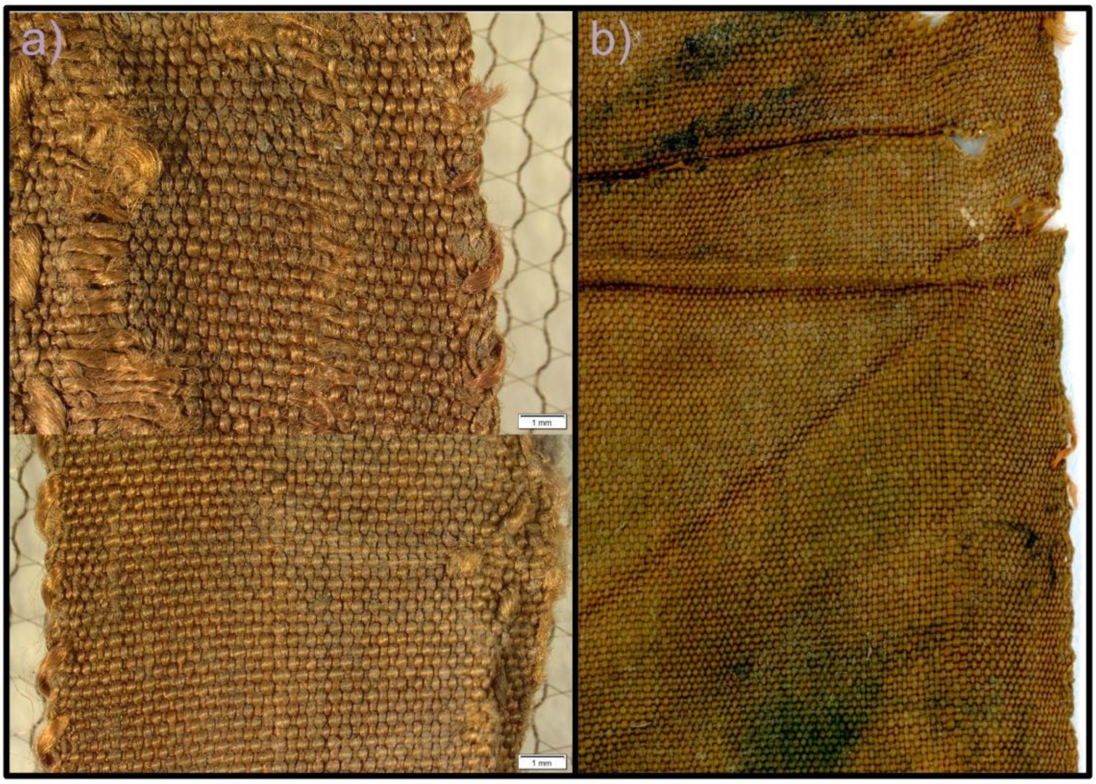


Figure 9.4:The SxS ribbon segments from Coppergate 1355 (a), and Winchester SxS silk ribbon CT26 (b) (Images of Winchester textiles courtesy of ASLab)

No ZxZ textiles from Winchester were analysed, but the ZxZ textiles from Coppergate are visually similar overall, except for textile 1351-ZxZ, which is not only lighter in colour, but also more balanced in woven structure, and with considerably less thread movement. This textile was also the only one of the ZxZ fragments to be confidently identified as being plied S2Z in both systems, meaning that the yarn does not twist upon itself (unlike the other ZxZ textiles, which do not appear to be plied, and are noticeably less stable in their twist, resulting in a crepe effect in the cloth). These differences may not only indicate that 1351-ZxZ would have been considered a higher-quality textile than the others, but also could be a strong indicator that it was produced in a different workshop to the crepe fabrics.

Apart from the SxS, the IxI textiles – woven from yarn without twist in both systems –are the most visually similar across the 2 collections, while not being identical. Coppergate fragment 1351_IxI has slightly thicker threads and a more open and balanced weave than Winchester textile CT8. One could argue that these differences in quality indicate that they were produced in different workshops, but that does not necessarily exclude them from having been produced in the same region, as both textiles share similar characteristics to 9th- to 10th-century IxI tabby samples from Cave 17 of the Mogao Caves, Dunhuang (Figure 9.5), which could indicate a Central Asian or Chinese origin for both textiles. The smooth texture of the yarn in these textiles contrast with the mostly hairy weft threads in the Coppergate ZxI samples, and may also be an indication of Chinese origins (Galliker 2015, 255).

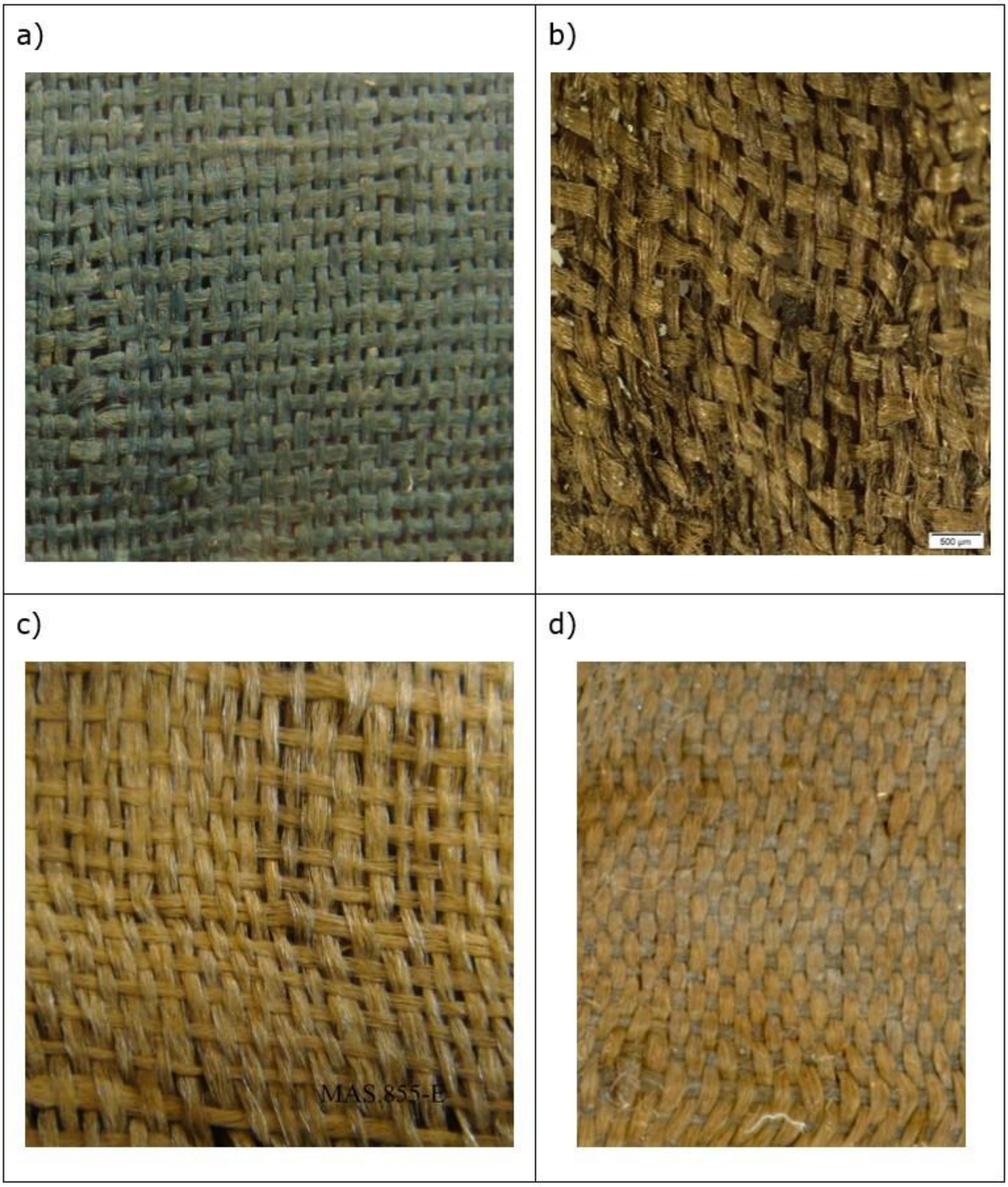


Figure 9.5: IxI tabby silks from the Mogao Caves, Dunhuang. MAS.861 fragment 9 (a) shows structural similarities to Coppergate 1351_IxI(b), and MAS.855-E (c) shows structural similarities to Winchester CT8 (d (Images a & c copyright the Trustees of the British Museum: Anon 2022)

Grouping these textiles by cloth density and balance generated at least 7 different categories of tabby textile, each of which could originate from a different weaving workshop. Due to variation of yarn diameter overall, the yarn categories were based on other characteristics. That said some conclusions may still be drawn from the yarn diameters. For example, while silk terminology provides some insight into the priorities of silk producers and consumers during the 10th century, more can be learned from the key producers of particular types of silk. For example, Iran was noted as a source of numerous popular and high-priced silk textiles in the Mediterranean up to at least the 11th century (Goitein 1967a, 104), with Tabaristan, the region on the Caspian coast of northern Iran, supplying most of the Islamic world's *Isbrisim/Ibrishm* (high-quality reeled silk) during the 10th century, although cloth structure is not specified (Serjeant 1972, 76). If quality is partially determined by the consistency of yarn diameter, then it is possible that the textiles exhibiting the smallest range of yarn diameters (such as CT23, CT26, and CT32) could be examples of *Ibrisim* silk, which would narrow down their possible yarn-production locations.

9.3.4 Degummed Vs Raw Silk

Distinguishing between raw, degummed, and partially degummed fibres was an important development during the textile-analysis process (Table 7.3), and may provide strong arguments for differentiating yarn origins across the Coppergate and Winchester textiles.

When considering the silk fibres of ZxI textiles, Winchester CT 23-b showed higher levels of sericin preservation and fibre groups and appears to have undergone less degumming (if any) than system B of any of the Coppergate ZxI finds. CT 38-b (weft) also shows signs of low or no degumming, with large groupings of fibres compared to CT23-b, while the warp in CT 38 also shows a higher level of sericin preservation. This further emphasises the technical differences between the Winchester ZxI textiles and the Coppergate ZxI textiles and suggests that the yarn used underwent different manufacturing processing and may have come from different sources. Furthermore, the fact that higher levels of sericin preservation were noted in the twisted warps of these Coppergate textiles than the weft yarns with no twist (chapter 8.3.1), suggests that the yarn was degummed prior to weaving. This complicates the assumption that yarn without twist will not hold together if it has been degummed prior to weaving (See chapter 2.2.3). Tensile strength is less of a concern with weft yarn, but some structural integrity would still be necessary for successful weaving, therefore the topic of degumming processes in relation to yarn twist and integrity merits further exploration.

Looking at the fibres of the SxS ribbons, both sections of Coppergate 1355, and Winchester CT26 show signs of degumming in warp and weft. In contrast, CT32 shows higher sericin preservation in both warp and weft and may have been woven from raw silk. This further distinguishes this ribbon from the other 3 analysed, and from the 3 non-ribbon SxS tabbies, which show low sericin preservation and appear to have been at least partially degummed. This could support an argument that CT32 was woven in a different location than the other ribbons given its other technical differences. This at least suggests that the yarn of CT32 underwent a different production process and may have a different origin to the other silk ribbons.

Both the IxI fragment from Coppergate 1351, and Winchester CT8 are woven from silk that appears to have been left raw rather than being degummed. Both textiles also show traces of an additional darker residue in at least 1 system, possibly contributing to their flat, smooth appearance.

It is notable that the textiles woven from yarn with no twist appear not to have been degummed, as this means that the overall production sequence for producing these textiles aligns with that depicted in the 13th-century handscroll by Liang Kai (Appendix A). This depiction shows reeled silk being combined and transferred to bobbins before being prepared as the warp to be set up on a loom, with no obvious indications of twisting or degumming in-between (See Desrosiers Chaine Opératoire I, chapter 2.2.3). This does not prove that the IxI textiles were manufactured in the Song Dynasty, but that is one possibility.

9.3.5 Selvedges

Five of the selected silk textiles from Coppergate have preserved selvedges, and 4 of these textiles – mostly differing in yarn composition share the common feature of a selvedge comprising paired warp threads (Figure 9.6). This selvedge treatment has been previously noted by Walton Rogers as being somewhat unusual, although it has been identified in some textiles from Dublin and 1 from Lincoln (Walton 1989, 374–375). This raises the question of whether this selvedge treatment indicates a shared place of origin. At the very least it could be considered evidence of a shared weaving tradition. What particularly stands out is that 3 of the textiles (1343, 1347, and 1349) selected for analysis from Coppergate that share this style of selvedge are notably different in density and texture, and all have been demonstrated to comprise different combinations of twisted yarn. The fourth sample, textile 1352, which appears to share a similar yarn type to textile 1349 comprises several cut strips of paired warp selvedge, but the thread count, density, and overall appearance of the cloth it was part of are unknown. This variation means that if this selvedge type is indicative of a particular region or weaving tradition, it is likely one that was known to produce a variety of types of silk, perhaps of varying quality. That said, more investigation is needed before it is possible to contemplate pinpointing an origin for this style of selvedge.

Figure 9.6: Coppergate textiles with paired warp selvedges, 1343(a),1347(b), 1349(c), and 1352(d)

The prevalence of paired-warp selvedge treatments in the ZxI and ZxZ textiles contrasts with the simple preserved selvedge of CT38, from Winchester. This difference in selvedge treatment further underscores the technical differences already noted between the Winchester and Coppergate ZxI fragments, and further supports the suggestion that the 2 subtypes of ZxI textile come from different workshops, regions, or weaving traditions.

A trend that spans both collections is the presence of a simple selvedge in the SxS ribbons, which suggests a shared weaving tradition informing the manufacture of this type of narrow ware. As previously mentioned, the precise dating of most of the silk textiles from Winchester cathedral has yet to be determined. Therefore, it is unclear if the subtle variations in these ribbons can be tied to different production sites, different dates of manufacture, or both. The shared characteristics of the Winchester and Coppergate ribbons could provide an excellent opportunity of a comparative study of all surviving ribbons in both collections. This might illuminate further trends in silk ribbon manufacture relevant for narrowing the determined dates of the ribbons from Winchester, or could highlight chronological differences in ribbon production in combination with other dating methods.

9.3.6 Yarn Combinations

What is particularly fascinating when comparing the differences between the silk tabby fragments analysed is the consistency with which certain types of yarn are combined in tabby fabrics. The fact that (1) yarn with an overall Z twist (plied or not) is frequently combined with yarn in the opposite system that has no apparent twist, while (2) yarn with an overall S twist is only combined with S-twist yarn in the opposite system in these examples suggests that these choices are not random or coincidental. Extrapolating further, we only find 2 variations of an SxI silk tabby amongst the Coppergate textiles, both in association with a reliquary pouch (Walton 1989, 371), and no examples of ZxS or similar variations of silk tabbies have been identified amongst the Coppergate or Winchester textiles, nor do they seem to appear in other comparable contexts. This further underscores the argument that technical choices remain consistent in relation to varied weaving traditions.

Throughout this thesis, the Coppergate and Winchester textiles have been primarily grouped by the overall direction of twist in each system, following a convention established by Penelope Walton Rogers (Walton 1989). The results of the identification of plied yarns in several of the silk textiles from Coppergate complicate the pre-established twist categories though should not be seen to completely undermine them. Ultimately the overall twist (that is the superseding direction of twist of the plaid yarn) categories remain unchanged, which is the most relevant characteristic when considering how the yarn would have been viewed by the weaver. These are useful groupings, and have been used as a shorthand throughout this discussion; however, as has become apparent, other descriptors (such as cloth density) are also important to distinguishing between the textiles. Relevant to this consideration are other researchers' efforts to link historical silk terms with surviving textile types.

In a 2018 article on the later-medieval Italian textile term *Sendal* (also referred to as *Cendal*, and *Zendado*), Sophie Desrosiers (2019, 343) identifies key characteristics that may be associated with this type of cloth: 1) It is dyed in the cloth, typically with Kermes; and 2) it is likely to have been woven with a Z-twisted warp and a weft with little or no twist. Desrosiers contrasts these characteristics with another type of silk tabby cloth (or rather 2: *Veli crespi* (crepe) and *veli piani* (flat) a specialty of 14th-century Bologna (Desrosiers 2018, 345). These cloth terms are notably much later than the context of our archaeological samples, but Desrosiers has identified earlier textiles that match the physical characteristics she has attributed to these terms. She argues that these textiles may be considered 'proto' versions of these later Italian silk textiles. The examples Desrosiers uses are of particular interest, as they are similar in appearance to some of the Coppergate silk textiles with overall ZxI and ZxZ twist. Unfortunately, as Desrosiers points out, the origin of the earlier "proto cloths" cannot be determined based on the later Italian terminology. While the continuity of these 2 types of silk textile is notable, it does not bring us closer to narrowing down a weaving centre or identifying the locations of the other associated stages of silk production. An additional question that may be asked is whether all silk textiles with a Z-twisted warp and I weft could be considered part of the cloth type later labelled *sendal*. This is pertinent to a comparison of the Winchester and Coppergate textiles, as the 2 examples of ZxI tabby from Winchester are wholly unlike the ZxI textiles from Coppergate, being both denser and more balanced in weave than the Coppergate examples, with the exception perhaps of Coppergate textile 1347. It seems therefore very unlikely that this term should be applied based solely on yarn characteristics.

9.3.7 Understanding Yarn twist

The structure of silk yarn has been identified as a key consideration from the onset of this research. The key factors are whether silk has been twisted, and if so, the direction and degree of twist. One relevant consideration to twisting yarn is time. As the throwing process became a bottleneck in the processing experiments, it seems likely that the process of twisting yarn must also have created just such a bottleneck for medieval silk production. The main reason that less attention was paid to degree of twist in the experimentally produced samples was that none could be compared visually to the archaeological samples, as the experimental samples all had significantly lower levels of twist. This illustrates the relatively high degree of twist that must be intentionally added to fine silk for it to be recognised visually. Given the occasionally high levels of twist observed in surviving medieval silk textiles, there is clearly a need for a more focussed exploration of medieval silk-twisting methods and equipment beyond the scope of this thesis.

9.3.7.1 Implications of Ply Analysis

The results of the preliminary ply analysis conducted on modern references highlighted potential pitfalls when identifying plied yarn, particularly as part of a woven textile. This also demonstrated the value of a drawing-assisted visual analysis approach when conducting silk yarn analysis, as this method helped to clarify key details such as the differentiation between fibre angle of twist and the angle of twist of a plied element. As shown with the modern silk reference material, it is not always immediately apparent that silk yarn has been plied. This means that the development of a new approach with clear criteria for identifying ply in silk yarn has created an opportunity for the re-analysis of archaeological silk textiles.

Furthermore, in-depth analysis of the twisted yarn in the archaeological textiles highlighted several previously unidentified plied yarn systems, underscoring the difficulty of identifying whether a fine silk yarn has been plied. The challenge in identifying whether reeled silk yarn is plied likely stems from 3 key factors:

1) Reeled silk is significantly finer than most spun yarn, and therefore requires a higher number of rotations before twist is considered significant;
2) Because reeled silk is made from a continuous filament, it can maintain strength with a significantly lower degree of twist than required by spun yarn;
3) When two elements are plied together in the opposite direction to their original twist, the latter will somewhat loosen (Zimliki et al. 2000, 991), which in already low-twist yarn is likely to reduce the visibility of the initial direction of twist, and obscure sub-elements.

Taking these 3 factors into consideration, it is unsurprising that it was necessary to establish new and detailed criteria to aid in the identification of plied silk yarn. The resulting identification of plied yarns in the Coppergate textiles demonstrates how complicated this interpretation can be and may indicate a need for the re-examination of other medieval silk textiles, which may lead to further identification of previously unknown plied yarns.

Silk textiles from the ZxZ category were the most challenging to identify, with one exception: Coppergate textile 1351_ZxZ, which was confidently identified as being woven from S2Z yarn in both systems. The remaining ZxZ textiles showed gaps that could be interpreted as the separation of distinctive elements, or could be a result of silk that has become more stiff or brittle over time, forming fibre clusters while under tension from extreme twist. While the definition of plying allows for the possibility of sub-elements being twisted in the same direction as the overall twist of the yarn (Emery 1980, 10), it is more common – particularly with spun yarn – to combine 2 or more elements by twisting them in the opposite direction to that in which they were spun. That said, it is not unreasonable to imagine that multiple strands of Z-twisted silk could be combined while being twisted again in the same direction. The practical purpose of this is unclear, but the reasons could be technical and aesthetic, as this compounding of Z twist would likely result in an over-twisted yarn that would produce a crepe-effect when woven.

Within the ZxI tabby category, some of the Coppergate fragments were confidently identified as being plied S2Z or S3Z, while others could not be identified with as much certainty. As pointed out in chapter 8.10, the noticeably thicker threads form a textural checked pattern in the cloth. This combined with the fact that the warp threads forming this pattern are plied S3Z (while the rest of the warp is plied S2Z), suggests that these thicker threads were intentionally incorporated as a design element, rather than the pattern being a coincidental outcome from weaving with yarn of an irregular diameter. This clear variation in texture and yarn construction is such that Coppergate 1347 merits further exploration, as another distinct textile type in contrast to the other ZxI tabbies from Coppergate.

Ply analysis of the Winchester ZxI textiles would determine whether there were further technical differences between the yarns used in these textiles, but regardless, the shared decision to pair yarn with an overall Z twist in one system, and with yarn lacking twist in the other system is intriguing and raises further questions regarding links between the 2 theorised weaving locales, as well as the potential sources of their raw materials.

One final indication of the significance of this ply analysis relates to the comparison of medieval silk textiles from different sites and time periods. Crowfoot et al. (2006, 141-142) contrast a number of 14th-century silk ribbons from London with the early-medieval silk ribbons from

Coppergate, Dublin and London. In this comparison, the earlier silk ribbons are described as primarily being woven from *grège* (raw) silk yarn, with no twist or with some S twist, while the 14th-century ribbons are all woven from Z-twisted, S-plied silk. While this description is somewhat accurate for the silk ribbons from Dublin, (Pritchard 1988, 157, 1984, 61), the 2 ribbon fragments from Coppergate 1355 were woven from degummed silk (first identified by Walton, confirmed by this analysis), and the recent identification of the yarn as plied Z2S may demonstrate a previously unrecognised continuity in the characteristics of silk ribbons imported to England between the 10th and 14th centuries. This is particularly important as Crowfoot et al. suggest based on the differentiation of characteristics, that the early-medieval silk ribbons may have been imported from small workshops in the mediterranean or central Asia, while the 14th-century ribbons might have been woven locally in London (Crowfoot, Pritchard and Staniland 2006, 142). Given the fact that at least 2 ribbon examples from Coppergate appear to share more technical similarities with the later medieval London ribbons, this distinction merits re-evaluation, as there may be more continuity in the source of the ribbons from early-medieval Coppergate and late-medieval London than previously recognised. The previously recommended re-examination of the remaining silk ribbons from Coppergate and Winchester could easily be expanded to other comparable medieval silk ribbon examples, such as those from Dublin and London. This would generate further knowledge of any chronological shifts in ribbon manufacture and from an early-medieval perspective might confirm multiple distinct ribbon types circulating in the 10th-century North Atlantic.

Another important consideration is that it can be confidently stated that multiple reeled filaments were combined in the archaeological yarn that has been plied, and it is likely that this was the case for all the yarn samples in question, meaning that the archaeological fibre samples analysed likely contain fragments from multiple different reeled filaments, whether degummed or left raw. This could also have implications for the overall regularity of yarn diameters, and merits further research.

When relating trends in overall twist direction back to the choices made when manufacturing silk yarn, we can improve our understanding of the production context of the silk yarn itself. Within the body of selected samples of tabby silk from Winchester and Coppergate can be found at least 6 distinct yarn structures; Z, S (pending further analysis), I, S2Z, S3Z, and Z2S. If consistency of yarn treatment in a specific production location or workshop is assumed, this could indicate a minimum of 6 different yarn origins, and that is without considering the other possibly indicative variables such as degree of twist, extent of degumming, and yarn diameter.

It is notable that in medieval sources there is frequently a lack of terminology to distinguish between silk with and without twist. This would appear to indicate a lack of concern with the distinction, whether because twisting silk was a rare occurrence, an argument made by Burnham (1968) and Desrosiers(2019) –both citing the low levels of twist in Chinese silks – or because it was assumed that it would be obvious to the reader whether certain types of cloth were woven from twisted yarn.

In contrast, the specification in Arabic sources that yarn was twisted suggests that a mixture of yarn with and without twist was produced and/or traded around the Mediterranean. This terminology also speaks to the importance of categorising different types of yarn rather than just finished cloth: a critical consideration in any region dealing with both the import and export of silk materials at different stages of production.

9.3.8 Weaving Flaws

The presence of weaving flaws is likely to impact the assessment of a textile’s quality, yet these are rarely discussed explicitly in historical texts. In a simple tabby-cloth structure technical errors are easy to spot, and the possibility that the frequency and type of flaws in a particular textile or set of textiles can be indicative of their production context should be considered. Paired threads in the warp system of a tabby textile can be the result of an error made while threading the loom or may indicate that a thread had broken during the weaving process. Both issues can be corrected easily but may require a certain amount of work being undone, depending on the stage of weaving at which the flaw has been noticed. Quicker corrections, such as introducing an additional thread during the weaving process may be easy to spot, as the "tail" of the introduced thread may survive, or the break from a paired thread to a fixed 1/1 tabby structure may be clearly visible. Paired threads in the weft system may also occur if the weaver forgets to change the shed between weft picks, but such a motion when producing tabby cloth is just as likely to result in the weaver accidentally un-weaving their most recent pick (particularly if no special selvedge treatment is used), so accidental paired weft picks are far less likely to occur. Problems with warp or weft threads "floating" over multiple threads in the opposite system can be the result of threads sticking together during the changing of the shed: a common effect of inconsistent thread tension on the loom. Other flaws such as knots can indicate a quick fix to a broken thread, or a shortcut taken by the yarn manufacturer (frequent knots in a skein of yarn is a sign of poor quality, particularly in silk), while loops can indicate overall tension issues or a loose or broken thread. In textiles such as Winchester CT25, where paired threads, broken threads, and thread skips likely resulting from a tension issue are observed in combination in a relatively small area (Figure 9.7), the cloth fragment may survive as a record of a weaver's particularly bad day.

Figure 9.7: Detail of CT25 showing a number of weaving errors (original image courtesy of ASLab)

The fact that these flaws survive in the archaeological record is evidence that the weaver did not take time to correct them, which begs the question: *why?* As Wendrich (2012, 257) has pointed out, it should not be assumed that a poor-quality object is necessarily the work of an apprentice. As Eleni Hasaki has pointed out, regarding craft apprenticeship in ancient Greece, "Very few practice pieces of craft apprentices survive from antiquity. If the practice pieces were successful, they were probably sold and have entered the archaeological record unnoticed except as 'second rate' products. If they were unsuccessful, then they were crushed, melted down, reshaped, painted over, or rewoven" (Hasaki 2012, 175).

Wendrich (2012, 257). further raises the question of how "poor" quality an object must be before it is attributed to apprentice labour In the context of tabby-silk textiles these points are particularly relevant as one might expect, given the precious nature of silk as a raw material, that silk textiles would be woven with particular care, and that errors made during the weaving process would be corrected. There are certainly historical records that seem to support this view (Goitein 1967b). Of course, there are also numerous accounts of inferior-quality silk (often not clearly described) being produced in specific regions (Egypt in particular) (Serjeant 1972). Could weaving flaws be the sort of inferiority described? If so, we must consider the motivation for producing silk with such a high number of flaws. Was it purely economic? Perhaps the weaver coasted on the prestige of the material to turn a profit, while cutting corners to save time? Equally, such flaws may have been considered so minor that they did not count against the quality of the cloth. For this point, the fineness of the threads and woven structure must also be taken into consideration. Is it possible that these errors, doubled threads, and floats went largely unnoticed by both weaver and buyer? Given how fine the cloth is, this cannot be discounted. Whether or not they went unnoticed, the seemingly high number of weaving flaws in the Winchester and Coppergate textiles, particularly the ribbons, could have implications for the speed at which these textiles were produced, and particularly in textiles such as CT25 could indicate a poorly constructed, or difficult to operate loom that would result in tension problems.

Ultimately, without knowing the weaver's intention we cannot assess skill accurately, although we can make many inferences. While the distinction between time-saving intentional choices and accidental errors may not be visibly evident in the cloth, it is important to be aware that the distinction exists. This is an ephemeral aspect of weaving that we may never know concretely; nonetheless, this consideration brings us closer to the original artisans who produced the textiles under analysis.

9.3.9 Textiles With Residue

Residue analysis on silk textiles is another area of research ripe for further exploration, as the identification of residues may help us to determine textile origins, or at least identify the location of key stages of production. This would be helpful in regard to the residue coating sections of both systems of Coppergate Textile 1351, and one system of Winchester Textile CT8, as it is uncertain whether these residues are a result of use, deposition conditions, or a deliberate part of the manufacture process. Furthermore, this sort of residue is not visible on the extremely well-preserved textiles from Dunhuang that were contrasted with the IxI textiles from Coppergate and Winchester. Evidence of residue is relevant to historical accounts of glazed silk textiles, which could theoretically link particular textiles to Spain. Written records of deceitful practices in silk manufacture are particularly interesting and provide some insight into the different treatments carried out on medieval silk, and the potential variation in quality. While slightly later than our time period, it is worth noting that an 11th-century Spanish manual on Hisbah (Islamic codes of morality) by Al-Sakati of Malaga describes a particularly interesting practice of weaving cloth for veils and turbans from raw silk, dyeing them, and stiffening them with a liquid gum so that they lasted for only a brief period of use before "the fabric becomes like a net of no use to anybody" (Serjeant 1972, 199), it is unclear whether the raw silk in question was twisted prior to weaving, but one could imagine that a loosely woven piece of silk (whether from twisted, or not twisted yarn) would hold shape when stiffened with gum, only to have the yarn shift and slide forming great holes the as it was worn.

Whether in association with deception or not, glazing of silk textiles appears to have been a common practice in Spain; Bakri, a contemporary of Al-Sakati also wrote of the Spanish practice of glazing silk with an imported gum derived from trees (this appears to refer to gum-arabic) (Serjeant 1972, 199), so it is possible that this process was not always motivated by fraud.

This Spanish practice of stiffening loosely woven textiles with gum brings to mind some of the ZxZ tabby textiles from Coppergate, and while the fibres in those silks were degummed rather than raw as described by

Al-Sakati, and obvious traces of such gum have not survived, it is not impossible to think that a similar practice of stiffening a piece of cloth, loosely woven from twisted yarn might have taken place in Spain or a neighbouring region even prior to the 11th century, and could merit further investigation. Although it appears more stable than the majority of the ZxZ fragments, Coppergate textile fragment 1351_IxI is in many ways a better match to this description, given that it appears to have been woven from raw silk, in a slightly open weave and with traces of dark residue in both systems. Potentially, chemical analysis of this residue could provide further insight, allowing for the identification of a location for the weaving or finishing of the cloth, if not the origin of the yarn itself.

9.3.10 Significance of Traces of Non-*Bombyx mori* Fibre and Other Inclusions

Inclusions of non-*Bombyx mori* fibres in some of the textiles analysed have the potential to provide further insight into the circumstances of their manufacture. The intentional “padding” of more expensive silk products with local silks or non-silk fibres is discussed in Chapter 1. Within Egypt, during the 13th century locally produced silks were noted to be of inferior quality, and it was apparently a not infrequent occurrence to mix local Egyptian silk with silk from Syria and sell it as Syrian silk, which had a better reputation (Goitein 1967a, 103). The mixing of floss silk with dyed (presumably reeled) silk, and combining other materials within a skein of silk were also known methods of deceit in the medieval silk industry (Serjeant 1972, 199). This could provide an explanation for the presence of possible vegetable and wild silk fibres in some of the samples analysed, and may give an indication of the overall quality of this silk in comparison to others produced during the 10th century. As discussed in chapter 8.3.4, the intrusive fibres appear so infrequently that they may not be the result of intentional mixing and might instead be due to cross-contamination within a workshop that worked with multiple fibres.

It is possible that these fibres were accidentally incorporated during the yarn manufacture, if they were produced in a workshop that also processed other types of yarn. This could still be an important indicator of production location, and if nothing else suggests a different workshop environment for the textiles highlighted than that for most other samples analysed, which appear to only contain *Bombyx mori* silk fibres.

9.3.11 Reconfigured Textile Categories as an Analogue for Trade Networks

As discussed in Chapter 9, categorising the textiles solely by direction of twist obscured many other relevant technical features. By considering the yarn and cloth structures separately, 11 distinct types of yarn, and 7 distinct types of tabby cloth were identified across the 2 textile collections. These categories were then visualised as a network, albeit one removed from geographic reference points. If each of these yarn and textile categories are assumed to have been produced in a different workshop, it is possible to infer some theoretical connections between the textiles. When considering these categories, it is important to note that ply analysis could not be conducted during the visual analysis of the Winchester textiles, so it is possible that the textiles in question contain more examples of plied yarn than Figure 8.77 indicates. This technicality should not detract from the overall impact of the illustrated networks. The previous sections have posited some of the possible production sites for several of the silk textiles analysed, but I am reluctant to make concrete identifications based on the data generated so far. For now, this means that Figure 8.77 remains a theoretical, floating network of production sites. Future analysis and collaboration across disciplines to compare archaeological, historical, and linguistic evidence may allow for the creation of a network map that grounds archaeological textiles with specific production locations.

9.4 The Coppergate and Winchester Silks in context

9.4.1 Differences in Textile Deposition

The silk textiles from 16-22 Coppergate were recovered from contexts in multiple phases at the site, the majority coming from period 4B (dating to between 930 and 975 CE), which is described as a period of intensive occupation (Hall 1989, 295). The preservation not just of silk textiles, but of a rich body of other textiles and organics finds is attributed to the high moisture and low oxygen levels of the soil in and around this site (Hall 1989, 285). A total of 29 silk textiles and yarns were recovered from phases 4A-6 (Hall 1989, 297), 9 of which were selected for this study based on the criteria discussed in chapter 6.2.2.1 and their availability. Of the 9 silk textiles selected for analysis, 7 date to period 4B. The other 2 textiles still date to the 10th century, but 1281 comes from period 4A (900-930/5), while 1371 comes from a pit fill dated to period 5A (c. 975) (Walton 1989, 434-38).

In contrast to the more firmly dated Coppergate textiles, the Winchester silk textiles are associated with royal and episcopal burials dating between the 7th and 12th centuries. The mortuary chests from which the textiles were recovered have been found to contain the skeletal remains of at least 20 individuals some of whom have been confirmed to be early-medieval through radiocarbon dating (Yorke 2021, 61). This chronology is complicated by the fact that royal remains interred at Winchester underwent several instances of removal and reburial in connection to the founding of the New Minster in 901, remodelling during the 14th and 15th centuries, and vandalism in 1642 during the civil war (Yorke 2021, 59–62). the mortuary chests are inscribed with the names of 9 royals; Cynegils, Cynewulf, Ecgbert, Aethelwulf, Eadred, Edmund Ironside, Cnut, Aelgifu(Emma), and William II Rufus (Yorke 2021, 63). Other suggested occupants include other rulers of Wessex and England

and prominent Bishops including Wini, Cenwulf, and Aelfwyn (Crook 2022, 27).

The textiles selected for analyses were just 8 of many figured and tabby silk fragments that were preserved in a circular tin from mortuary chest N1 (Swire 2024) meaning that unlike the Coppergate textiles, they did not benefit from anaerobic preservation. One figured textile from this collection that is associated with CT32 has been radiocarbon dated to late 9th-10th century (Walton Rogers 2023), but connected to known customs of textile re-use that will be discussed in Section 9.4.2, CT32 may have been produced earlier, or later than the textiles to which it is attached. This means that pending the development of concrete morphological criteria for dating silk tabby textiles, the silk tabbies from Winchester cannot be pinned to a specific century without radiocarbon dating.

9.4.2 Different Uses?

The silk textiles from Coppergate provide an important example of silk use in an Anglo-Scandinavian urban environment. An in-depth analysis of all the silk textiles recovered from the site, and further information on the context of textile production at Coppergate can be found in Walton 1989 and Walton Rogers 1997 respectively. The following discussion draws partially on information from these 2 volumes.

Within the larger body of surviving silk textiles from Coppergate, most with clearly identified uses have been described as head coverings. This includes Coppergate 1349 which, based on its size, is suggested to have been a child’s cap (Walton 1989, 367). Other fragments, such as the ribbons, are likely to have been used in finishing the edges of garments, and in the case of 1355 (which was found enfolding a smaller piece of heavily decayed cloth of unidentified fibre composition), may been used to finish a garment or object made from a different material such as wool (Walton 1989, 367-69). Aside from use as head coverings and edge finishes, some of the silk fragments may have been used as patches or decorative trims on other garments, in some cases being recycled. This may be the case with textile 1343 a narrow strip that must have been stitched to another piece of cloth at some point, which has a surviving hem formed in the opposite direction that the 4 edges have been folded, suggesting reuse (Walton 1989, 363).

Of the Winchester silks selected for further analysis CT8, CT32, and CT38 were found in association with figured silks (Lampas, and Samite, respectively). The remaining silk tabby textiles were not stitched to other cloth fragments, but CT22 and CT25 both show fine finished seams, suggesting that they may have been part of larger garments. There are no structural indications that the silk textiles from Winchester were re-used but this cannot be ruled out, as Fleming(2007, 130) describes the English kings' receipt of 'hand-me-down" silk garments from popes or German emperors particularly during the early Middle Ages, and citing other practices of pious donation to high status members of the church states "It seems that a good deal of recycling was taking place" (Ibid, 144).

Yarn movement was not a focus of the previous Coppergate textile analysis (Walton 1989) but is relevant to use. The more the yarn in a woven textile is likely to shift, the more likely it is that the cloth will deform, stretch, and even form large holes as the threads bunch together (See Coppergate textile 1349). Visual analysis of the Coppergate and Winchester textiles demonstrates that the majority of the Winchester textiles show low to moderate yarn movement. While the Coppergate textiles vary in the extent to which this is observed, the majority show moderate to very high movement. When these textiles are compared by the density of their woven structures, a clear relationship between cloth density and yarn movement is demonstrated across both collections; yarn movement is reduced as cloth density increases. Therefore, cover factor can be used as a proxy for textile stability. Most of the ZxI and ZxZ textiles from Coppergate (excluding 1347 and 1352) show an overall low thread density, with most textiles showing a cover factor of lower than 100% (meaning that there are visible gaps between threads) and a high degree of yarn movement. These characteristics are important when evaluating textile use, as they indicate that the textiles are relatively structurally unstable, more likely to drape softly, wear quickly, and less likely to maintain their structure under tension. These characteristics suggest that the majority of the ZxI and ZxZ variation textiles would be better suited to use as caps, veils, and decorative patches or trimming, rather than as a structural garment or lining. In contrast, the SxS variation ribbons are densely woven, and significantly more structurally stable. Their likely use as garment edging has already been mentioned, and they could probably also be used effectively as ties on a garment or cap, and easily withstand strain. These observations on the stability of the Coppergate textiles reinforce the aforementioned use-identifications made previously(Walton 1989, 360). The 2 ribbons from Winchester CT26, and CT 32, also show low yarn movement, but are slightly less dense than the Coppergate ribbons. In contrast to the ribbon fragments from Coppergate, which have been folded as if to encase the edge of another fabric, the Winchester ribbons appear to have been stitched flat. CT32 was used to finish the edge of a samite garment, one selvedge attached along the folded edge of the samite, the other selvedge stitched against the cloth, perhaps as a way of stabilising the garment edge without covering the more opulent silk fabric.

These 2 collections of textiles show some overlapping use, particularly regarding the silk ribbons, but their overall use as discussed clearly varies. In addition to the differences in deposition context discussed, it is important to recognise the different use context of these textiles.

The Winchester textiles come from an early-to-high-medieval, mortuary context, with probable royal links. Importantly, any of the textiles analysed that were deposited prior to the mid 11th century were done so in a Saxon context. Furthermore the choice of burial at Winchester is argued by Yorke (citation, 72) to have been a tool for securing royal stability, in the case of Cnut and his successors suggesting a connection to the West Saxon kings. This same approach was apparently then taken by Norman rulers, emphasising their connection to Cnut. The use of silk in these burial contexts is also significant considering Fleming's arguments that acquiring and wearing silk became increasingly important to the performance of status and prestige during the early to high-Middle Ages in both secular and ecclesiastical contexts (Fleming, 144). The context of the presence of silk textiles and these mortuary practices could be regarded as part of a performance, not just of status, but of the right to rule. In the case of Coppergate these garments and embellishments have nothing to do with Saxon royalty, but certainly may be an expression of status or wealth, within a secular Anglo-Scandinavian context more strongly linked to the everyday workings of craft production. The presence of so many silk textiles at Coppergate is reflective of an apparent increase in the availability of "pedestrian" silk pieces in England attributed by Fleming(2007, 130) to increased production of low and medium-grade silk in the Byzantine empire, but as demonstrated by our theorised textile network, it seems unlikely that all of the silk textiles from Coppergate share a single origin. A final obvious contrast emphasised by their respective deposition is that of life and death; the Winchester textiles, interred with deceased royalty experienced a very intentional "death" (Joy 2009) themselves while the Coppergate textiles, given their deposition are more likely to have been lost, or perhaps in some cases discarded in the context of daily life, their "death" therefore could be considered accidental or at the very least, incidental. Given these differences in use context it is no surprise that the Winchester and Coppergate silk textiles overall show indications of different production origins.

9.5 Medieval Tabby Silks and the concept of quality

A challenge previously mentioned in relation to examining the origins of the textiles analysed is the relative lack of focus on tabby silk textiles in a medieval context. Part of this problem comes from the often-vague nature of early-medieval silk terminology. Reflecting on descriptions of historical silks in relation to the archaeological textiles analysed may provide further insight regarding the relative quality of these textiles.

Arabic sources seem to make frequent reference to the quality of silk, such as *Ibrisim*/*Ibrishm*, which refers to silk of high quality and may speak specifically to woven reeled silk (Serjeant 1972, 198, 201). *Lasin* was a cheap variety of silk that may specifically refer to the yarn (Goitein 1961, 174; Gil 2002, 33), while *Ladh* was a cheap variety of silk probably made in imitation of Chinese silks (Goitein 1976, 222). Unlike the Chinese terminology, these terms rarely indicate the cloth’s structure, focussing instead on quality, and frequently yarn treatment. For example, *Kazz* refers to raw silk (Serjeant 1972, 89-90) and *Khazz*, refers to floss silk, ie. waste silk that must be spun (Serjeant 1972, 19), while *Maftul* refers specifically to twisted silk yarn (Goitein 1967, 65). Such terms do provide insight into the types of processes carried out and/or taken note of in a particular region. For example, it is unsurprising to see a variety of specific classical Chinese terms for silk cloth with different woven structures and degumming treatment given the history of silk production in that region.

9.6 Can the Origins of the Archaeological Silk Textiles be Determined Through Technical Analysis?

Given that whether the origins of archaeological silk textile can be determined through technical analysis is a central question of this thesis, one might hope that the straightforward answer is “yes”. In reality, the answer is closer to “perhaps”. The likelihood of determining the origin of a single silk textile fragment is significantly complicated by the *chaîne* *opératoire* of silk production, because the social context of silk manufacture is deeply linked with the transport of silk products from one place to another. For example silk filaments may have been reeled, thrown, degummed (or not), and woven on the farm at which the silkworms were raised, as was often the case for tabby cloth paid in tax in the Tang and (to a lesser extent) Song dynasties (Zhao 2012, 205–206). Equally, however, silk may have been reeled in a specialist workshop from local cocoons, imported cocoons, or a mixture of both, which seems to have been the case in the Byzantine Empire (Chapter 1.3.1).

Thus, the question "where did this silk come from?" will rarely have a simple answer. At each stage of silk production –caterpillar to cocoon, cocoon to raw filament, filament to yarn, yarn to cloth (or other finished good), dyeing (of yarn, or cloth), and cloth to finished garment – there is potential for the transfer of goods to a new production locale. This is an important consideration and is the reason a focus on both yarn and fibre characteristics within silk tabby textiles has been taken in this research. If a single answer had been desired, such as the origins of the silkworms that produced the fibres, it may have been pragmatic to investigate the chemical structure of the silk fibres, but such an investigation, while fascinating, would give no further insight regarding the production methods or the social and political context of the textiles in question.

Rather than asking if a specific origin can be determined, a more useful question is, "how can the results of experimental and technical textile analysis be related to an early-to-high-medieval context?". Equally "What can be learned about the production and trade of medieval silk from this research?" is a relevant question given the scope of this research, and one that this chapter has attempted to answer by contrasting the results of the archaeological and experimental textile analysis with further historical context of the medieval silk trade. The analysis of the experimental and archaeological silk textiles has supported the identification of previously unidentified production steps in the

Coppergate textiles, such as the plying of yarn, while demonstrating how these differences in production steps influence the overall texture and appearance of silk cloth. Working with both a microscopic and macroscopic approach of archaeological silks unlocks new potential for understanding silk production methods in relation to the broader context of the medieval silk trade.

9.7 Further Research Potential

Both the experimental research and textile analysis carried out have highlighted many avenues for future research that have been highlighted in the above discussion. While the silk-processing experiments were designed to cover as many technical variations as possible within an achievable time frame, it was impossible to test every theoretical combination of variables. It was also beyond the scope of this research to fully explore potential variations in throwing techniques and the resulting influence on angle of twist, yarn morphology and diameter. A future comprehensive study focussed on yarn production techniques, ideally informed by the silk yarn characteristics commonly observed in surviving medieval textiles, would generate further useful data. Further experiments focussing on the efficiency of different silk-reeling and throwing techniques also have the potential to address the topics of skill and economy in relation to medieval silk production.

Furthermore, the analysis of the experimental and archaeological silk samples raised new questions that can be addressed through future research. Of particular interest is the effect of more degumming variables on sericin degradation, which would couple well with artificial aging experiments as a means of comparing sericin and fibre deterioration in archaeological examples.

The implication of the ply analysis of the Coppergate textiles has been discussed at length, which highlights the value of reanalysis of the yarn structure of medieval silk textiles across collections. Data on the use of plied silk yarn in medieval textiles may have tremendous potential for the further characterisation of tabby types, which in turn has broader implications for interpreting production origins.

Many of the topics highlighted can be best addressed through the expansion of a silk reference collection. Extensive and targeted data gathering from the expanded reference collection, such as a comparison of twisted yarn diameters with their degree of twist, or a comparison of angle of elements twist vs. angle of fibre twist, would provide further useful data that can be applied to archaeological and historical silk textiles.

9.8 Conclusion

This research has resulted in the development of new protocols in the analysis of silk textiles that have fostered a number of important observations that have implications for the future of silk textile analysis (Table 9.1). A key finding of the silk-production experiments and microscopic analyses is that raw, reeled silk takes on distinguishable physical characteristics because of particular variables in reeling method and equipment. The experiments also demonstrated the time-consuming nature of combining silk filaments with twist and highlighted the importance of haptic experience and tacit knowledge to silk production processes.

Observation/Problem	Research Output	Result
Theories about medieval silk production are typically not based on hands-on experience or the study of samples with known processing conditions	Construction of medieval-style silk reeling equipment and the development of an experimental silk processing protocol → A reeled-silk reference collection reflecting varied silk reeling and processing techniques which may be expanded upon and compared to archaeological silk textiles	The identification of different processing techniques used to produce the Coppergate and Winchester silk textiles
It is difficult to identify plied, reeled silk when looking for the visual cues associated with spun yarn	Silk yarn ply analysis flowchart	New identification of previously unobserved plied yarn in Coppergate textiles
Visual differentiation of raw and degummed ages silk is challenging. There is also no clear criteria for visually differentiating partially-degummed and degummed yarn.	Visual criteria for differentiating raw, partially-degummed, and degummed silk based on reference collection and archaeological silk textiles	New identification of potentially raw and partially-degummed silk in Coppergate and Winchester textiles
Analysis of the archaeological silks identified many variations in processing methods which cannot yet be confidently linked to specific production sites	"Floating" Silk production network based on technical variation	Identification of "Anchor points" of silk yarn and textile characteristics which may be associated with specific production sites in future

Table 9.1: Summary of key research outputs and results

The technical analysis of the selected Coppergate and Winchester silk textiles identified some shared fibre characteristics across the samples, such as the relatively high level of sericin preservation in the IxI silk textiles. The analysis of the Coppergate silks led to new observations on the complexity of analysing reeled silk yarn for ply in contrast to spun yarns. Importantly, this has led to new identifications of plied yarn resulting from the development of a silk-specific ply identification protocol. These observations, along with the identification of visual traces of reeling methods in raw silk constitute a significant step forward in the areas of silk fibre and yarn analysis. These new protocols and observations have implications for our understanding of the medieval silk trade; differences between the 2 silk collections have also indicated the likelihood that tabby silk textiles imported to England during the early- to high-Middle-Ages came from multiple sources. This challenges a previously noted trend of a default Byzantine attribution for tabby silk textiles (see chapter 1.3.2).

The comparison of measurements including **yarn diameter and thread count** have supported categorisations of archaeological silk tabbies by Walton Rogers based on twist direction, while the **visual analysis of yarn structure** has complicated these categories and demonstrated how variations in yarn quality may be used for visual effect. These observations have raised further questions regarding the many factors that may influence the appearance and morphology of silk, and the decisions made by medieval silk workers.

Consideration of these textiles in relation to other surviving medieval silk tabbies has demonstrated that there are many ways in which simple cloth structures such as these can vary in appearance and texture through subtle differences in technical choice. However, there also seems to be some long-ranging historical continuity in the types of silk tabby cloth we encounter throughout the Middle Ages. This observation particularly emphasises the need for further in-depth technical analysis of other surviving silk tabby textiles. While the precise production sites and raw material sources for the textiles analysed cannot be determined based solely on the analytical results, variations in the methods used for multiple stages of production can interpreted as indications of different production sites, and be used to model a theoretical network of material exchange that could in future be refined, and potentially anchored on specific production sites.

Ultimately, while it is possible to speculate on their origins, this research cannot yet confidently assign places of production to the archaeological textiles analysed. The results of the experimental programme and textile analysis have, however, identified new “hooks” on which to hang the varying characteristics of medieval silks, and it may be possible – through further experimentation, analysis of medieval silk textiles, and cross-checking of historical records – to identify not a single origin of a given medieval silk textile, but the sites of multiple stages in its manufacture, which will ultimately further our understanding of the global context of medieval silk production.