The Development of
Technology for Arresting Falls Using Textiles

by

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ABSTRACT

This cooperative research work is concerned with the development of fall arrest equipment constructed from textile materials for use in mountaineering, caving and industrial safety applications.

The range of webbings available for use in fall arrest equipment is examined, and some basic experiments to determine the effect of severe abrasion are described.The methods of stitching slings (loops of webbing) are examined, and the effects of external abrasion on conventional lap joints and bartacked joints are compared. The development of harnesses is examined and the factors affecting their future design are considered. The major part of the work is concerned with the way in which the energy of a falling body is absorbed in a fall arrest system and with the peak impact loads imposed on the system's components . To measure these loads, apparatus was developed at the cooperating company's premises, together with appropriate instrumentation. A series of tests were carried out to determine loads in falls of increasing severity.

The ensuing development work concerned textile shock absorbers, which are designed to limit the impact force in a fall to a predetermined maximum. Using the drop test apparatus, it was shown that such shock absorbers have very little practical effect in a climbing situation. However, the principles embodied in these devices were used to develop an

industrial safety lanyard with an integral shock absorber which conforms to British Standard 1397. This device is lighter and more compact than others currently on the market and represents a step forward in the field.

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Chapter I

INTRODUCTION

The field of fall arrest technology is so vast that to attempt a comprehensive review would achieve little. In addition, the investigation of any one area in depth requires a high degree of specialisation. The aim of this chapter is to provide the reader with a basic knowledge of fall arrest equipment and technique, and to show the way in which both are developed and refined.

1.1 The Subject of this Thesis

It is felt that some explanation of the degree and direction of specialisation is called for, so that the reader is aware of the aims of the research work. The accent is on fall arrest in a climbing/mountaineering situation, and the reasons for this are three-fold:-

1. The cooperating company who sponsored this CASE study is Troll Safety Equipment Limited. Although it is involved in the areas of climbing, caving , industrial and military applications of fall arrest and (to a lesser extent) rescue, the company's roots lie firmly in climbing. All three directors were at one time very active climbers, and still pursue it to varying degrees.
2. The climbing arena is perhaps the worst environment to which equipment can be subjected. Extremes of temper-

ature, humidity, ultra-violet radiation, abrasion, loading and, unfortunately, misuse are all present in the application.

3. As the author, I have a personal interest in climbing and at the time of writing have over seven years of practical experience. This ranges from small crags in the Peak District of Derbyshire to twenty thousand feet high mountains in the Himalaya. It is therefore inevitable that my experience in these areas should lead to a certain degree of specialisation.

The major problem with a study of this type is its incompatibility with theoretical analysis. The situations, although conceptually simple, such as a falling body being brought to rest, are complex when examined in detail. The major problem lies in the extreme non-linearity of textile properties which makes quantitative analysis very difficult. In addition, the data relating to textiles is often confined to ultimate tensile strength and elongation at failure with little or no relevant information available concerning other properties such as stiffness. At fibre level, the problems are also relatively simple, but once spun into a yarn and woven into a narrow fabric the situation becomes yet more complex.

As an author with a background in mechanical engineering I initially experienced difficulty altering my approach to suit these properties peculiar to textiles. Once I had understood and appreciated the differences between textiles and the more common engineering materials, I felt more able to decide which particular subjects in the field might lend themselves to suitable research.

1.2 Selection of Research Topics

The following topics were finally chosen for a variety of reasons:-

1. The development of the drop test equipment and the very basic programme of tests conducted arose from a gap in the knowledge of the fundamental processes of fall arrest. How strong do the components of the system need to be?
2. The work on shock absorbers arose partly from a commercial demand and partly from design/innovation at a fundamental level. Would the shock absorbers work and, if so, which designs were the most effective?
3. Work on tape, slings and harnesses was conducted in parallel with the continuous development which occurs at the Troll factory. As fast as the author learnt another aspect of design by observing in-house development at the factory, a further new aspect would arise. Economic factors and the continually changing market were also taken into consideration and this also affected the area of research.

It is hoped that this thesis presents the area covered in a comprehensive manner, but it should be appreciated that it represents a small section of the subject. Little academic research has been conducted in the field of fall arrest as the majority of the developments and knowledge have been derived from commercially orientated innovation. However, it is hoped that the thesis shows that research of this type can actively contribute to the development of safer, more effective technology whilst not cramping design flair and new ideas. The future of fall arrest has much in store.

Chapter II

INTRODUCING FALL ARREST EQUIPMENT AND TECHNIQUE

The purpose of this chapter is to inform the reader of the basic terms involved in the equipment and technique of fall arrest in the spheres of climbing, caving and industry. An apparently simple task, that of protecting a human body from ground impact, is complicated to a large degree by historical development, geographical differences and related to this, the situation in which the equipment is being used. To educate the reader and thus allow him to understand the logic behind decisions taken later in the research programme, this chapter will cover climbing, caving and industry in varying detail.

Mountaineering and rock climbing will be covered most thoroughly. This is because it is here that the greatest restrictions are placed on equipment design due to the nature of the activity. As a consequence of this, techniques have evolved to cope with a variety of situations with the minimum of equipment. To complicate a situation already crowded with the problems of equipment and techniques, the sphere of climbing fall arrest is also governed by unwritten self-imposed rules known as ethics. These ethical considerations are perhaps the most unfathomable idea to the non-climbing lay-person yet play an important part in the way climbers operate. The evolution of equipment and techniques will be covered right up to the present day so that the reader will emerge with a view of the state-of-the-art of climbing and its associated fall arrest technology. It will be noted that this section, indeed the whole chapter, will be very much orientated towards the British scene. This is because it is here that rock climbing first arose as an activity in its own right seperate from mountaineering in a more general sense. This specialisation in cliff or crag climbing entailed the most complex techniques and equipment and by some quirk of the British national character also provided the arena for the greatest risk of falling large distances, preferably but not necessarily without hitting the ground.

Caving is entirely different in philosophy and approach, both with regard to the activity, the techniques and equipment used to pursue the activity, and the cavers' attitude towards the above aspects. In summary, where the purpose of climbing technique and equipment is to arrest a fall once it has occurred the caver is intent on preventing that fall in the first place. A review of current caving practice will be given in order that the different restrictions imposed by a caving environment may be appreciated.

Industrial applications of fall arrest technology are different to the outdoor leisure field in many respects. The equipment is designed for a specific application usually to prevent a fall as in caving. Briefly, although weight and bulk considerations are lifted, the arduous area of industrial workplaces and the restrictions rightly imposed by safety legislation necessitate a completely different set of design criteria for industrial equipment. Once again, a brief review will be given of some of the industrial applications in which fall arrest technology is used.

2.1 The History of Mountaineering

2.1.1 Pre-History of Mountaineering

Indigenous peoples of mountain areas have been moving in and around their environment since pre-history, but the first ascent of a mountain for its own sake is generally taken to the 1358 ascent of Rochemelon in the Graian Alps by one Bonifacio Rotario, a knight. The ascent is, however, easy in Alpine terms and it was not until 1492 that a French noble made the first ascent of Mont Aiguille in the Vercors by means of ladders and ´subtle engines´ to establish the world´s first difficult mountain route.

From this date until the eighteenth centurythere is very little recorded evidence of mountaineering. In 1760, de Saussure arrived in the village of Chamonix below Mont Blanc, the highest mountain in Europe, and offered a reward to the first person to ascend it. In 1786, the mountain was climbed by Balmat and Paccard and the sport of mountaineering, that of ascending mountains purely for sport, rather than scientific interest, was born[1].

2.1.2 The Origins of Safety Technique

At this time, few safety techniques were used and virtually no equipment was available for the prevention of falls. Climbers and their mountain guides would climb mountains with no ropes or other safeguards and, if any one of them fell due to bad rock, lack of ability or other factors such as stonefall then there was little chance of survival.

It is uncertain at what stage the rope made its first appearance. In the middle of the nineteenth century, it was undoubtedly in use by the local Alpine guides to safeguard their aristocratic Victorian clients on steep ground. Thus the two or more climbers would move together, the upper climber or leader totally without security providing the lower climber or second with a physical pull or morale-boosting presence of the hemp rope from above. However, there was little or no means of attaching the party securely to the side of the mountain, as evidenced by the disaster after the first ascent of the Matterhorn by Whymper and party in 1865[2]. A slip by one of the party of six dragged three more off, while the remaining two held onto the rope tightly. Fortunately for them, the rope snapped and the two survivors made their way back to Zermatt to face an outraged public. Thus the rope, far from safeguarding the party in this case caused three more deaths than otherwise would have happened.

In order to introduce the ways which were designed to prevent this type of disaster, it is convenient at this stage to turn to the development of rock climbing in Britain. There were both similarities and differences to the events in the mountains of the Alps, and with British Victorian gentlemen mountaineers playing a major part in the 'golden age of Alpinism' it was inevitable that there should be a close relationship between the two areas. The development of mountaineering will be examined at a later stage in the chapter when it is appropriate to use it to further the development of safety equipment and technique.

2.2 The History of Early British Rock Climbing

The Victorian gentlemen who accompanied their Alpine guides also practised on smaller mountains at home in Britain. Generally, they walked or scrambled in the fells of the Lake district. Although some of the scrambles were undoubtedly quite difficult it is generally considered that the first rock climbing in Britain took place in the early nineteenth century, when W.P. Haskett-Smith made first ascents of several routes around Wasdale Head. The important difference was that rather than regarding the climbs as practice for the Alps Haskett-Smith climbed very much for his own enjoyment so that the climb was an end in itself. These climbs were usually done solo, that is with no ropes and were certainly as difficult as any climbs ascended today if only because the psychological barriers of the unknown were at the time completely intact and unbroken by any previous experience.

As the climbs achieved became harder, certain climbers introduced ropes to obtain a small degree of safety for the second man, usually the weaker member of the party. The rope would be made of hemp, and would be used to give the second both physical and psychological protection once the first climber (the leader) had negotiated a difficult section. There was little or no technique available to attach either leader or second to a firm anchor. The ropes themselves were weak, prone to rotting and were probably of greater help psycologically than anything else. Even as late as 1903, this is evidenced by the deaths of four climbers on Scafell in the Lake District when a leader fell dragging his three companions from their stance or ledge.

Thus the first safety equipment for climbing was introduced but was found to be inadequate to cope with the demands placed on it. More interesting to note, however, is the reaction of certain sections of the climbing community to the innovation. Haskett-Smith and his companions

> "were heretical towards the use of the rope. Not having one ourselves, we were inclined to scoff at those who had;and in the gall of bitterness, we classed ropes with spikes and ladders, as a means by which bad climbers were enabled to go where none but the best climbers had any business to be" [3].

This conservative reaction shows very simply the opposing influences governing the development of equipment and techniques for rock climbing. On the one hand are the parties wishing to tackle harder climbs with the same degree of safety (and risk). They argue that, not only will these test pieces be done, but also that the introduction of improvements will enable other(less able) climbers to tackle what was previously a hard route. Furthermore, nobody wants to die while on a climb. On the other hand, there are the established old guard who resist the changes, arguing that the test-pieces of their day were done without these improvements, that they should remain the preserve of the elite, or those bold enough to attempt them and that in any case they could not afford the equipment.

Since Haskett-Smith and his companions first opposed the use of ropes, this ethical debate has continued with every new development right up to the present day, and shows no sign of abating. It says much for the sport of British rock climbing that the level of risk, an inherent part of the sport and inexplicable to the lay-person, remains nearly as high as it was when Haskett-Smith first soloed Napes Needle in 1886 'without ropes or other illegitimate means'.

2.3 The Basic Elements of Climbing Safety Technique

Despite the protests of the old guard, techniques evolved, first of all to secure the stationary members of a climbing party. The climbers would be belayed to a natural feature such as a rock spike, a chockstone(a rock jammed in a crack)or a tree. With the rope tied round the waist of the climber and around such a feature, should the leader or second fall, at least his belayer would not be dragged off the ledge.These fixed belays were the vital development in technique necessary to make the most of the rope.

However, should the leader fall, then there was nothing to stop him falling right past the fixed belay, continuing to fall until either he hit the ground or he fell a distance equal to the amount of rope run out above the fixed belay. In order to avoid this, leaders started to place running belays or runners, where a short loop of rope was tied to a natural feature and the climbing rope threaded through this loop. Thus, should the leader fall, the runner would act as a pulley arresting the downward flight after the leader has fallen twice the distance between him and his last runner(see fig.1). This system of fixed and running belays was certainly in use by the time of the First World War and forms the basis of fall arrest technique. Since then, development has concentrated on refining this technique using stronger, lighter and more versatile equipment.

2.4 Refinement of Basic Fall Arrest Technology

It has been shown that the technique used to safeguard a falling climber is conceptually very simple. However, the method of implementing this concept has gradually become more complex. This is partially due to the difficulty of finding places for fixed or running belays in the rock. Natural rock spikes, chockstones and trees have already been mentioned as commonly used forms of protection. when natural features are not available to protect a difficult climb the climber has three choices:-

1. Not to do the route
2. To do the route without protection risking serious injury or death if he should fall
3. To place artificial protection

Taking 1. to its logical conclusion, nobody would go climbing at all. While 2.is ethically admirable, the number of climbers willing to risk all on a regular basis is small. Thus 3. emerges as the only safe way to improve climbing standards.

The first form of artificial protection was a derivation of the natural chockstone. A climber would carry in his pocket a number of rounded pebbles of differing sizes which could be inserted into cracks and encircled with a loop of rope.

The major development in the early part of this century was the use of pitons, metal spikes which were hammered into cracks in the rock, and which provided more versatile and secure protection than the artificial chockstone. Originating in Europe, it took some time for them to be accepted in

Britain where the use of a hammer was considered 'unsporting'. These metal pitons were attached to the rope via a metal snaplink or karabiner, and the lead rope would run through the karabiner or series of karabiners on a pitch (section of a climb).

As technology developed during the twentieth century the use of metal artificial chockstones became more popular in Britain, as the hammer could then be left behind, to reduce both the weight carried and the ethical problems to a minimum. Furthermore, these metal chocks were much easier to insert in cracks than pitons.

The first artificial chocks were simply old machine nuts with rope loops threaded through them[4]. However, in 1961 purpose-built chocks were introduced in the shape of tapered wedges with two holes drilled to take a loop of rope. With minor modifications, this type of protection forms the main part of the climber's rack of equipment. In the smaller sizes, it is not possible to thread loops of rope through the holes, so swaged wire loops are often used although they are not as strong as rope loops. A multitude of shapes and sizes of protection equipment have become available, and the most commonly used types will be examined in "State-of-the-Art Rock Climbing Technology" on page 13

Apart from protection, there have been other developments in technology. Ropes are a prime example of where modern technology has taken over. Hemp has been replaced by nylon- since it has greater strength, elasticity, resistance to rotting and abrasion. Hemp slings have been similarly replaced by nylon tape or webbing as they are stronger, less prone to rolling off spikes, more compact, less prone to abrasion and easier to handle.

The introduction of the harness into rock climbing was a major event. Previously, climbers had tied the rope directly around their waists. This was simple and unencumbering, but in the case of a fall would at best be uncomfortable and at worst could cause death. To improve on this, climbers in the late 40's started to use several wraps of rope to spread the load and used loops of tape round the thighs to redistribute load from the waist to the legs.

The first purpose-built harness to gain popularity was designed by Don Whillans, the famous British mountaineer, for an expedition to climb the South face of Annapurna in 1970[5]. Although designed originally for high mountain use, it is now the most popular general purpose harness in the world[6]. Falls of up to 300 feet have been sustained in them without injury and climbers have hung in them for as long as 8 hours[7].

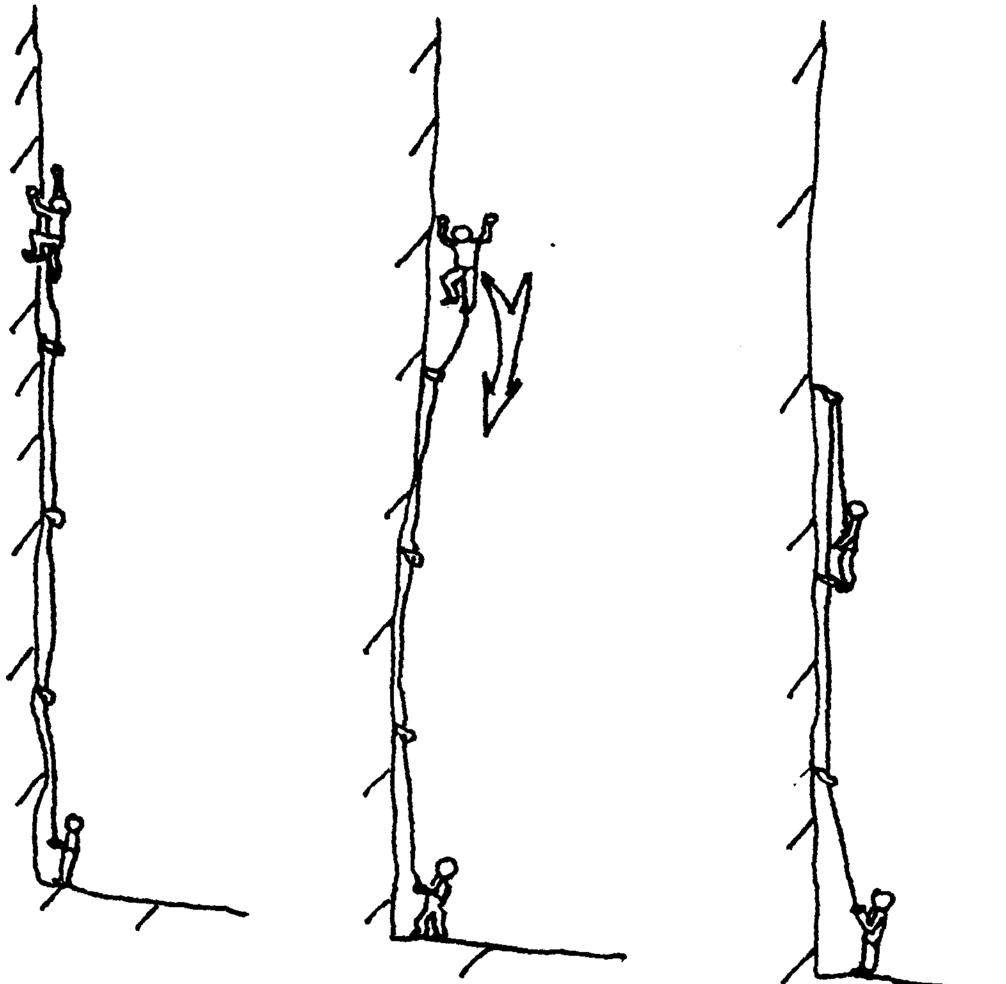
2.5 State-of-the-Art Rock Climbing Technology

Having covered the historical development so that the reader is aware of how the technology peculiar to rock climbing evolved this section covers the current state of rock climbing safety technique in the U.K. Thus the reader will be able to understand the conflicting demands placed on the equipment by what is now very much a 'high-tech' sport rather than a gentlemen's pastime.

Climbing as practised in the U.K. is now almost exclusively known as 'free climbing'. Climbers, generally operating in pairs, arrive at the foot of a cliff which may be anything from twenty feet to five hundred feet in height. They don lightweight flexible boots soled in high friction rubber, a harness which supports the waist and legs and clip onto it a selection of artificial protection equipment. The lead climber then ties onto the one or, more often, two ropes and climbs up the rock face using his hands and feet for upward progress, placing artificial protection(runners) and clipping these to the lead rope(s) to safeguard him in the event of a fall. When he reaches either the end of the rope, the top of the cliff or a suitable stance, whichever comes first, he stops and belays himself to a secure anchor point. The second climber then follows, removing the artificial protection behind him.

Should the leader fall, his flight will (hopefully) be arrested after a distance equivalent to twice that between him and his highest runner(see Fig.1). If he is to one side then the fall will be of a swinging nature known as a pendule or pendulum.

The particular types of artificial protection are numerous but it will be useful to cover those more commonly used. Natural rock spikes and threaded chockstones remain the most secure types of runner when used in conjunction with tape. Artificial chocks come in a vast variety of shapes, sizes and cross-sections including wedges, curved wedges, hexagonal and hexcentric(an offset hexagon with different widths across each of its three facets). The smaller sizes have swaged wire loops rather than rope loops and these are in common use on hard routes where all the rock features (holds



Immediatly before Fall

Immediatly after Fall

Figure 1: Diagram of Running Belays

and cracks) are, by the nature of the route, very small. These swaged wire loops tend to be stiffer than the rope loop so the friction of the rope passing through the karabiner as the leader moves upwards may cause the runner to lift out. In order to prevent this, wires are commonly extended by using two karabiners joined together with a short loop of tape (known as a quick-draw or extension).The smallest of these wires are constructed by silver-soldering the wire into the body of the wedge itself, and the strength is correspondingly reduced by their small size.

In addition to these simple devices, more complex runners are in use to protect climbers in more unusual situations. There are devices incorporating rotating cams which hold in parallel sided or even flared cracks and these despite initial opposition have gained great popularity [8][9].

It has already been stated that the second man removes all the protection as he follows his leader up the climb. However, in certain cases, the climb will have what is known as 'in-situ' protection. The fixture is already there, ready for the leader to clip into with a single karabiner or usually an extension and is left by the second man. Different types of in-situ runners include:-

1. Threads:Many routes on limestone are protected by narrow gauge tape, threaded into a natural pocket in the rock and out of another.
2. Pitons:As described in "Refinement of Basic Fall Arrest Technology" on page 11, pitons are hammered into cracks and are generally left there since it is impractical to carry a hammer.

3. Bolts:Where no other protection is available, it is becoming more common to drill a hole and place an expansion bolt in it[10].

The use of bolts in the U.K. is currently under ethical debate the latest subject since Haskett-Smith denounced the use of rope. It is not the place of this study to debate the ethics but it may be valid to make a technical contribution to the debate.

The technical advantage to in-situ protection is that it provides security where there is little or no possibility of placing one's own. When new, in-situ protection is very strong, certainly safer than wire protection. Furthermore, it is far easier to clip a quick-draw to in-situ protection than to select the correct size of wire, place it, check it is secure and then clip a quick-draw to it. The difference may appear to be small but on the steep routes of the modern genre on very small holds, often in out-of-balance positions it could mean the difference between success and failure.

Further, the presence of in-situ protection above, ready to be clipped provides a psycological spur to the hard-pressed climber and this can be of comparable benefit to the technical aspects already outlined.

The technical drawback to in-situ runners is that by its very nature, it remains in place on the rock face subjected to both the ravages of the elements(corrosion and related effects) and repeated falls(fatigue). Nylon tape is subject to degradation by ultra-violet radiation(sunlight) [11], and metal hardware such as bolts and pitons are subject to corrosion. Both of these effects are exacerbated by the presence of salt water in the air, which is often the case on sea cliffs. There is currently a trend in rock climbing to climb very hard routes using in-situ equipment of all three types on cliffs either rising directly out of the sea (Pembroke, Cornwall)or positioned above the sea and frequently covered in spray-laden air. At the risk of sounding pessimistic, it is felt that serious accidents are inevitable in the near future as the in-situ equipment deteriorates[12]. A climber attempting this type of route would be well advised to inspect the in-situ protection by abseil if he expects to fall off.

To conclude the technical aspects of fall-arrest it should be noted that the rope is held by the second who feeds the rope out as his leader climbs. The rope is fed through a friction device which usually involves bending the rope around a smooth metal radius[13]. In the event of a fall, this device provides a high, but limited braking force which brings the falling leader to a stop. The precise nature of this force will be covered in subsequent chapters.

To sum up the function of climbing fall arrest technology, it is generally a passive system, in that it remains in the background until called upon. In general, the leader will climb the route without falling off, but the technology provides a vital psychological as well as a physical safeguard. However, should a fall occur, the system will have to withstand high impact forces to arrest the falling climber. In addition, the system must also fulfil a number of ancillary functions most of which involve the static loading of the climber's weight. Abseiling(descent of a fixed rope using friction devices)has already been mentioned, and to this can be added the ascent of a fixed rope using different friction devices and sitting in a hanging belay where no ledge is available to make a stance. In all these aspects, the comfort of the harness, rather than the strength of the safety system, plays the primary role.

2.6 State-of-the-Art Mountaineering Fall Arrest Technology

The basic concepts behind mountaineering fall arrest technology are identical to those described for rock climbing. There are, however, minor differences in equipment and technique as a result of the environment in which the activity is conducted.

The climbs are generally much longer than the average British rock climb, both in terms of their height and the amount of time which they take. Whereas a rock climber might take an hour to lead a single pitch a route in the Alps usually takes a day and sometimes more. In the Himalaya, this is taken to extremes and routes take days and often weeks to complete. Added to this is the problem of the thinner air at high altitude and the necessity to move fast to avoid being caught in bad weather and it can be seen that the prime consideration for mountaineering equipment must be simplicity of use and light weight.

The climbing tends to be less difficult, so there is less protection placed than would be normal on a British rock climb. Thus, the technology plays an increased psychological part in 'protecting' the climber as he makes hard moves. As a further consequence of this, when falls do occur, they tend to be much larger than those encountered in Britain. The author has fallen 100 feet without serious injury in the Alps whereas his largest fall in Britain is 40 feet. Therefore the mountaineering environment possibly places a more severe demand upon the equipment as the falls are larger(though less frequent), it has to be lighter, able to withstand stronger UV radiation, to perform at lower temperatures(-20 degrees C is common in the Himalaya or Alpine winter), and also when covered in snow or saturated with rain.

Mention should also be made of the additional equipment used to protect the mountaineer when climbing ice. Ice screws or pitons can be screwed or hammered into the solid ice although their strength is very much dependent on the consistency of the ice being used, and is very unpredictable[14].

2.7 A Review of Caving Safety Technique.

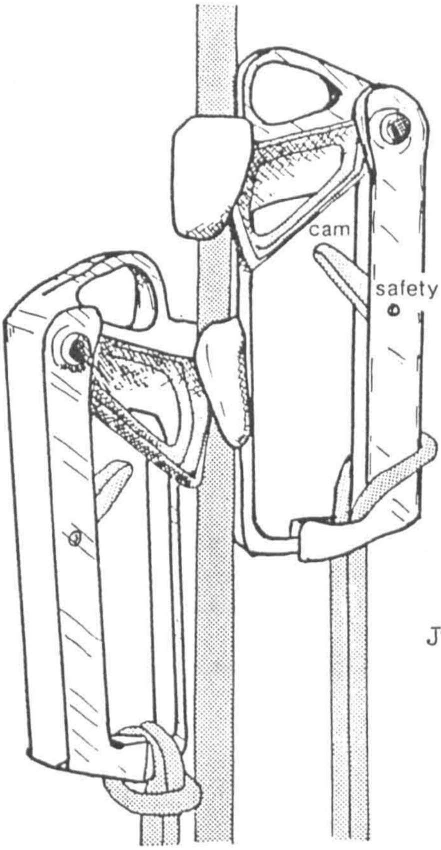
To the layman the only marked differences between caving and climbing are the environment in which they are conducted and the fact that climbers first go up then down whereas cavers go down and then up. While these factors do play the major roles a series of minor implications derive from them. The effect of the caving environment will be examined later. The way in which caving technique has developed to cope with the unique problems posed will be explained together with the necessary adaptions to the equipment.

Broadly speaking, caving can be split into the two categories of horizontal and vertical caving. The former concerns itself with progression along flat passageways, bedding planes and narrow rifts and its problems are associated with fitting the human body through increasingly smaller orifices so that the danger of falling is conspicuous by its absence. Vertical caving, howeverinvolves the descent and ascent of shafts of all shapes and sizes and this is achieved by one of two methods, laddering and Single Rope Technique (SRT).

Using laddering the caver both descends and ascends on a ladder with tubular alloy rungs and wire 'uprights'. While laddering the caver is usually belayed from above, very much in the way that a second man in climbing is belayed. In caving, this is known as 'lifelining'. For this purpose, the caver will commonly wear a sit harness of the form described in "State-of-the-Art Rock Climbing Technology" on page 13

SRT, however, is a great deal more complex. The rope is decended using a friction device which allows a rope loaded with body weight plus the weight of rope below the attachment point to be fed through in a controlled manner. The most popular devices used in Britain are the figure-of-eight descender, the rappel rack and the bobbin[15] (see fig. 2 after Montgomery[16]).

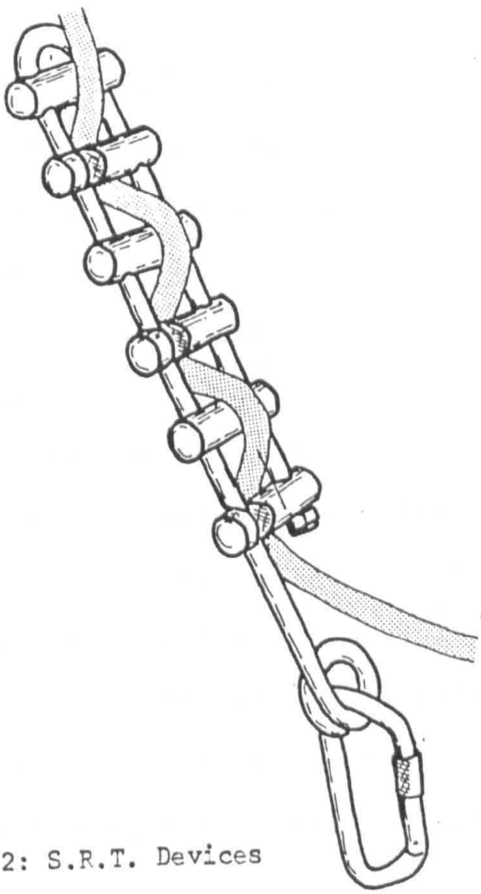
To ascend the rope, cavers use a wide variety of techniques all based on camming devices which slide easily up the rope but when downward load is applied, lock onto the rope (see fig.2). By using two or more of these devices, ropes can be ascended very quickly and easily.



Jumar Ascender

Figure-of-eight Descender

Rappel Rack



Petzl Bobbin

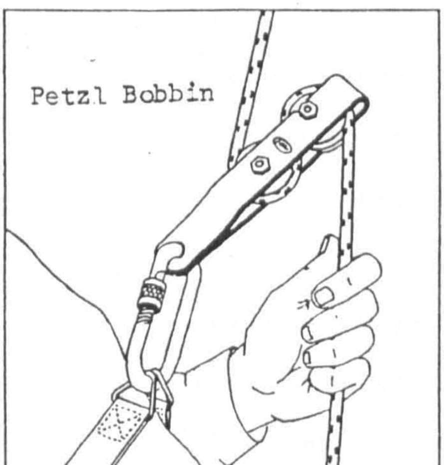


Figure 2: S.R.T. Devices

It can be seen that, in theory, the rope in a caving situation is only loaded with body weight (static loading). In practice, however, loads can be higher. When ascending, the effect of stepping up on the ascenders places approximately twice body weight on the rope [17][18]. Worse, if the belay system fails partially, due to one of the anchor points coming out, for example, then an impact load will be placed on the system. This fall would still be short compared to those experienced in a climbing situation. However, the ropes used in caving are much stiffer (to reduce bounce while ascending) and thus the impact forces will be higher. To summarise this, it can be said that while in climbing, falls are expected and catered for, in caving a fall would rarely occur unless a technical error was made.

Two factors contribute to the stiffening of the equipment:-

1. Primarily, stiffness is deliberately increased to reduce stretching of the system while ascending.Thus the rope will not rub up and down against rocky protuberances and be severely abraded.
2. Further, the caving environment means that acid from torch batteries can come into contact with textiles. Nylon is susceptible to degradation by acid, so caving equipment is generally manufactured from polyester, a much stiffer material. In certain cases, however, cavers will use alkaline substances in batteries which degrade polyester[19] and either nylon or polypropylene will be used. Polypropylene, while proof against chemical attack, is extremely susceptible to abrasion.

3. The problem of abrasion is another major environmental effect of caving. Particularly in Britain, the caves are full of mud, sand and water, all of which attack textile products. Practical experience shows that caving use is much more detrimental to equipment than climbing.
4. The presence of water also weakens the textile and the user will have to take great care to check his equipment for damage[19].

It has to be borne in mind that in vertical caving the equipment is in active use all the time, compared to climbing where the system is more passive in nature.

2.8 Applications of Industrial Fall Arrest Technology

The variety of applications in which textiles are used in industrial fall arrest is large. Safety systems can be passive as in climbing, or active as in vertical caving. Depending on the application, the problems of abrasion, heat, weathering and chemical degradation can be present. However, by a combination of design techniques from caving and/or climbing, the problems of industrial use can usually be solved. Applications include steel erecting, steeplejacking, electricity supply, broadcasting, mining, forestry and sewerage. All these have their own particular problems and designs can be modified appropriately.

One problem of industrial applications which is absent in caving or climbing is the presence of rules and regulations governing the design, manufacture and use of safety equipment. In Britain, the use of such equipment is stipulated by the Health and Safety at Work Act[20], and equipment used has to be manufactured to the appropriate British Standard, which covers raw materials, manufacturing methods and the quality of the finished product, both in terms of measurable quantities such as ultimate tensile strength and in qualitative terms such as comfort.

Chapter III

A REVIEW OF THE WEBBINGS USED IN HARNESSES AND SLINGS

3.1 Introduction

The purpose of this chapter is to give the reader basic information on the webbings used in this research, rather than to conduct investigative work. Although a small amount of experimental work has been carried out on abrasion resistance, the development of web constructions lies with the narrow fabric manufacturers rather than the product (harness and sling) manufacturers. Nevertheless, it is important for the product manufacturer to be aware of the factors governing webbing construction and for the fabric manufacturers to be aware of any special problems which may be encountered in end use. The author is particularly indebted to yarn manufacturers, weavers, dye-houses and Troll Safety Equipment for help and information provided for this chapter.

3.2 Yarns:The Basic Material

The three base products from which the webbings are woven are nylon 66, polyester(Terylene) and polypropylene. Each material has different properties and is therefore suitable for different applications

Property	Nylon 66	Polyester	Polyprop
Specific Gravity	1.14	1.38	0.92
Tenacity	7.75	7.65	8.5 to 9.0
2% Modulus	38	85	
Elongation at break	13.5%	11%	18%
Abrasion resistance	Very high	High	Very high
Regain at 65%, 20 C	4%	0.4%	
Strength Loss (Wet)	10-20%	Marginal	None
Shrinkage when wet	Marginal	Marginal	
Melting Point	250 C	254 C	165 C
Resistance to Acid	Low	High	High
Resistance to Alkili	High	Low	High
Effect of Sea Water	Marginal	Marginal	
Effect of Sunlight	Low	Marginal	High

3.2.1 Nylon 66

From the table[19][21]it can be seen that nylon 66 is a suitable material for climbing purposes having good elongation, energy absorption and abrasion resistance. Conversely, it is susceptible to acid attack and loses a significant proportion of its strength when wet or dyed. In contrast to the effect of water, ultra violet radiation (UV) can cause polymer chains to be broken or cross linked. This can cause a reduction in strength and/or abrasion resistance. I.C.I. give data for degradation of both polyester and nylon 66[22]where, after 84,000 Langleys of radiation, undyed nylon 66 fabric lost 50% of its burst strength (84,000 Langleys corresponds to approximately 6 months of Arizona sunshine). It is however vital to note that certain dyestuffs can seriously exacerbate the effects of UV as well as reducing the strength of the tape when new[19]. Further, tests have been conducted by Troll where lengths of webbing commonly used in mountaineering were left in desert sunlight for 9 and 18 months and lost 30% and 70% of their respective tensile strengths [23].

Despite this, the advantages of nylon 66 as a webbing material for climbing outweigh its drawbacks. To avoid problems, the end-user must be made aware of the limitations of the material and persuaded to replace equipment which is suspect.

3.2.2 Polyester

The major drawback of nylon is its susceptibility to acid attack. This is not a major problem in a climbing environment although care must be taken to avoid storage of equipment in car boots where battery acid may have been spilt.

In caving, however, battery acid forms a vital part of the caver's equipment. If batteries leak and the acid reaches the tape equipment it can be seriously weakened without any outward sign of damage. It is therefore important when using acid cells to have a webbing material which resists this attack and polyester manufactured by I.C.I. under the trade-name of Terylene is found to be suitable[25]. Not only does it resist acid attack, it also exhibits lower stretch properties than nylon. This is important for cavers using SRT in order to eliminate movement of the rope when jumaring or abseiling. Further, it loses very little strength when wet and has a low moisture regain, a significant factor when the caving environment is considered.

In contrast to nylon 66, polyester is susceptible to attack by alkalis. There are batteries used in caving which run on alkalis (for example the Nife or Ceag cells) and the caver should select his cell/webbing combination accordingly. It should also be noted that the low stretch properties of polyester make it a poor energy absorber. Thus falls will produce a higher impact force than in nylon and care should be taken to avoid situations in which falls could occur.

3.2.3 Polypropylene

Polypropylene exhibits poor energy absorption to an even greater degree than polyester, resulting in melting of the yarn under shock loading. Accidents have occurred in caving where polypropylene ropes were used for SRT[24] resulting in rope failure and fatalities.

Polypropylene does, however, resist attack from both acids and alkalis and this chemical advantage can in certain circumstances, outweigh its mechanical drawbacks. Troll Safety Equipment have, in conjunction with yarn and and webbing manufacturers developed a webbing suitable for use in harnesses. Its precise specification, however, has to be kept confidential for commercial purposes.

3.3 Yarn Manufacture and Treatment

The yarns used for the construction of safety equipment are almost exclusively of man-made fibres. The processes by which the yarns are produced are complex and outside the scope of this study. Produced from molten polymer, the yarns can be heat-treated, drawn, twisted or cabled before delivery to the weavers. All these processes will affect the mechanical properties[25] , the aesthetic appearance and the final cost of the yarn.

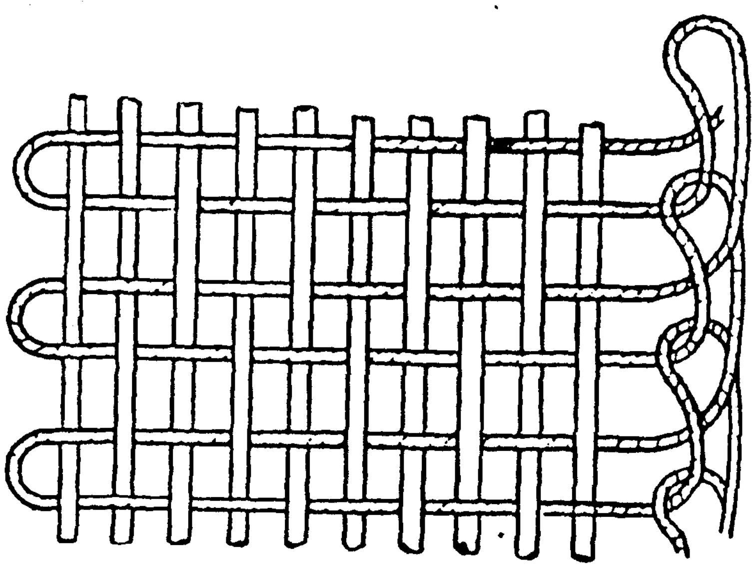
These yarns are then sent to the weavers where they are warped up onto a beam in preparation for weaving.

3.4 Weaving

It is not proposed to go into great detail in this section on weaving, but simply to set down the various parameters in the weaving process which may affect the final product. A basic knowledge of weaving on the reader's part is assumed.

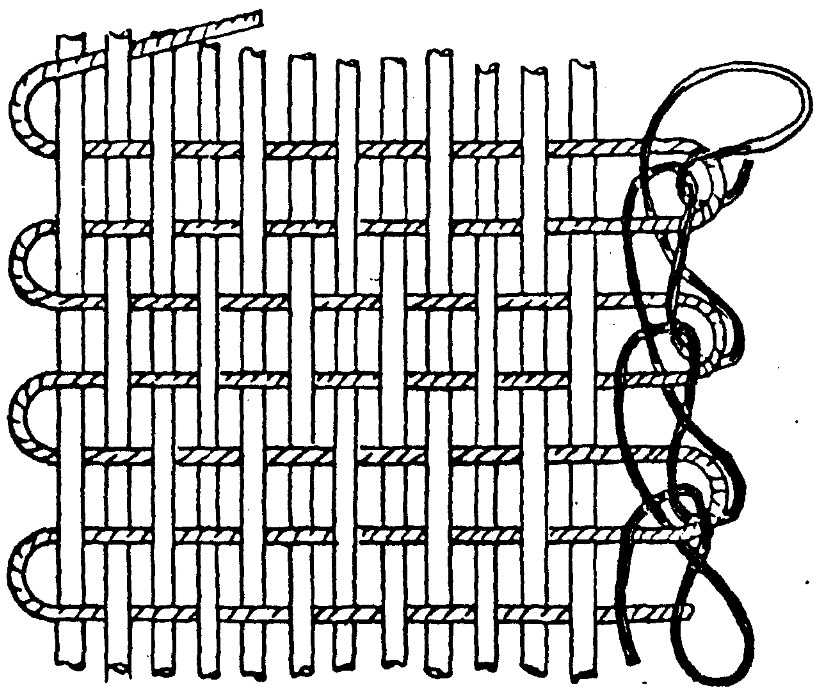
3.4.1 Weaving Methods

The first and possibly most important factor to be considered is the actual method of weaving. In the conventional weaving process, a shuttle is passed through the shed, the shed changes and the shuttle is passed back. This traditional method produces a strong stable weave but is slow and the end product is more expensive. In recent years, a different method has been introduced into the area of narrow fabric weaving. The weft thread is inserted by a rapier or needle, is looped or knitted on the far side, the needle is withdrawn and the shed changes. There are thus 2 weft threads per shed change and on the far edge (away from the needle), a knitted edge is produced. In its simplest form, the weft threads are knitted on themselves (see fig.3) and this is known as System 1. The fabric produced by this method of weaving is significantly cheaper than conventionally woven tape because the looms are that much faster to run. Studying fig.3, the disadvantage of knitted edge fabrics are readily apparent. If the thread on the knitted edge is cut through (by abrasion for instance), then the entire structure will disintegrate rapidly as each knitted loop is pulled through, which is unacceptable. Further, the doubling over of the weft to form the knitted edge will produce a thick bulge on that edge which will make it stand proud and thus render it more liable to abrasion



1. Weft knitting,

Figure 3: System 1 Weaving



2. Catch thread knitting.

Figure 4: System 2 Weaving

To avoid this bulging problem, System 2 has been developed. Rather than knitting the weft with itself, a binder or catch thread is knitted into the edge of the web. This catch thread is of a much lighter thread than the weft itself and the bulging is thus reduced. Nervertheless, the still remains prone to disintegration if the catch thread is severed (see fig.4), and further improvements have been made to attempt to eliminate the problem.

System 3 is a construction in which both weft and catch thread are knitted and produces a fabric which resists disintegration to a far greater degree than System 2. Bulging of the edge is , howeverstill prominent and this may be an aesthetic problem rather than a technical one.

System 4 introduces 2 catch threads in order to avoid this problem. With each subsequent weft insertion, the first catch thread, the second catch thread, followed by both catch threads are are knitted into the weft loops. To cause disintegration, both catch threads have to be severed and then subsequently unravelled seperately. Thus a fabric is produced which is nearly proof against disintegration.

To improve on this, System 5 has been developed. Here, the catch thread is held in position by a locking thread (see fig.6) so that, even if both threads are cut by abrasion or damage, the fabric is almost run-proof. The knitted loops of catch thread cannot be unravelled unless both they and the locking thread are pulled out at different rates simultaneously. System 5 is accepted by the M.O.D. for construction of webbing equipment.

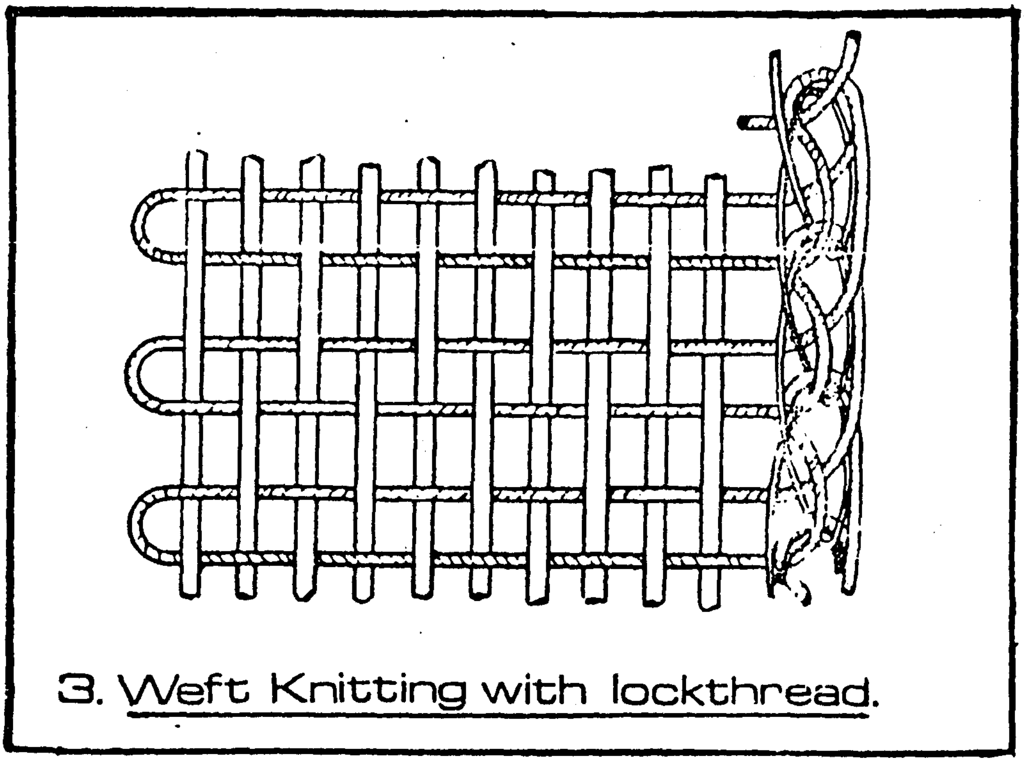


Figure 5: System 3 Weaving

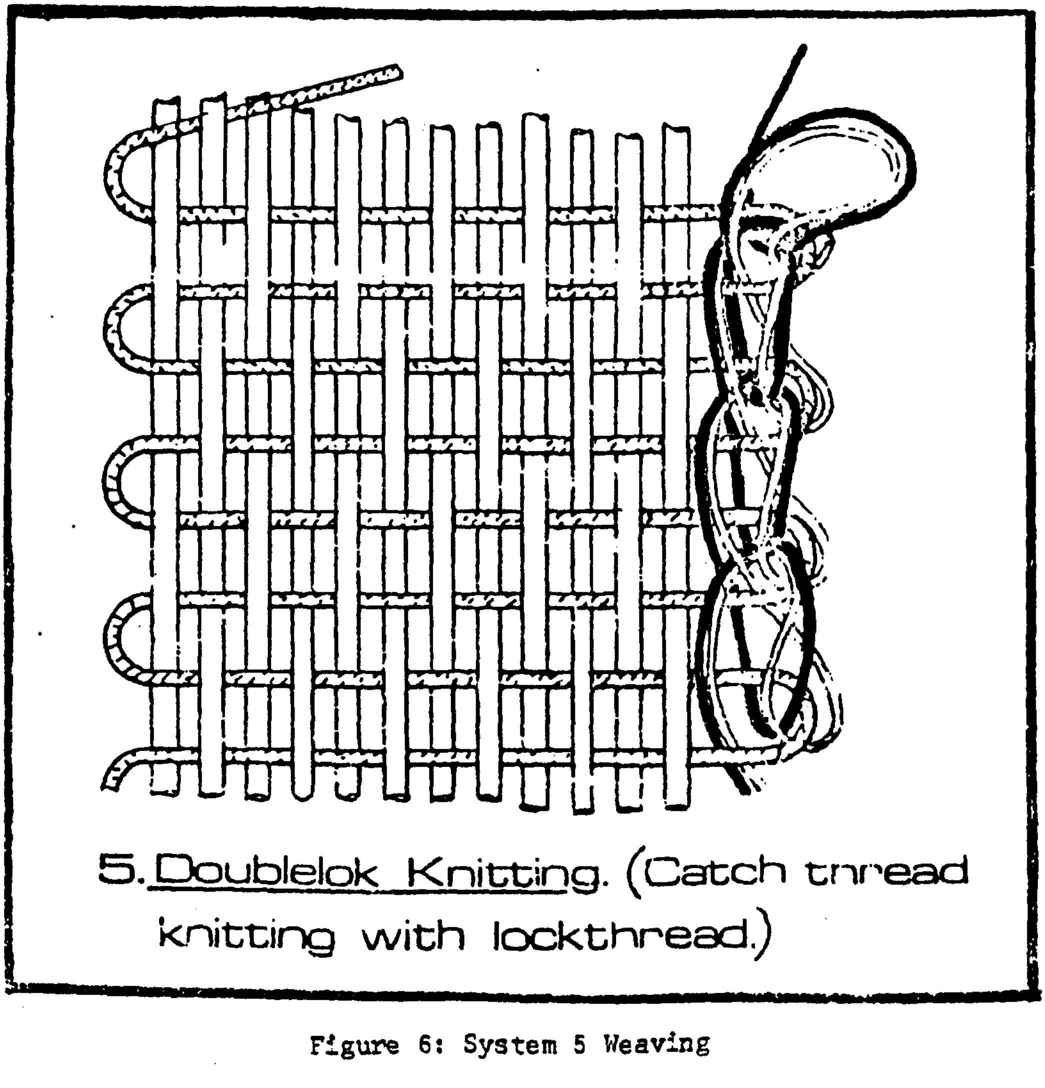


Figure 6: System 5 Weaving

Essentially, the choice has to be made between conventionally woven web and System 5 needle/rapier loom technology. The former is absolutely proof against unravelling and disintegration but is slow to produce and is correspondingly expensive. The choice between the two has to be determined by the level of safety the manufacturer desires to build into the product and the price which the market will accept.

3.4.2 Weave Constructions

Having made the choice between the two weaving methods there are a variety of constructions to choose from. Webs can be produced single ply, 2-ply or tubular with any number of refinements such as stuffing threads or binders to alter the characteristics of the final product. In the final analysis, the correct balance has to be struck between strength, elasticity, abrasion resistance, suppleness, knot-ability and sewability. The tighter the weave the more abrasion resistant it will be, but it will lose suppleness and knot-ability.

3.5 Finishing

Dyeing will further affect the handle and strength of the web although with the market in its current state colour can often play a more important role than the mechanical properties.

Further treatment can also affect different properties of the web. Heatsetting, for example, will give a tighter structure to the web if done at the final stage. However, if the yarn is heatset before weaving, a softer more pliable structure will result.

More specialist treatments include coating with protective finishes. As part of this research, a programme of experiments was carried out to determine the abrasion resistance of webbing which has been coated with a polyurethane varnish. These tests were based on a treatment involving an industrial deburrer or tumbler, and were therefore dubbed the "Tumbler Tests".

3.6 The Tumbler Tests

3.6.1 Objective

The objective of these tests was to simulate the treatment which webbing receives while underground in a caving situation. This is a severe environment in which equipment is subjected to water, dirt and mud for long periods of time. It has been observed that slings lose 50% of their strength within a short period of being introduced to caving[26]. It was hoped to find the mechanism causing this strength loss and to devise a way of preventing it.

3.6.2 Abrasion Simulation

In order to simulate the caving environment in a controlled situation, a large quantity of sediment was removed from a cave entrance in the Yorkshire Dales and brought to the Troll factory. Although the sample might not be strictly homogeneous it was felt that it was representative of the conditions encountered that is a mixture of different particle shapes and sizes. Providing the same sediment was used throughout the testing programme it was felt that the results could be meaningfully compared.

The sediment was subjected to particle analysis using a sieving method. 50 grams of sediment was passed through sieves of decreasing size and the mass of particles in each sieve measured to give the percentage by mass in each size interval. The results are shown in table 1. Once the abrasion was completed, photographs of the samples would be taken on a scanning electron microscope and the sizes of the particles compared with fibre diameter.

10 kg of the sediment was placed in an industrial deburrer (tumbler) and mixed with 45 litres of water. The tumbler was then set revolving at 1 revolution per second and the samples of webbing placed in it.

3.6.3 The Webbing Samples

The webbing used in this experiment was almost exclusively 50 mm in width, and each sample was 2 metres in length. The three major samples to be compared were a nylon 50mm twill web. One was coated with a polyurethane (PU) of medium hardness, one with a soft PU and a control web with no coating. Prior to the experiment, it was hoped that the PU coated webs would perform better than the control by protecting the yarns from the cutting effect of the sediment particles.

To provide further information on webs already in use in commercial production, two further 50 mm nylon webs were comprehensively tested. JC-HS and WW-11[27][28] are both extensively used in climbing harnesses. Information on abrasion resistance would therefore be useful to attempt to predict the life of a harness.

Apart from these webs, a small number of tests were conducted on various prototype webs which were being developed at the same time as the abrasion tests were being carried out. These included a 50 mm polyester web, already used in caving harnesses a 50 mm polypropylene web and a 25 mm web known as Coreweb. This Coreweb is constructed using a two-ply or tubular web with loose warp yarns held in between the two plies. These ´stuffers´ are held together by binder threads and, in theory this core is protected by the outer plies. More than 50% of the web´s strength is supplied by the core and it was hoped to show that the process of abrasion could be reduced by using this type of web construction.

3.6.4 The Testing

Because of the large number of samples involved and the number of time intervals required to gain a clear picture of the progressive strength loss, the actual number of samples for each data point was restricted to two. Values quoted are generally the lowest value recorded unless the test was somehow invalidated by, for example uneven loading of the sample.

The time intervals initially selected were 8, 24, 48 and 104 hours, but this was expanded after this first set of tests to include some very low times (2, 4 and 6 hours) as well as long term testing up to 600 hours. It should be noted that this latter period is 25 days of continuous abrasion, and is therefore a very severe treatment of the web. Further, the tests of this time-scale are extremely time-consuming.

After these abrasion tests, a set of tests was conducted by placing tape samples in a tumbler filled with 45 litres of water and no sediment. In this way, it would be ascertained whether the mechanical action of simply tumbling the web caused any significant strength loss. Tests were also conducted with some of the webs simply saturated with water to check existing data on their wet performance.

The subsequent tensile tests were conducted on an RDP tensile test machine in the Physics department of Leeds University using bollards specifically designed for this type of testing at an extension rate of 0.1 of the gauge length/min, generally about 30 mm/min. Failure usually occurred between the bollards and on the few occasions that the failure occurred across the back of the bollard, the result was generally low and would be discarded. The results of the tensile tests are shown in table 2 and figs. 7 and 8

3.6.5 Discussion of the Results

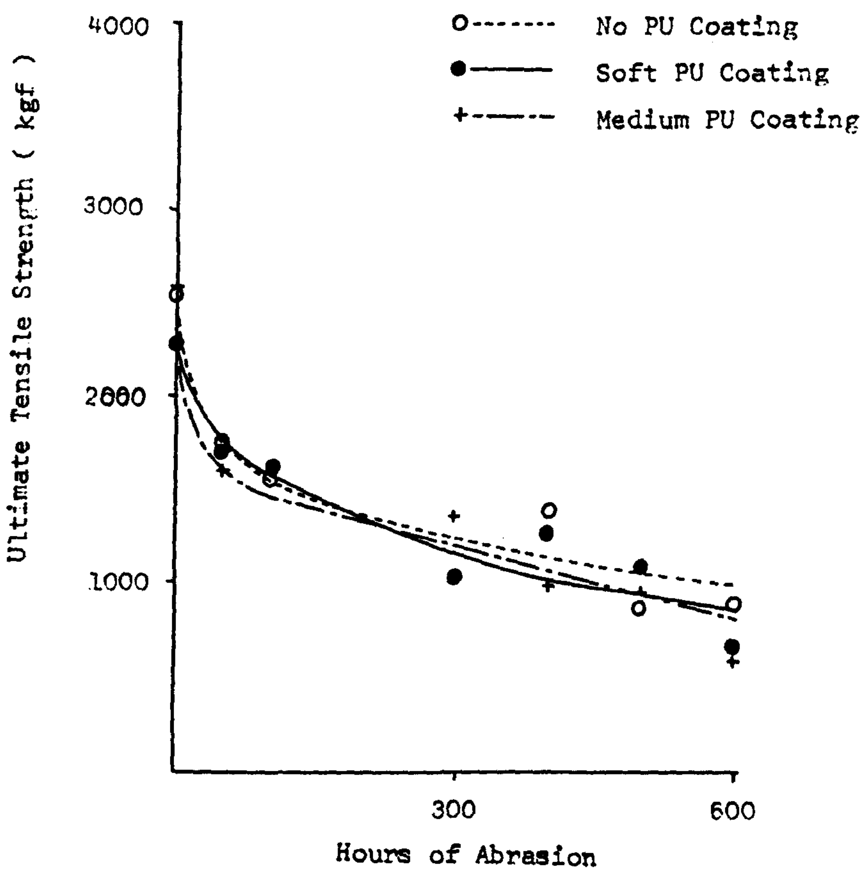
As the web is steadily abraded, it is expected that the strength will gradually decrease. This is generally the case for all the samples. Every type of web loses over 25% of its tensile strength in the first two hours of abrasion, but then takes 300 hours to lose a further 25%. By 600 hours, approximately 60% of tensile strength has been lost. Thus it can be confirmed that this type of treatment causes strength loss equivalent to that found in reality.

However, within each sample there are anomalies, such that the strength frequently increases with further abrasion, because the scatter of the results is of a greater order than the effect of the abrasion. Examining the table and graphs, a scatter of 10% either side of the mean can be observed. This may be due to variations in the abrasion treatment of each sample. However, a much more likely source of error is the tensile testing method. The webbing samples are wrapped twice around a steel bollard which is 100 mm in diameter with a steel leaf in between the two wraps to prevent excessive slippage. Some 'stick-slip' does occur and this inevitably causes uneven loading rates. Further, the tape may be unevenly loaded across its width which will cause progressive failure or tearing at a lower load.

Nevertheless, it was hoped that some differences would show up between the samples over and above this scatter. From the table, it would appear that every type of web performs in a similar way. Thus the coating of the PU makes very little difference in percentage terms. The mechanism of abrasion is completely unaffected by the PU.

To check that it is the sediment causing the deterioration rather than the flexing of the web involve in the tumbling a series of tests were conducted with just water and no sediment in the tumbler. These clearwater tests were conducted over a period of 104 hours at which point the abraded samples had lost between 30 and 40% of their strength. In the former tests, the changes in strength are insignificant thus proving that it is the sediment which causes strength loss.

Measurement of the samples indicates a small decrease in length with an appropriate increase in thickness but no change in width. Under examination using a scanning electron microscope photographs of the control samples and those



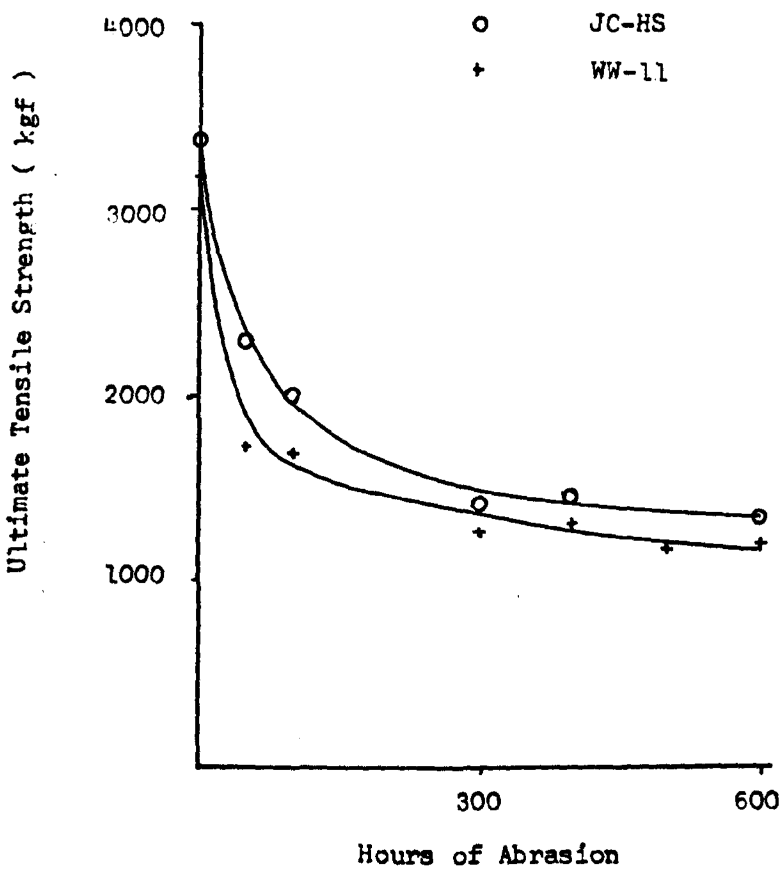
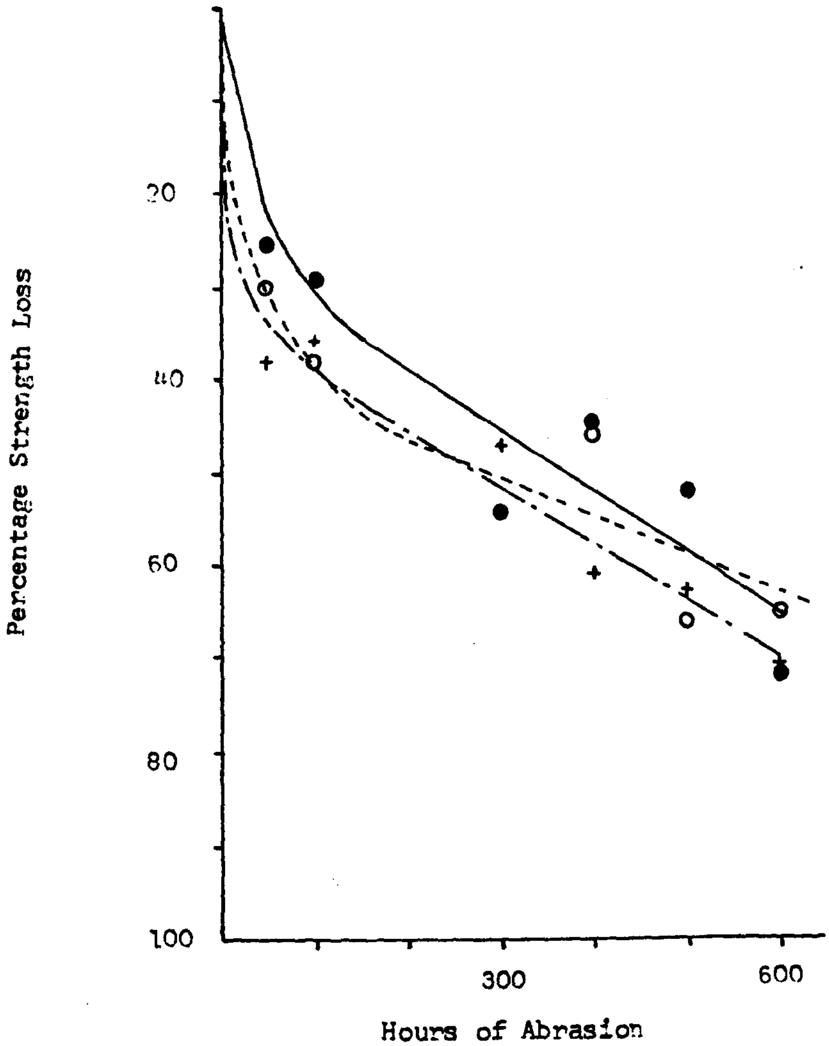


Figure 7: Tumbler Tests; Overall Results



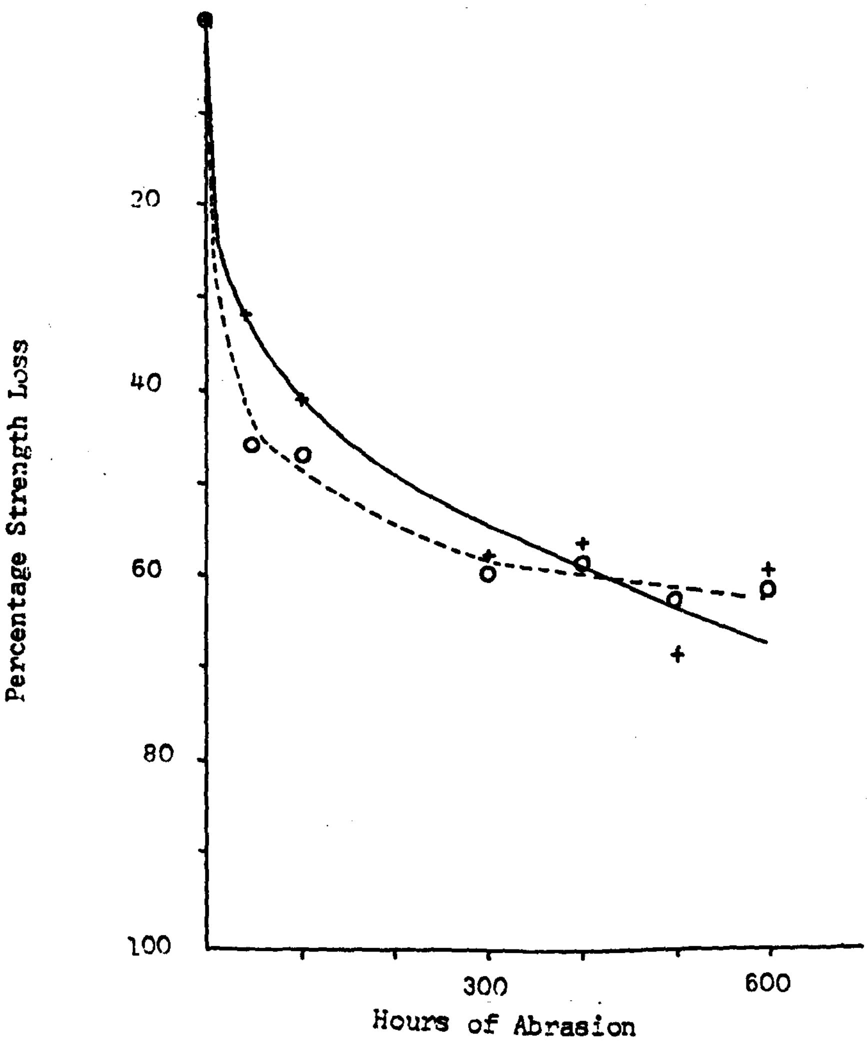


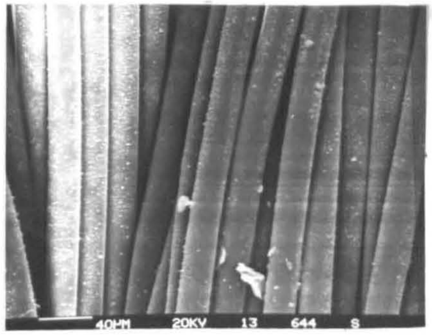
Figure 8: Tumbler Tests
Percentage Results

with maximum abrasion (600 hours) show marked differences (see fig.9). Examing the fibres of the control samples, it can be seen that they are approximately 20μm in diameter with fibre interstices of less than 10μm in the twill web but up to twice that in JC-HS and WW-11. Comparing this to the particle size analysis, although only 15% is less than 65μm in diameter, observation of this fraction under a microscope reveals a proportion of particles less than 20μm in diameter of varying shapes, many with sharp corners capable of damaging the fibres.

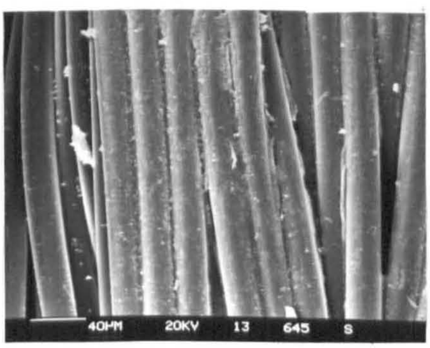
The effect of the abrasion can be seen in fig.10. It would appear that the external surfaces of the fibres have started to flake away, producing cracks in the previously smooth surface. These cracks act as stress raisers and consequently weaken the fibre, the yarn and the web. Under more detailed examination , it would appear that the inner fibres of the yarn are similarly damaged and the sediment is therefore getting inside the yarn structure.

It is very difficult to formulate any hypothesis as to the abrasion mechanism and the means of preventing it. Increasing the thickness of the PU coating will inevitably reduce the abrasion, but to eliminate it completely would mean an unacceptable loss of flexibility in the web. Tightening up the web structure will prevent external abrasion to a certain extent, but internal abrasion will not be affected.

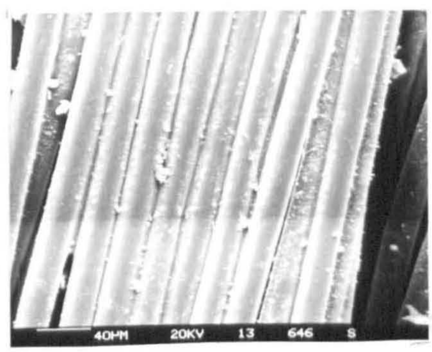
Overall, it would seem that the process of abrasion is very difficult to prevent, and it is better to allow for its effects by increasing the strength of the web when new. To



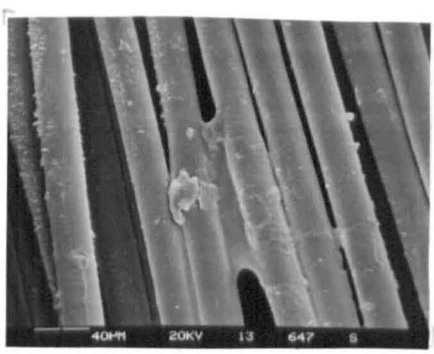
No PU



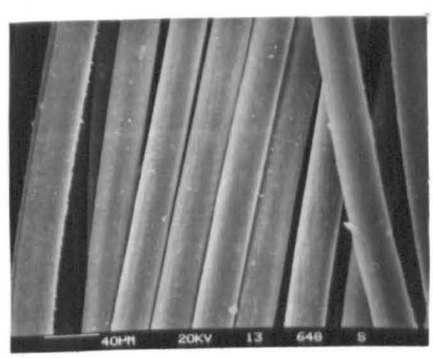
Soft PU



Medium PU

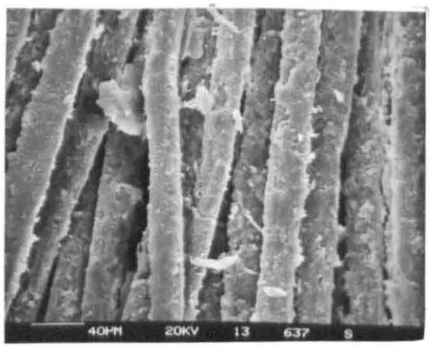


JC-HS

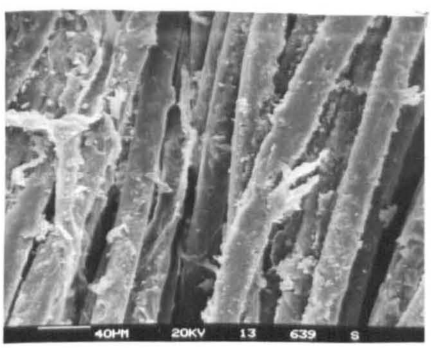


WW-11

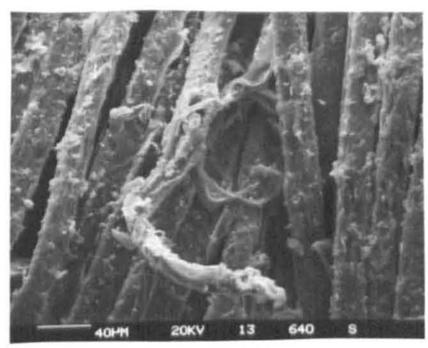
Figure 9: SEM Scans of Control Web



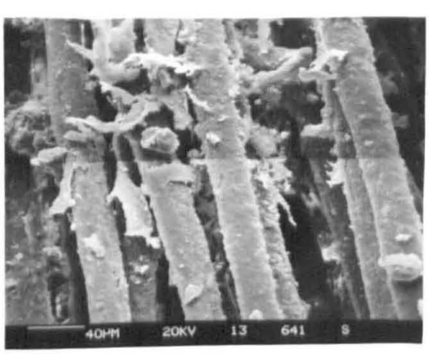
No PU



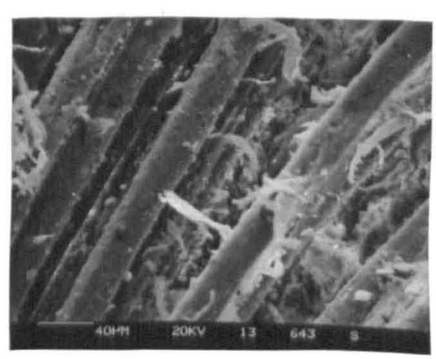
Soft PU



Medium PU



JC-HS



WW-11

Figure 10: SEM Scans of Abraded Web

finish this section, the tests conducted on wet web show a marked decrease in the strength of nylon, while polyester and polypropylene maintain their strength. Further, the high tenacity polypropylene performs equally as well as the nylon under abrasion, which is very encouraging for its use in a caving situation where abrasion, acid and alkali attack form the major hazards to web strength.

3.7 Conclusion

The sphere of webbing manufacture is in a state of continuous development. Different weave constructions, different materials(such as Kevlar) and different treatments are being introduced all the time. Frequently, the prime factor to be considered is the web's aesthetic or handling properties. In this field, there is no substitute for practical experience of dealing with webbing.

Chapter IV

SEWN BLOCKS

4.1 Introduction

In order to join web together to make slings and harnesses there are two methods available: knotting and sewing. Two lengths of tape can be knotted together using the tape knot, which is effectively a double-overhand knot (see fig.11 after [19]). In comparison to a sewn joint, the knot has two advantages:-

1. Low cost.The tape can be cut to the correct length and the user can join it himself.
2. Speed of construction.In a mountaineering situation it is often necessary to take a length of tape and knot the two ends together to form a sling of a specific length to use as an abseil point. Speed and adaptability are important here and the knot lends itself to the situation.

In most other applications, however, knots have disadvantages. They are bulky, cause strength loss by stress concentration within the knot[19]and if tied carelessly can come undone. Further, the bulk of the knot makes the tape more susceptible to abrasion by increased pressure rubbing on the knot. For harness manufacture, the tape knot is only suitable for joints with collinear axes, so others will require sewing.

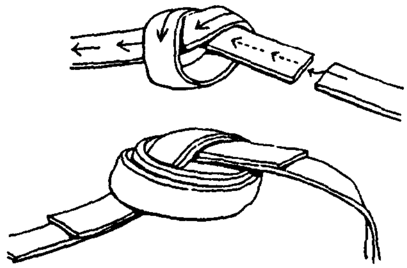


Figure 11: Tape Knot

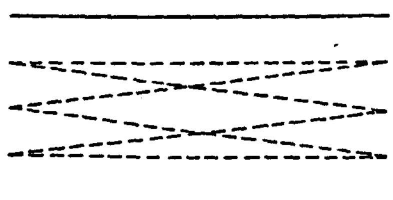


Figure 12: Lap Sewn Joint

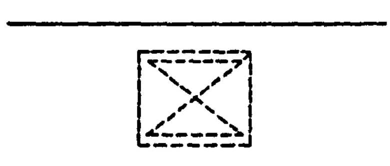


Figure 13: Gate Block

The large number of different types of sewn joint in use in safety equipment makes a complete review impractical. However, the most common type is the lap joint sewn with a double-W pattern (see fig.13) whose properties are reviewed thoroughly by Webb[29]. In practice, this joint is exceedingly strong when a 9-row 4 inch block is used on 25 mm web with 20's nylon thread so that often the joint is stronger than the web itself [30]. The other major type of conventional sewing block used is the gate block where the stitching is in an X-form with border stitching around the edges (see fig.13). This joint, having less stitches than the 9-row double-W is weaker but has the advantage that it can be easily inserted using automatic machines and also leaves a more flexible joint.

Details of other less common joints, plus information on threads, stitch density etc.are too extensive to consider here. Readers should refer to Murray[31] for a general review and direct further research as necessary. For manufacturing purposes, however, there is no substitute for practical experiment, together with design flair and common sense. The author has learnt a great deal through studying the designs of Troll Safety Equipment and believes them to be one of the state-of-the-art companies in this field.

The major development in the field of sewn joints in recent years has undoubtedly been the bar-tack. Using an automated sewing machine, a large number of stitches are inserted across the width of the web with the stitch line running parallel to the warp.Thus a bar of stitching is inserted. The advantage of the bar-tack is its speed of insertion compared to the 9-row 4 inch block. Further, using 5 of these bartacks, a joint can be constructed whose strength when new is equal to the 9-row 4 inch block whilst retaining far greater flexibility in the joint. The major drawback of the bartack, however, is its susceptibility to abrasion. Because of the large number of stitches inserted into a small area, the thread does not bed down into the body of the web but stands proud of the surface, thus exposing itself to more potential abrasion. It was decided to conduct a study of the two types of joint under controlled abrasion conditions and then compare the strengths and appearences of the joints in order to match it up to real conditions.

4.2 Resistance of Stitching Blocks to Abrasion

4.2.1 Method

The object of the exercise was to compare the resistance to abrasion of two types of stitching block when incorporated into a sewn sling. The slings were made from 4 feet lengths of conventionally woven 1 inch dyed 'standard' tape (a stock item produced by Troll). These were sewn into loops using:-

1. Troll's standard 9-row 4 inch double-W lap joint
2. A 5 bar-tack joint each bar seperated by one inch.

The abrasion was applied using a method employed by webbing manufacturers. The tape was passed in a reciprocating motion across a hexagonal mild steel bar. This bar measures 6mm across flats and the tape is led through a right angle over it. A tension of 7lbf is applied using a weight. It

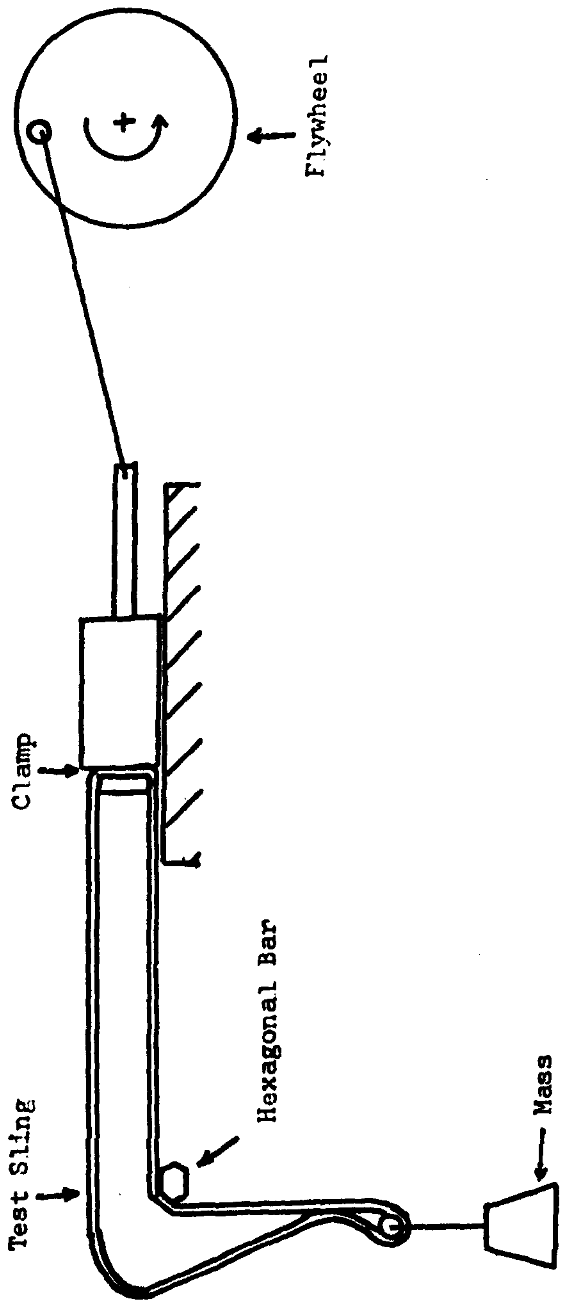


Figure 14: Sling Abrasion Apparatus

is ensured that this is taken on the block alone by sewing a loop in its lower end (see fig..14). The machine was reciprocated at 30 cycles/min (0.5 Hz) as this gave a variation in load due to inertial effects of less than 10% and therefore applied the abrasion evenly along the length of the joint. The amplitude of this reciprocation was 4 inches peak-to-peak.

A selection of abrasion cycles was applied to both blocks and their condition noted. It was observed that the bar heated up due to frictional effects so a blast of compressed air was used to cool the bar to eliminate thermal effects. Following the abrasion, the slings were subjected to tensile tests using the U.I.A.A. approved method[32] and the results are shown in table 3 and fig.15.

4.2.2 Discussion and Conclusions

As can be seen from the table and graph of results the two types of joint perform almost identically for the first 10,000 cycles of abrasion. Thereafter, the double-W joint retains a constant strength of approximately 1750 N while the bar-tacked joint continues to deteriorate and , after 30,000 cycles, has negligible strength left.

The difference in performance is caused by the fact that the bar-tacked joint stands proud of the web thus abrading the thread. In the double-W joint, the thread beds into the body of the web after 10,000 cycles, protecting it from further abrasion.

However, it is questionable whether a joint would receive the equivalent of 30,000 cycles of abrasion during its normal life. From the table, it is noted that the slings take

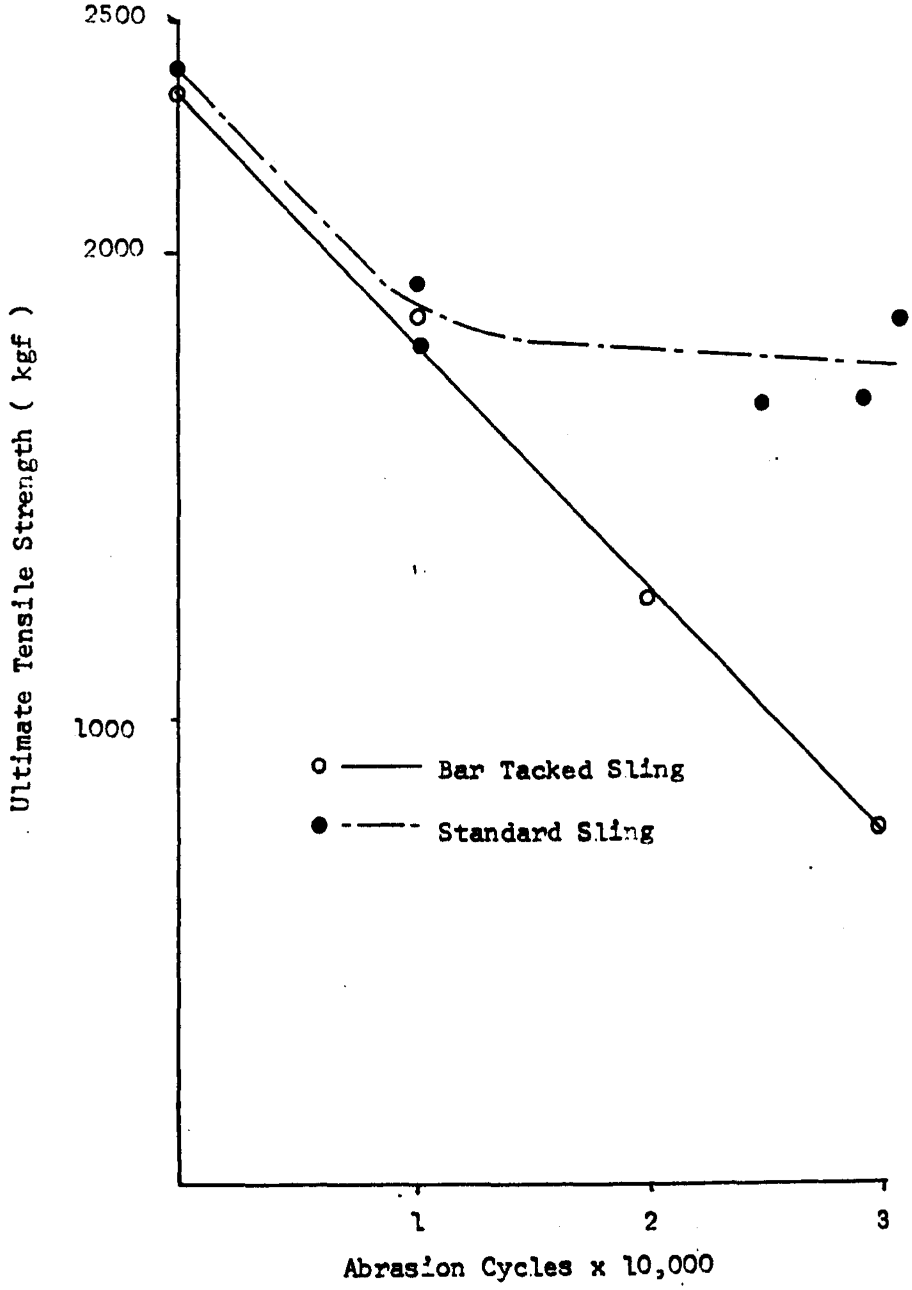


Figure 15: Sling Abrasion Results

on a worn appearance after 10,000 cycles and, if in use by a careful climber, would be discarded.

The abrasion process follows a pattern of:-

1. 0-10,000 cycles: The thread in the double-W is initially abraded and weakened but sinks into the web after this. The bar tacking is similarly weakened.
2. 10,000 cycles upwards:The thread in the standard joint is protected but the web is abraded, taking on a furry appearance. However, it suffers little or no strength reduction. In contrast, the threads of the bar tacked joint continue to be abraded with a consequent loss in strength.

Summing up, a double-W joint retains its strength even when its appearance would suggest that it ought to be discarded. A bar-tacked sling performs equally well up to this point after which it continues to deteriorate. From a practical point of view, the bar tack is a suitable alternative providing its user is aware of its limitations and retires the equipment when it takes on a furry appearance. However, given the customers reluctance to spend money, the bar tack should be used with caution by a conscientious manufacturer. Designs should take into account the deterioration of slings with age, and the strength of the sling when new up-rated accordingly. Finally, the manufacturer should attempt to educate the user as to the limitations of the equipment.

Chapter V

MISCELLANEOUS RESEARCH ON HARNESSES

This chapter will be concerned with a number of minor points rather any one major area of research. However, the author feels that this is potentially the area where a great deal of work could be done to improve the designs of harnesses. The current designs are not bad or unsafe but there are unknown areas which , under investigation, might lead to improvements.

5.1 Development of the Harness

The harness provides a means whereby the climber (or caver, or worker) is connected to the rope and should be comfortable while suspended in it for long periods of time. It should also be able to withstand the forces imposed in a fall. A brief history of the development of the harness will be given after which the design conditions of the harness will be examined.

As was mentioned in the introductory chapter on fall arrest technique, the original method of fastening on to the rope was by a direct tie around the waist of the climber. While being simple and unobtrusive, this method is at best uncomfortable to hang in and at worst can kill by the restricton in blood supply causing heartstop[33]. Deaths have undoubtedly occurred;in one well documented case the German climber Toni Kurz died on the Eiger, only a few yards from rescuers unable to reach him because he was hanging in free space below an overhang[34]. Factors such as cold and exhaustion also contributed to his death, but the author has no doubt that a modern sit harness would have improved his survival chances considerably.

In the U.K., there has been an incident where a climber fell off steep overhanging rock and was unable to regain contact with either the rock or the ground. In the 10 minutes that it took for a rope to be lowered to him from above, he had died from heartstop[33].

Climbers were certainly aware of the problem, and even before the development of the harness techniques were in use to avoid this kind of fatality, similar to slow hanging. Essentially, the problem involves removing load from the waist area where it restricts the blood supply, and placing it on some other area more fit to carry the load, specifically the legs. This is because these form some of the strongest muscles in the body, and have no vital organs associated with them.

The technique developed uses a sling, 4 feet in circumference wich is wrapped around both legs and over the waist line thus placing load on the upper thighs. This could be done either before the start of the climb or in an emergency, by hanging upside down on the rope, sliding a sling over the legs and then righting oneself, a technique known as the 'Baboon Hang'[35].

This form of support, in which the load is shared between the waist and the legs forms the basis of the sit harness. The first purpose-built harness was designed by

Don Whillans for the first ascent of the South face of Annapurna in 1970. The harness, designed for use on fixed ropes (jumaring and abseiling)undoubtedly contributed to to the success of the climb and has since gone on , with very few changes, to become the world's most popular sit harness. As in fig.16, The weight is distributed between the belt and a crutch loop which splits into two thigh straps between the legs. These thigh straps are held in place by buttock straps running from the centre of the back to the centre back of each thigh.

Despite initial opposition, the 'Whillans' reigned supreme until 1978 when Troll, the manufacturers of the Whillans introduced their Mark V harness, the first two-piece sit harness. The design differed radically from the Whillans in that the legs were supported in seperate loops, each closed with T-joints at the top front of the thighs and were connected to the wide belt by a belay loop at the centre of the waist and by a non load-bearing buttock strap, looped over the back of the belt and secured to the leg loops with a small buckle(see fig.17). Since the Mark V, the market has been flooded with new designs of harnesses.

To finish this section it should also be mentioned that full body harnesses exist which support the thighs, waist, back and shoulders. Two-piece harnesses comprising a sit harness and chest harness perform the same task (with less comfort but more versatility) and some climbers in Europe wear chest harnesses alone. When the design features of a harness have been examined the merits and drawbacks of these designs will become apparent.

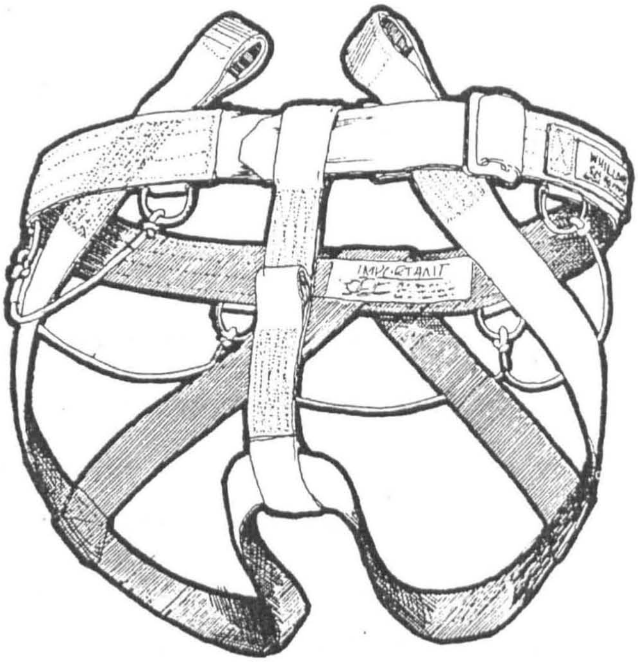


Figure 16: Whillans Harness

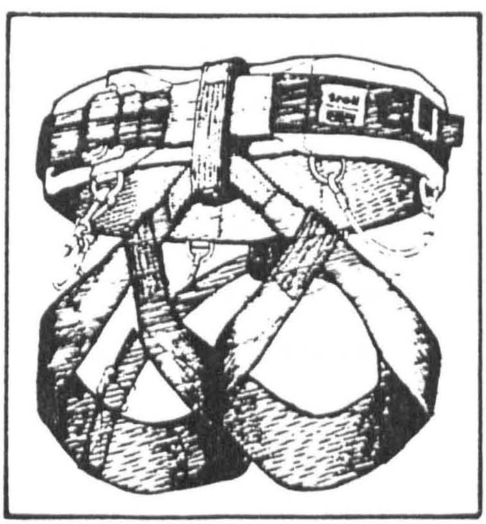


Figure 17: Mark VI Harness

5.2 Design Considerations of a Harness

The prime function of the harness is to support the subject during fall arrest and in the suspended position immediatly afterwards. This latter part will also apply for abseiling and jumaring. This functional requirement can be split into two technical requirements:-

1. The individual components of the harness must be strong enough to withstand shock loading applied in a variety of orientations.
2. The harness must not exert such a pressure on the body that undue pain or injury is caused.Such a specification is less quantitative than 1. Nevertheless, by thorough laboratory and field testing it can be ensured that a product is safe before marketing.

It is straightforward to determine the necessary strength of the harness. Any U.I.A.A. approved rope must exert a force no greater than 1200 kgf at a fall factor(see chapter on Drop Testing) of 1.78 Thus the highest force which could possibly be exertedis $1200 \times 2.0/1.78 = 1350$ kgf. The U.I.A.A. standard[32] lays down that a harness must withstand a proof loading of 1600 kgf before being approved. This allows for stiffening of the rope (producing higher impact forces) and deterioration of the harness components in use. The strength of each individual component of the harness is determined by its load distribution which is examined below.

5.2.1 Load Distribution in a Harness

When considering the strength of each component of the harness the load distribution must be analysed. This depends on the design of the harness and the attitude of the body during fall arrest, which will itself be changing as the body is brought to rest. The stiffness of the harness components and the subject will also affect load distribution. With all these parameters , load distribution is difficult to predict or determine. Attempts were made during this study to determine load distribution but none of the alternatives proved viable.

5.2.1.1 Experimental Methods

To affix strain gauges to a rigid metal structure is a simple task but when the material is flexible with a high extension under load, the use of strain gauges is difficult. The maximum strain which a foil gauge can withstand is 20%[36] which is far exceeded by the strain produced in webbing under load. Even if a suitable specialist gauge could be found, the probelm of bending of the web means that gauges could only be fixed to web in free space and therefore tensioned in a uniaxial manner. Further, the establishment of a point of zero strain in a textile material is difficult and warrants a thesis in itself[37]. To develop a strain gauging system the initial study would have to be done under uniaxial tension to establish a feasible design, then calibrate it in terms of strain and load and finally incorporate it into a harness. There is evidently scope for further work which could give useful results. As the author, I believe that the development of a strain gauging method for harnesses will be fraught with the difficulties of handling webbing, a material which only has significant stiffness in 2 axes (warp and weft) out of the 6 available. Even in these 2 axes, the webbing is much more flexible than the materials with which strain gauging is normally associated.

The use of pressure transducers between the subject and the web was considered. If the pressure could be measured, the tension in the web could be found using the radius of curvature of the web at that point. Thus, the system would only work if the web was in contact with a rigid surface, ruling out the use of human subjects. Further, the presence of the gauge would distort the web and alter this radius, thus making calculation of the tension inaccurate.

The use of strain gauge buckles, threaded onto the web, was considered. This method is mentioned in the development of harnesses by the R.A.F. Institute of Aviation Medicine[38][39] where the web is threaded through the buckle in a bent configuration. As tension is applied to the web, the buckle tends to straighten out thus producing a signal on a gauge attached to the buckle.

The problems of this system are that it distorts the configuration of the harness, it cannot be used in a live situation with a human subject and the most reliable results are only achieved when the web is under uniaxial tension. Nevertheless, as the author I feel that this type of system represents the best hope for measuring load distribution in a harness. The design of the buckle, the application of the gauge, the calibration and its limitations form the basis for a thesis in themselves. Once this is done, the harnesses themselves can be studied.

The insertion of metal buckles loaded in tension rather than bending was also considered. To incorporate such an insert into a harness would mean cutting the web, sewing two loops and replacing the missing section with a metal plate, with suitable strain gauges attached. The change in the harness stiffness by using such an insert was felt to debar this method, as well as the problem of using it with human subjects.

5.2.1.2 Theoretical Methods

There are many methods, both simple and complicated, for determining the load distribution in a structure. In most of the mathematical models, the procedure is to give the properies of the structure under analysis (stiffness, mass, geometry etc.) the boundary conditions imposed on the structure (restraints, degrees of freedom etc.) and the direction and magnitude of the input loads. Simple structures can be easily analysed but more complex ones may require computer techniques such as finite element analysis.

Although the harness is a simple structure, there are many problems associated with the prediction of load distribution. Firstly, the geometry changes significantly as the load is applied. Even in a situation where the subject is rigid, the high extension of the web changes the angles which the various components take up. Secondly, the stiffness of the web is a very difficult property to model, being non-linear in its main axis and virtually zero in all the others. Thirdly, if a human body is used in the model, then the prediction of its properties is even more difficult than those of the harness. Fourthly, the restraints of the harness and the degrees of freedom at its joints are difficult to represent, being quite unlike any metal structure.

It is thought that the subject of load distribution, even in a static situation, warrants further study in both experimental and theoretical directions. A crude model was developed at this stage to show the basic mode of operation of a harness

5.2.1.3 Simple Modelling of a Harness.

A known input load is split into branches which form the seperate components of the harness. A number of assumptions are made about the properties of the harness and its boundary conditions.

1. The material has low extension under load.
2. It has no resistance to bending, compression or torsion.
3. The joints cannot transmit moment, i.e. are represented by pin joints.

Thus the loads at a joint can be resolved in fig.18 parallel and perpendicular to P to give

$$P_0 = P_1 \cos X_1 + P_2 \cos X_2$$
$$0 = P_1 \sin X_1 + P_2 \sin X_2$$

Substituting:-

$$P_1 = -P_2 \frac{\sin X_2}{\sin X_1}$$

and so

$$P_1 = \frac{P_0}{\cos X_1 - \sin X_1 / \tan X_2}$$

and

$$P_2 = \frac{P_0}{\cos X_2 - \sin X_2 / \tan X_1}$$

In a symmetrical case, where

$$X_1 = \pi - X$$
$$X_2 = \pi + X$$

$$P_1 = \frac{-P_0}{2\cos X} = P_2$$

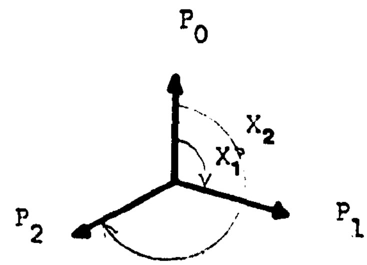


Figure 18: Diagram of Loads at a Joint

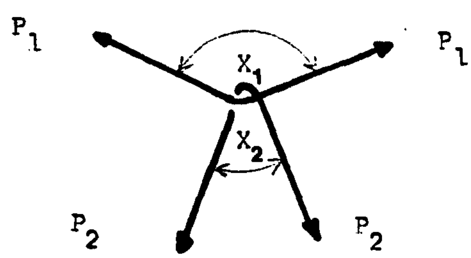


Figure 19: Diagram of Loads at Two Intersecting Loops

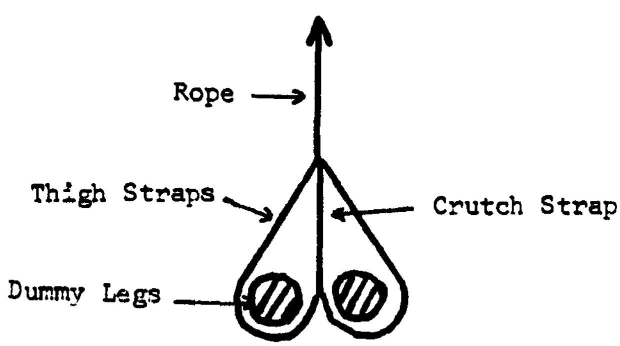


Figure 20: Idealisation of Whillans Harness

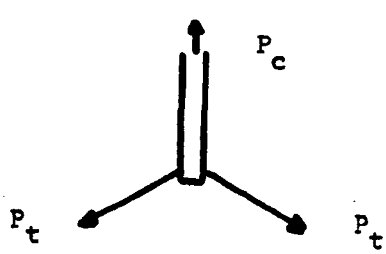


Figure 21: Idealisation of Crutch Strap Loop

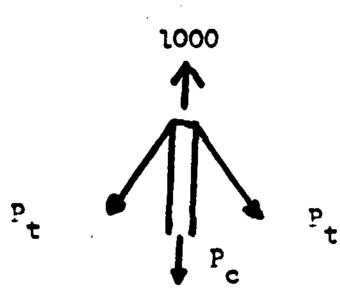


Figure 22: Idealisation of Rope Attachment Point

Where two sections of tape intersect, there are four forces rather than three. However, it is assumed that there is no friction at the intersection, so the tension in each arm of each tape section must be equal (see fig.19):-

$$2P_1 \cos X_1/2 = 2P_2 \cos X_2/2$$

and so $P_2 = P_1 \dfrac{\cos X_1/2}{\cos X_2/2}$

As X_1 tends to 0

P_2 tends to $\dfrac{P_1}{\cos X_2/2}$

If these equations are then applied to a Whillans harness under load on the rigid dummy, then the loads can be predicted

1. Assume a load of 1000 kgf on the rope
2. Assume there is no friction between the web and the dummy.
3. Assume no load is taken on the belt
4. The harness is idealised as in fig.20, and the load distribution is computed.
5. Assume a tension of P in the thigh strap
6. Let the angle between the thigh strap and the centre line be 45 (measured on the dummy during a static tensile test).

At the crutch strap loop, the layout is as in fig. 21

$$P_c = 2P_t \cos 45 = 2.\frac{P_t}{\sqrt{2}}$$

For the rope attachment point, see fig.22.

Resolving vertically,

$$
\begin{aligned}
1000 &= P_c + 2P_t \cos 45 \\
&= \frac{2P_t}{\sqrt{2}} + \frac{2P_t}{\sqrt{2}} \\
&= \frac{4P}{\sqrt{2}}
\end{aligned}
$$

So

$$P_t = \frac{1000.\sqrt{2}}{4} = 353 \text{ kgf}$$

and

$$P_c = \frac{2P_t}{\sqrt{2}} = 500 \text{ kgf} \quad \text{(see fig.23)}$$

Naturally, these findings are very basic and the analysis has severe limitations. No tension is being taken on the waist belt, so this is a 'worst case' situation. If the load on the harness is 1000 kgf, then these predicted loads are those which the thigh and crutch loops must withstand in this configuration.

5.2.2 Harness Comfort

As stated earlier, the legs are the most appropriate part of the body for load-carrying. However, if load is borne exclusively on the legs in a hanging situation, then the attachment point will be low compared to the body's centre of gravity. This is located approximately 5 cm above the waist level in an upright man with his arms at his side, and 16 cm in a seated man with arms raised to shoulder level (a typical falling position) [40].

Thus the subject will turn upside down unless some form of waist or upper body support is introduced. This is particularly important if the subject is unconscious. However, if both feet and head of an unconscious subject remain in a lower position than the waist, then this is a self-righting position, as blood flow to the head is retained. It is felt that this is better than a fully upright position as would be attained with a full body harness, up till now considered to be the safest harness.

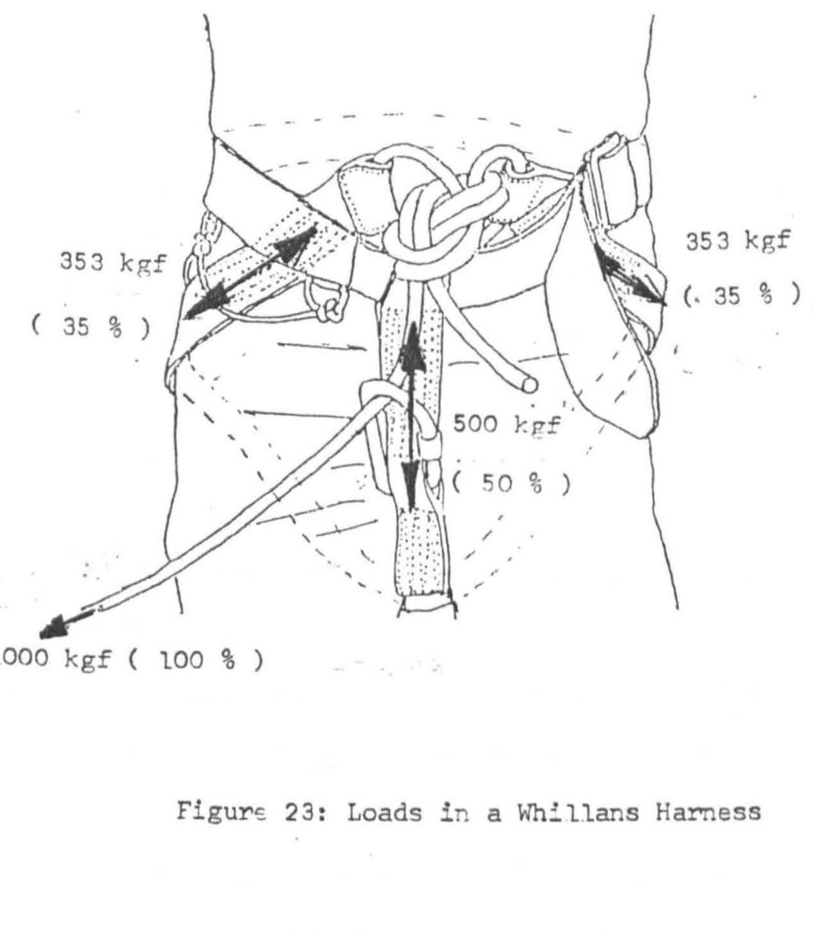


Figure 23: Loads in a Whillans Harness

For most purposes, however, the subject will be conscious after the fall and can hold himself upright. Comfort is a subjective criterion and no two people will find the same harness identical.

5.2.2.1 Systematic Comfort Tests

A review of 12 sit harnesses was conducted as an in-house exercise at Troll in an attempt to define comfort more strictly. The harness designs were both from Troll stock, prototype Troll designs and competing harnesses on the market both in the U.K. and abroad.

Five different testers were employed who were of different weights, builds and sexes. A fixed testing procedure was followed, whereby each tester put on the harness, hung for two minutes in it, readjusted it if necessary and then hung in the harness for 10 minutes. Immediatly after this, a subjective mark out of 10 was given for comfort, the ease of putting on the harness and the clarity of the instructions(if any).

There were nevertheless problems with the method. It is difficult to obtain subjects with the necessary experience to grade harnesses. Only two harnesses per person per day could be tested, as often the effects of a previous test would affect the testers judgement. The results are shown in table 4. Even with 2 tests per day, achieving repeatability was difficult. On different days the same tester would give the same harness a different mark.

However, some useful conclusions did arise from the study and, without naming any particular brands of harness, these were:-

1. The key to comfort is even load distribution, although load should be kept away from the inner thighs and the kidneys.
2. Under load, the body should naturally assume a position between seated and standing, with an angle of approximately 45 degrees between the legs and torso.
3. The hardness of the web is a compromise. If it is too soft it will not provide enough support. If it is hard then the edges of the web will bite into the body.
4. Wide padded belts gained universal approval, although whether their bulk and weight is acceptable is a matter for the individual.
5. Correct adjustment of leg loop size proved critical, with a snug fit of loop around the leg being essential.

The variation in the results and their subjective nature prevents more detailed analysis. To quantify comfort accurately is difficult[41]. Dr. R.Ellis[33]has used the product of Blood Pressure and Pulse Rate in a series of hanging tests to compare a simple waist tie on a rope with a Whillans sit harness. As expected, the sit harness proves far more comfortable. As with the subjective tests, repeatability proved to be a problem, as testers will be physiologically different on different days.

5.2.3 Miscellaneous Design Points of Harnesses.

Apart from the load distribution and comfort of the harness, other minor design features are significant. The ease of putting on the harness has already been mentioned. The ease of complete removal (or partial removal for bodily functions or change of clothing), the simplicity of the buckles, the tying-in method, the provision of equipment racks, the adjustability for different wearers or different thicknesses of clothing, the durability, the weight and the restriction of normal movement, if any, also play a part.

It should be noted that only sit harnesses have been covered in this review. Full body harnesses, while being very comfortable, are restrictive and are thus only appropriate where the user is definitely going to be in a free hanging position for long periods of time where the possibility of inversion also exists, or for deliberate long falls where the subject may invert during free fall. It has been mentioned that chest harnesses alone are sometimes used in Europe. The dangers of doing so cannot be too strongly emphasised. In the comfort tests described, the subjects were unwilling to withstand the initial two minute adjustment period, and any prolonged period of free hanging was out of the question.

5.3 Conclusion

The chapter has dealt very briefly with a small area of harness design. There is much scope for further work, but the direction in which it should proceed is uncertain.

Load distribution is the major area where research is necessary but, before any applicable results are obtained, a great deal of basic work will have to be done in designing the measuring system, calibrating it and fitting it to the harness. Theoretical prediction will be very valuable, but needs validation by experimental results before the prediction can be relied upon.

Since the inception of the harness, its design and development has been by subjective means rather than quantitative study. This subjective design process is so far advanced that any quantitative study will have limited use even if it could be developed into a reliable method. Its application would be in the refinement of existing designs rather than the innovation of new ones. In the latter field, there is no substitute for experience.

Chapter VI

DROP TESTING

6.1 The Need For Drop Testing

When testing fall arrest equipment, it is desirable to subject the test specimen to loads and conditions as closely as possible to the 'real life' situations within the constraints of laboratory equipment and scientific testing technique. While static testing can provide valuable information on the load distribution within the system and on the ultimate tensile strengths of individual components, it inevitably has its limitations. In a real situation, the load is applied over a very short time period at a high rate. The material properties of textiles vary under different loading rates, particularly under dynamic loading[42]. Further, the only way to determine the actual loads applied during fall arrest is by dynamic loading, as any prediction using static methods or theory is, at best, unreliable. On a basic level, it is necessary to ensure that the fall arrest system will withstand the loads to which it will be subjected in use.

Thus drop testing is crucial to the test programme, both in its own right and in combination with static testing.

6.2 Design of the Troll Drop Rig

The apparatus or rig on which all the tests were conducted was located at the Troll factory. It had been constructed in its basic form by Troll before the project started, specifically for carrying out a systematic series of tests. Its design was determined by the limited space available and from the desire to conform as closely as possible to the standard U.I.A.A. test method[32]. The rig was constructed from steel tubing anchored in a concrete base, with four legs rising to a height of 5 metres where a loading door in the upper floor of the factory provided access to a gantry on the top of the rig(see fig.24). Directly under this gantry, two flange plates were located with a hole drilled in each one to take a 25 mm bolt. The distance between these holes and the ground was 4.75 metres. In order to raise the weight, an electric winch was mounted on an I-section girder directly above the loading door. The girder itself could not be used as an anchor for the drop tests, as it was only rated for a safe working load of 0.5 tonnes. Loads greater than this were expected in testing[58]. Although it could have been safely used for expected impacts of less than 0.5 tonnes, the vibration of the beam could possibly have affected the results. The winch was mounted on rollers, as it was normally stored inside the loading bay door, but during testing it was clamped in the desired position above the rig. The weights used for drop-testing were in two forms, both having a mass of 80 kg. For simple drop tests on rope and slings, a barrel filled with a mixture of lead and sand was used, with chains extending from its rim to a ring and

Figure 24: Overall Drop Rig Set-up

Figure 25: Barrel & Dummy

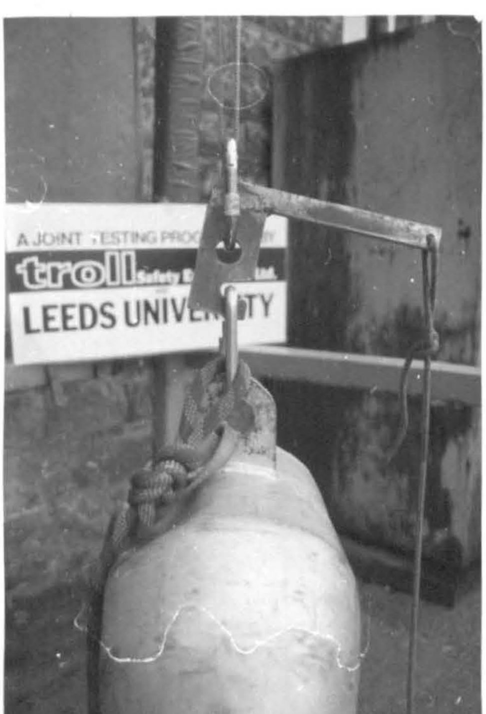


Figure 26: Trigger Bar Detail

Figure 27: Pre-trigger Position

shackle connection. For harness tests, a hollow steel dummy was used, with a steel flange on its base to which was fastened a lead ingot in order to ballast the dummy to the required 80 kg, as used in the U.I.A.A. test method[32]. (see fig.25) In order to actually conduct the test, the weight was raised using the winch, whose chain and hook was attached to a purpose-built trigger bar (see fig.26). The weight was raised to the desired height(fig.27), attached to the safety system and then released by pulling the cord attached to the trigger bar.

The advantage of this system is that it is cheap and simple to operate, although two people are required to to operate the winch and attach the trigger. The major problem with the rig was that it was located outside the factory. Testing was frequently delayed or interrupted by bad weather, and it was impossible to conduct the tests in a controlled atmosphere, as there were no conditioning facilities at Troll.

<u>6.3 Instrumentation of the Troll Drop Rig</u>

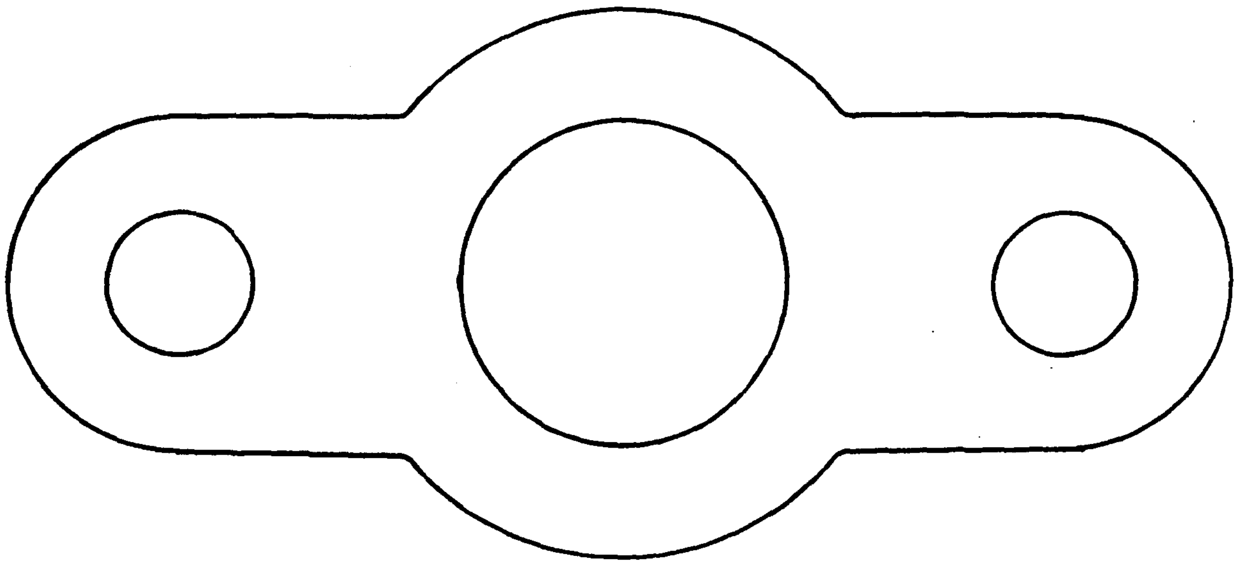
Upon arrival at the department in 1983, preliminary work was under way to design a load cell for use on this drop rig. Straight bars with strain gauges fitted either side were tried but were not considered very suitable, as there was a definite lack of sensitivity in the load ranges desired. It was therefore decided to design a load cell along the lines of a proof ring. This would have the advantages of being

1. Independent of temperature
2. Independent of bending stress, and
3. More sensitive than the straight bar design.

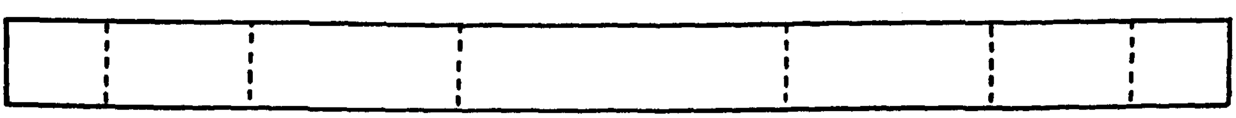
It was necessary to design the cells to perform up to a maximum working load of 5 tonnes, yet still give accurate readings as low as 200 kgf. It was therefore decided to construct two rings of different sizes, one to handle loads of up to 1 tonne and the other up to 5 tonnes. The subsequent designs were constructed for a safe working load of twice their capacity i.e. 2 tonnes and 10 tonnes, although this did reduce their sensitivity.

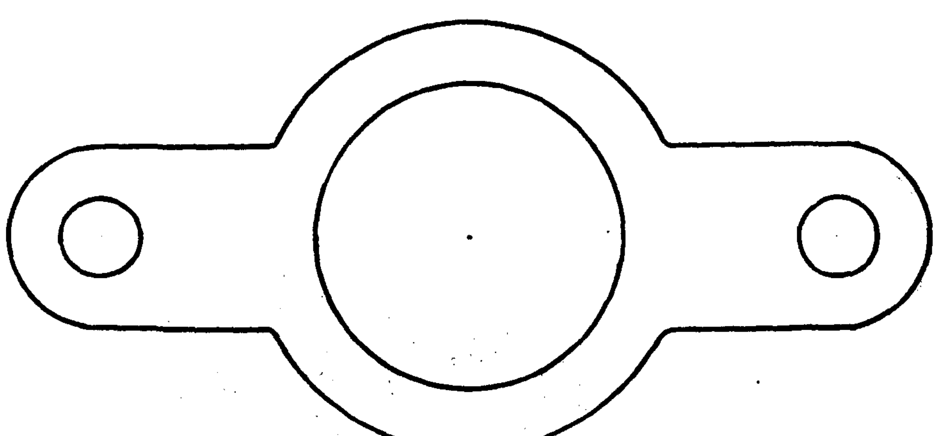
The final dimensions of the 2 rings are shown in fig.28 The next stage was to fit strain gauges to the rings to produce an electrical output. Foil gauges of resistance of 120 ohms were fitted to the inner and outer circumferences of one arm of each ring. It had been planned to use semiconductor gauges because of their greater output, but cost, temperature sensitivity and the difficulties of attachment to a curved surface meant that the foil gauges were perfectly adequate providing a suitable amplification system could be selected.

The gauges were wired up on the ring to form a half-bridge system, with two dummy resistors to be installed to form the other half of the bridge. From a Bakelite junction board, araldited to one end of the ring, 3 wires lead off. One of these splits into two arms to form the common supply line to each gauge. The other two form each arm of the bridge. In addition to these three wires, a fourth line is firmly secured to the body of the ring and leads back to earth in order to prevent capacitance effects from distorting the very small signals emanating from the gauges.



5 tonne SWL





1 tonne SWL

Figure 28: Dimensions of Rings   Scale 2:1

These four signal wires were connected to the amplification system using two strands of twin core screened signal wire. At each junction, six connections were necessary:-

* Common supply to the gauges
* Outer gauge signal
* Inner gauge signal
* Earth
* Screen for line A
* Screen for line B

These junctions were made using 6-pin all weather connectors, originally designed for carrying 3-phase mains in an outside environment. Their robustness and reliability made them suitable for the purposes of this project.

Each ring had a short length of cable approximately 30 cm long linking it to its first connector. From there, a length approximately 8 m long led from the connector into the test-room window and down to the amplifier. During calibration, it was ensured that the presence of this long lead did not affect the gain of the system, although the two halves of the bridge did have to be re-balanced.

The amplifier to which the strain gauges were attached was an RDP E307-3 Transducer Indicator[43] specifically designed for this application. The dummy resistors are fitted internally to form the other half of the bridge.Initially, standard 120 ohm resistors were used, but it was found that as the temperature of the amplifier rose markedly during operation, the bridge became unstable and it was impossible to balance it correctly. Accordingly, resistors with a very low temperature coefficient of 25 ppm/ degree C were installed and this eliminated the problem.

The ring/amplifier systems were calibrated on an Instron 1344 hydraulic tensile test machine in the Department of Textile Industries. Seperate amplifier systems were used for each ring, in order to avoid having to change the gain settings. The amplifiers were zeroed, then their rings loaded to their full working capacity(i.e. 1 tonne and 5 tonnes respectively) and the output voltage adjusted to the desired level (1 volt and 0.5 volts) so that the voltage scale corresponded to the load on the ring in kilograms force. The load was then gradually removed with checks carried out all the way through the working range. If necessary, the zero was re-adjusted and the process repeated until an accuracy of less than 10 kgf at full scale deflection(1000 kgf or 5000 kgf) was achieved.

This is therefore a system which electronically measures load and is available for output to various display or recording systems. It is relatively cheap compared to buying in ready-made load cells and is tailored to the requirements of the Troll drop rig. The disadvantages are that it took a long time to manufacture, assemble and calibrate correctly. Once installed and working, the screws on the 6-pin connectors tended to work loose occasionally, resulting in one arm of the bridge becoming disconnected and the bridge becoming completely unbalanced. It is, however, fairly obvious when this occurs, and the only work necessary is to track down the disconnected wire(s), reconnect them and rezero the amplifier. When installed at the Troll factory, the calibration of the rings could be checked approximately by loading them on the pneumatically driven tensile test rig. The calibration of the ring/amplifier systems was checked at the Department of Textile Industries after a year's use and was found to be accurate.

6.4 Recording Equipment

In order to gain information on changes which occur during fall arrest, it is necessary to be able to record transients in the signal output from the amplifier. Although the E307-3 is equipped with a facility to measure the peak value of a transient, this single piece of important knowledge is only one aspect of the information gained when observing more complicated systems such as shock absorbers.

To record a rapidly changing signal, a digital data collection instrument was used. The Datalab Single Channel Datalogger[44] takes an electrical signal over a preset period and digitises it into 2000 digital units[44]. Collection of the data is initiated at a preset level of signal and once the signal has been recorded, it is repeatedly output through an output channel at a specific amplitude and frequency. The signal can thus be displayed on an oscilloscope. Alternatively, hard copy results can be obtained by connecting the datalogger to a chart-recorder and initiating the PLOT process, which outputs the digital information at a steady rate of bits/minute. Thus, if a chart recorder is connected, a voltage history will be produced on the chart.

Once all the components of the measuring system have been connected (proof ring, amplifier, datalogger, oscilloscope and chart recorder), the next task is to calibrate the system to ascertain the voltages produced on the displays for specific loads. As mentioned above, the proof ring/amplifier system has alredy been calibrated so that 1 volt is equivalent to 1000 kgf or 10000 kgf for the small and large rings respectively. When this signal is fed into the datalogger, it is scaled by a factor which is dependent on the full-scale setting of the datalogger. The output of the datalogger is always 1 volt full scale deflection. Thus, a 1 volt input gives an output voltage of 1/Full Scale Setting. By scaling the oscilloscope display and the chart recorder correctly, these signals can be converted to kgf equivalents. The whole system was checked by two processes:-

1. Connecting a signal generator with a sine wave of peak-to-peak of 1 volt to the input port of the datalogger, and observing the output at the oscilloscope and chart recorder.
2. During the tests the observed peak of the datalogged signal was checked against the value of the digital display of the amplifier using its peak-store facility.

There were minor problems encountered when setting up the instrumentation, principally the lack of sensitivity of the triggering system. Although it is stated above that triggering is initiated by a preset level of signal being exceeded, this is in fact an over-simplification. In reality, data collection is triggered by the input signal level crossing a fixed band, whose mean postion is altered by the 'trigger level' control. Because of the proportionately large width of the band compared to the overall signal, it is difficult to set the trigger level accurately. For example, a typical signal might start at 300kgf (0.3 volts) and rise to 700 kgf (0.7 volts). Thus triggering is required at 0.3 volts, but a full scale of 1 volt required to record the entire signal. The facility of the datalogger to 'pre-record' information before the trigger point was very useful in this respect, but the setting up process was still very complex, with no oppurtunity of reproducing the input signal other than by actually conducting the test. The signal can be crudely represented by altering the 'zero' balance of the amplifier to produce an artificial output voltage, but this was not entirely foolproof, as complete triggering and recording could take place before the maximum expected level of signal was produced. In this respect, there was no substitute for experience in setting up repeated tests.

Another minor problem occurred during testing, in that the winch which is used to adjust the height of the dummy or weight immediately prior to the drop is operated by a heavy duty relay. When the off-relay operates, a large back e.m.f. produces a spark which, despite screening of the cables, can cause the datalogger to trigger. Immediately prior to any test, the last part of the procedure was to check that the datalogger had not already been triggered by the winch.

During testing, it was observed that the peak-store facility of the amplifier did not operate correctly at high voltages(above 1 volt output and at high rates of voltage increase, and it was felt that the datalogger was a more reliable display system than than the amplifier's digital display. It was not possible to detect the root cause of this fault, as it was neither consistent nor reproducible at low rates of voltage change. Communication with the manufacturers produced no further information [45], and it was not considered practical to return the amplifier to the manufacturer for checking, as it was frequently in use.

Using the equipment described above, a system was produced to measure dynamic loading in a reliable way and produce force histories which will be useful in improving the understanding of the process of fall arrest.

6.5 Development of a Drop Test Method

Having assembled the equipment, the next task was to establish a workable test method in order to produce meaningful comparative tests. As a basis from which to start, the U.I.A.A. test method [32] was consulted. From this, the method was examined for reproducibility and practicality. Using a series of tests, the method was gradually adapted to produce a method suitable for sling and harness test purposes with the hardware available at the Troll factory.

Initially, the rig was set up with a proof ring bolted to the plates on the drop rig and a 3500 kg karabiner clipped into the ring's lower attachment point. To this karabiner was clipped a length of rope knotted in a 'figure-of-eight' knot at both ends. These knots were pre-tensioned prior to the test in order to attempt to eliminate any effect of energy absorption by the knot [46]. It is desirable to eliminate the effect of the knot in order to:-

1. Produce a repeatable test, and
2. Produce the most severe loading conditions possible.

Nevertheless, it was felt important to limit the level of pretensioning in order to avoid making the rope too stiff through permanent deformation of the weave structure.

With this in mind, the level of pretensioning was set by consulting rope manufacturers' figures on their predicted impact forces[47][48] as there was no other data available on the levels of impact force likely. For this first set of tests, the length of rope was measured at 80 cm from end to end. After a pre-tensioning to 800 kgf for a period of 5 minutes, its length had increased to 90 cm due to a combinationof of knot slippage and deformation of the rope weave. It should be noted at this stage that this was the complete length of rope sample, whereas the loops and knots form a stiffer section which will not extend as much as the single length between the knots. Naturally, the longer the sample, the less effect the knots and loops will have compared to the length of rope between the knots.

For the purposes of the test, it was assumed that the loop/knot structure did not absorb any energy and, to allow for this, fall distances were calculated on the basis of <u>Free Rope Length</u>, the length of rope between the knots.

Before analysing the results of the preliminary drop tests, it is necessary to examine the theory behind fall arrest which has been developed specially for the peculiarities of its application in climbing.

6.6 The Theory of Fall Factor

Energy absorption has been mentioned briefly above. This concept is critical to the understanding of fall arrest. Once the fairly simple theory has been outlined, the quantities of energy, force etc. must be examined to show how the theory relates to the actual phenomenon of fall arrest.

In 1950, Wexler[49] developed the theory of fall arrest which forms the basis of all calculations in this field. These calculations were made on the assumption that the whole problem was concerned with energy absorption.The energy of the falling mass (the climber)has to be converted into another form and stored in the safety system to bring it (him) to a halt. To develop the theory, the following assumptions are made:-

* That the rope is elastic. i.e. obeys Hook's Law.
* That the weight is concentrated at the end of the rope and that the weight of rope is negligible.
* That the effect of knots, attachment loops etc are negligible compared to the effect of the free rope length.

In its simplest form, the theory deals with a static belay, where the rope is attached firmly to a rigid anchor point. Consider a mass of m kg which is a distance of L m above the anchor point and is currently a distance H/2 m above its highest runner (see fig.29, and compare it to fig.1). In order to arrest the fall, the kinetic energy of the mass has to be absorbed. Thus:-

$$Mg(H+X)=PX/2 \quad (1)$$

where P is the maximum tension developed in the rope, and X is the extension in the rope at that tension. Since the rope is assumed to be elastic,

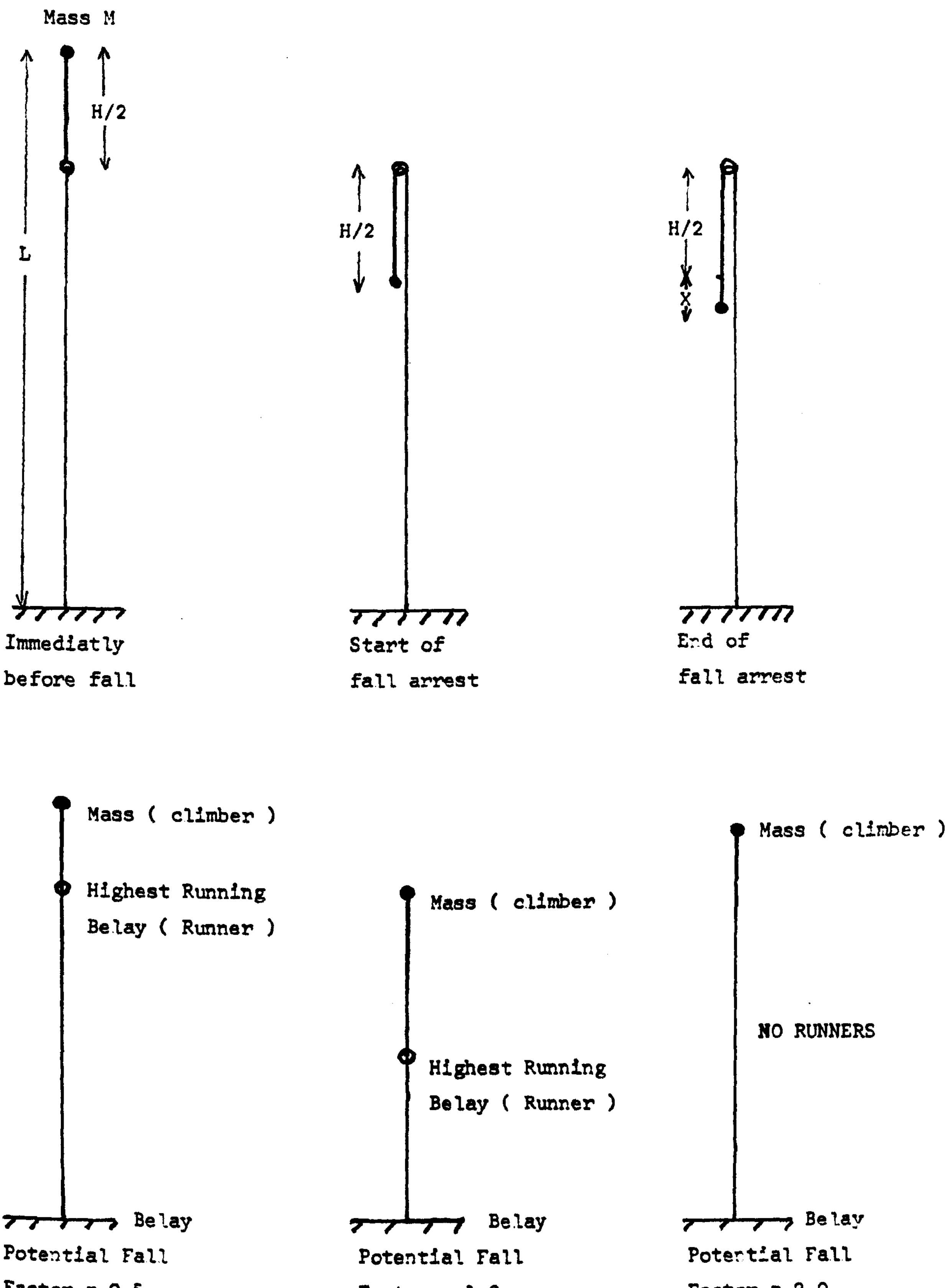


Figure 29: Layout of Fall Factor Theory

$$P=KX/L \quad (2)$$

where K is a proportionality constant governed by the properties of the rope such as material, diameter, construction and past history.

Substituting (2) into (1) yields the quadratic equation:-

$$X-\frac{2MgLX}{K}-\frac{2MgHL}{K}=0 \quad (3)$$

whose solution is:

$$X=\frac{MgL}{K}+\frac{MgL}{K}\sqrt{1+\frac{2KH}{MgL}} \quad (4)$$

Thus, the maximum tension in the rope is given by substitutng (4) into (2), which yields:

$$P=Mg+Mg.\sqrt{1+\frac{2KH}{MgL}} \quad (5)$$

Therefore the tension developed in the rope for a given mass and rope type is given by the ratio H/L, which is known as the Fall Factor. The significance of fall factor in considering fall arrest cannot be emphasised too highly.

Having stated this, it is immediatly apparent that there are problems equating theory and practice, both in a laboratory and a field environment. Ropes do not obey Hook's Law, anchor points are not rigid, and the effect of knots, as will be shown, is far from negligible. However, very little data exists on these problems, and it was therefore one of the main objectives of this study to conduct basic research in this sphere.

6.7 Fundamental Drop Tests

In order to establish a base line of control tests, the first test series was carried out with no sling or harness components in the system. The weight was a barrel weighing 80 kg as shown in fig.25 . At this stage, it was not known what magnitude of impact force would be produced, nor even if the system would remain intact. In case of catastrophic failure of any part of the system, a safety line was connected from a fixed point on the barrel to the bolt attaching the ring to the rig, ensuring that this line was long enough to avoid any tension being placed on it during normal fall arrest, but short enough to prevent the barrel hitting the ground should any component in the system fail. It should be noted at this stage that at no point in the drop testing of new unused equipment has any such failure occurred, thus confirming the confidence placed in the equipment by its users. The rope used for the tests was a nominal 11 mm kernmantel rope manufactured by Beal[50]and widely used by British climbers. The rope was all from the same batch in order to eliminate variations in between tests. The karabiners used were manufactured by DMM Engineering of Wales [13]and were rated to 3000 kg.

Three tests were carried out in each case and the results are shown both in Table 5 and graphically as force histories.

6.7.1 Barrel at Fall Factor 1.0

It has been shown above that the magnitude of Fall Factor in a drop test is the most significant parameter.Further, this can vary from 0.0 up to a maximum of 2.0. For the purposes of these tests, it was decided to conduct these tests at Fall Factors of 1.0 and 2.0 to gain an approximate picture of the variation of peak impact force with increasing Fall Factor. A Fall Factor of 2.0 is necessary in order to measure the highest force possible on the system. Fall Factor 1.0 is easy to set up, with the fall distance equal to the rope length, i.e the attachment point level with the anchor immediatly prior to the drop. At this stage it should be noted that standard rope tests [32] are conducted at a Fall Factor of 1.78 for historical reasons. In order to compare the results of this study with the standard tests, all work would have to be conducted at 1.78. Further, no pre-tensioning of the knots would have been possible. It was therfore elected to conduct the tests in an in-house style, without attempting to relate them to the standards. The free rope length used in this first series was 0.9 m.

The results of the first tests can be seen in table 5 (series 1.1 to 1.3) and a sample trace is shown in fig.30. It can be seen that the level of peak impact force is approximately 650 kgf on the rope and is consistent at this level as this does not exceed the pre-tension. It is higher than would be predicted from the rope manufacturer's data[51], but this is because the rope weave has been stiffened by this pre-tension.

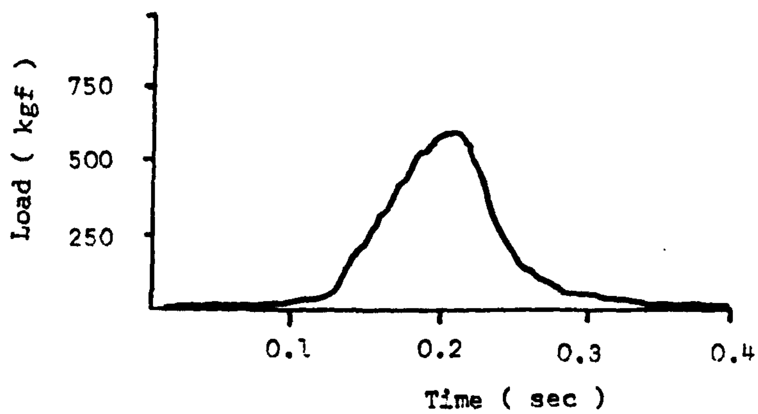


Figure 30: Barrel at Fall Factor 1.0

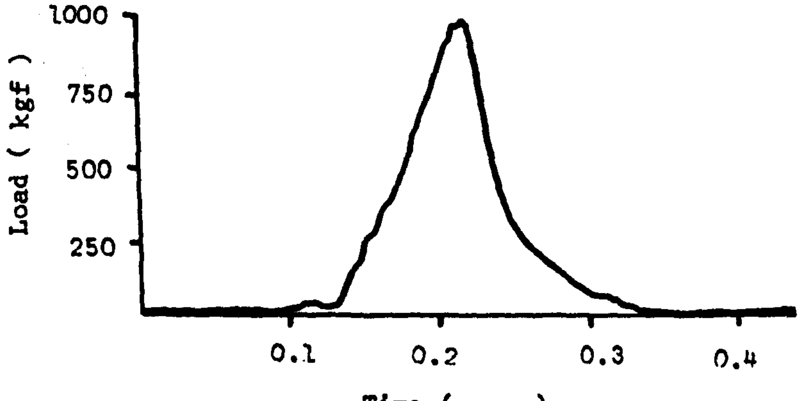


Figure 31: Barrel at Fall Factor 2.0

6.7.2 Barrel at Fall Factor 2.0

In order to obtain data for the maximum possible impact force on the system, the following drop tests were conducted at Fall Factor 2.0. The level of pretension was maintained at 800 kg in order to achieve comparability with test series 1. The results are shown in table 5 under 2.1 to 2.3 and a sample trace is shown in fig 31. In the first drop, the level of peak impact force exceeds the level of pre-tension, and some knot tightening may have occurred, together with deformation of the rope structure. Thus the level of peak impact force is held at an artificially low level.In the subsequent drops the level remains steady at 1000 kgf and it can be assumed that this is a reliable figure.

6.7.3 Barrel at Fall Factor 0.5

Falls of factor 1.0 and 2.0 are comparatively rare in practice. Falls of factor 0.5 are much more common and a set of tests was therefore conducted to find the impact forces at this level. The test set was conducted at two levels of pretension as it was thought that the high levels of pretension might substantially affect the impact forces expected at this lower level.

The results of the tests are shown in table 5 under 3.1 to 3.6, and it can be seen that, even at falls of factor 0.5, there is still a load of 250 kgf on the rope, with therefore a corresponding load of 500 kgf on the runner.

6.7.4 Barrel at Fall Factor 1.0, Increased Length

In order to eliminate the effect of the knotted loops as much as possible, the length of the rope and fall was increased to the maximum possible given the geometry of the test rig. It was difficult to estimate this maximum, as elongation during fall arrest was difficult to measure.

A length of rope was taken and pre-tensioned to 1000 kgf for 5 minutes, after which the free rope length was measured at 200 cm. The drops were then conducted as in the previous tests and the results are shown in table 5 under 4.1 to 4.4 with a trace in fig.32.

6.7.5 Barrel at Fall Factor 2.0, Increased Length

To provide a comparison with test series 2, a set of tests were conducted in an identical manner to set 3, but with an increased rope length of 200 cm and a fall length of 400 cm. The results are shown in table 5 under 5.1 to 5.3 and a sample trace in fig.33.

Comparing the results of 4 and 5 with 1 and 2 respectively, the principal observation to be made is that the peak impact force increases for the same fall factor with increasing fall and rope length. This contradicts the Fall Factor Theory, and it was therefore essential to find out the causes of this phenomenon. It has to be discovered whether this anomaly is due to the limitations of the theory or the effect of some unknown variable in the current testing method. Because the theory is well established, it was assumed that the latter was causing this anomaly, and a series of further tests were carried out to attempt to identify the cause of the problem.

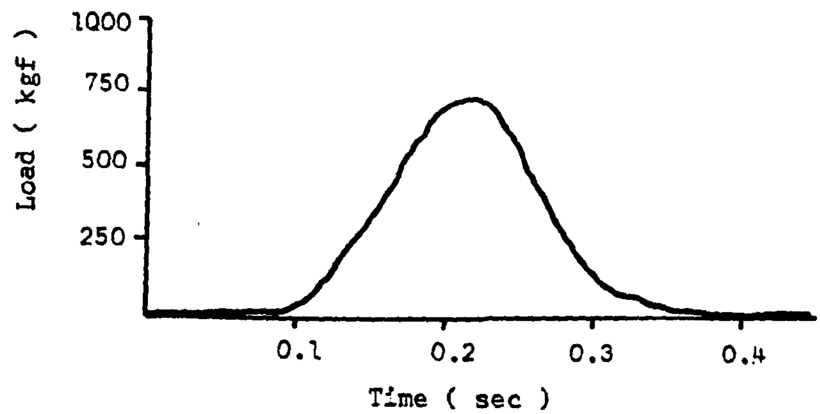


Figure 32: Barrel at Fall Factor 1.0; Increased Fall Length

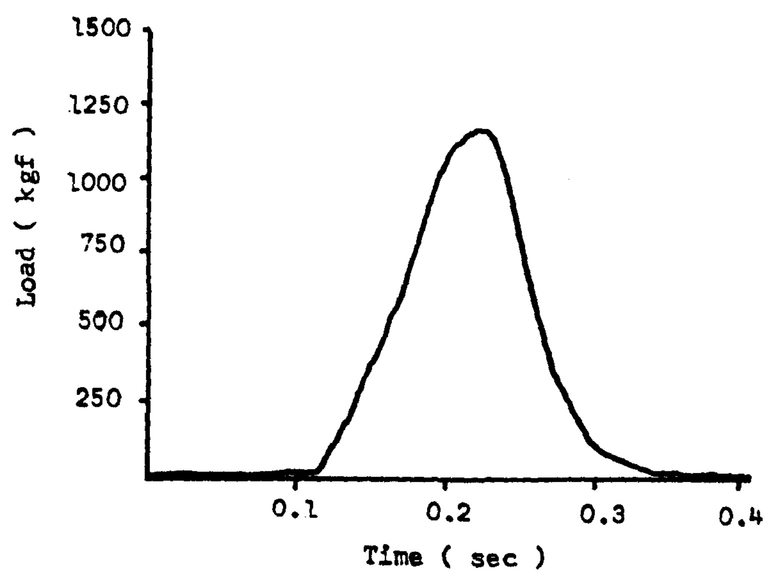


Figure 33: Barrel at Fall Factor 2.0; Increased Fall Length

6.7.6 Vertically Aligned Drop Tests at Fall Factor 1.0

It was observed in the tests being carried out that the barrel swung in a pendulum motion immediatly after its arrest. This is due to the geometrical nature of the rig in that the barrel, immediatly before the drop has to be positioned vertically out of line in order that:-

1. The hoist chain does not catch on the rig during raising of the weight.
2. The barrel does not strike the rig during its drop.

It was suspected that the pendulum motion might have the effect of reducing the peak impact force. By studying the geometry , it was noted that this reduction will be more significant with decreasing lengths of rope. Thus in the short case, the pendulum will have greater magnitude and will reduce the peak impact force by a greater margin.

In order to test this hypothesis, three sets of tests were conducted with the weight aligned vertically with the anchor point. To do this, the trigger bar was replaced by a loop of lightweight cord which was used to attach the barrel to the anchor point. To drop the weight, this cord was severed with a knife and the weight dropped vertically with absolutely no sideways swing. The results of the tests are shown in table 5, numbers 6.1 to 6.9, and the first drop of each set is illustrated in fig.34.

From these tests, two observations can be made:-

1. Despite the elimination of the pendulum effect, the peak impact force still varies with rope and fall length at a constant fall factor.

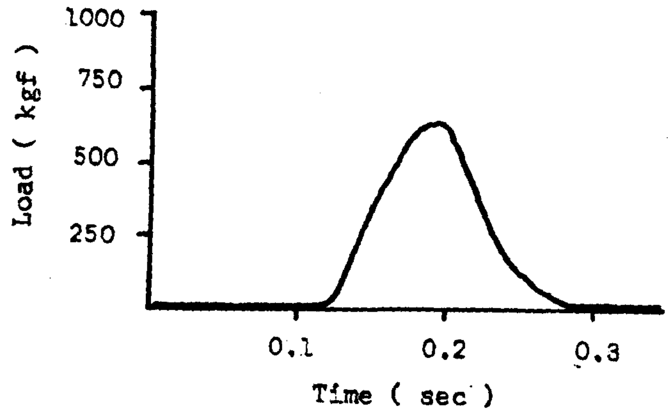
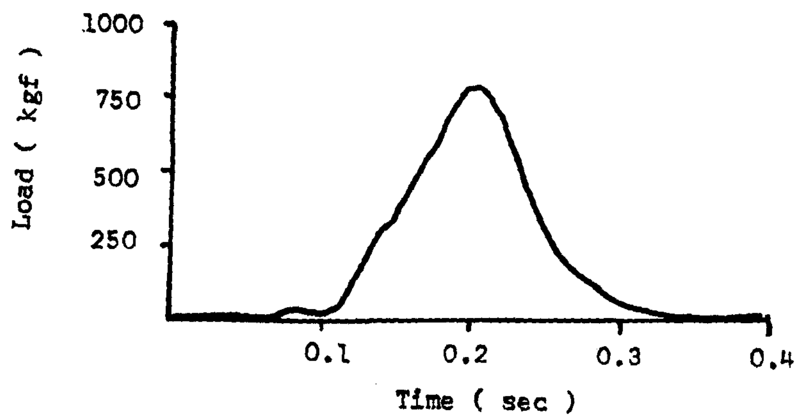


Figure 34: Vertically Aligned Drop Test



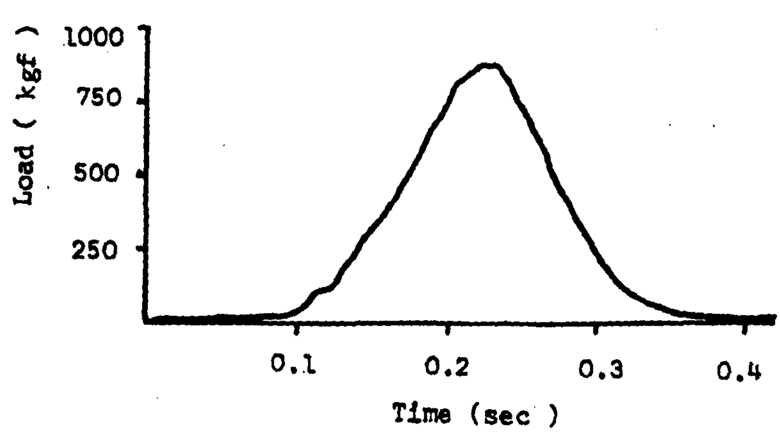


Figure 35: Rope with Controlled History

2. The results of these tests compared to previous ones are similar, indicating that the pendulum has a negligible effect on the peak impact force. Subsequent tests were therefore conducted with the trigger bar system which is quicker and more convenient to set up than the lightweight cord.

6.7.7 Rope with Precisely Controlled History

The most likely source of experimental error during this series of tests was variation in the pre-test rope treatment. Up to this point, it was not completely certain that this treatment had been identical. A set of tests at Fall Factor 1.0 was therefore carried out with differing rope lengths and identical pre-test treatment. The rope samples, both from the same coil, were pretensioned at 1000 kgf for 5 minutes, followed by a relaxation period of 30 minutes, after which the tests were conducted. The results are shown in the table under 7.1 to 7.6 and the force histories are shown in fig.35.

Even with this identical pre-treatment, the peak impact force still varies at constant Fall Factor with different rope lengths. At this point, the manufacturers of the rope, Michel Beal, were contacted via their U.K.agent to see if they had experienced similar phenomena in rope testing. An exchange of letters and telexes followed[51], and the final outcome is that the phenomenon occurs only at rope lengths less than 2.5 m. This is possibly due to the wavelength of the shock waves in the rope becoming comparable to the length of rope in the test, which will affect the final result.It is not, however, the purpose of this study to research rope properties in detail.

Thus, depending on the length of rope, its pre-test treatment, and the geometry of the fall, the peak impact force for a fall of Factor 1.0 has been observed to vary between 630 kgf and 850 kgf for a pre-tensioned rope, compared to a manufacturers figure of 700 kgf [48] for an untreated rope. Similarly, Fall factor 2.0 falls vary from 850 to 1340 kgf. No manufacturers data exists for factor 2.0 but the U.I.A.A. test fall of the rope at a factor of 1.78 reveal varying manufacturers figures. These will be quoted as low as possible, and are therefore of limited use in such a study.

The implications of this preliminary work are two-fold:-

1. Any tests carried out on the Troll test rig will be less than or equal to 2.5 m in rope length. Caution will have to be exercised when relating test results to 'real' falls.
2. Comparative tests when the effect of alteration of parameters are examined will have to be conducted with identical rope lengths. If not, this rope length effect will obscure any differences in results.

Whether the peak impact force will continue to rise at rope lengths above 2.5 m is a matter for conjecture. According to Michel Beal, the Fall Factor Theory is valid above 2.5 m [51]. By contrast, tests conducted by Arova-Mammut[46] indicate that at extremely high fall lengths, ropes are unable to withstand the loads produced. The scope for further research into rope properties is immediatly obvious.

The increase in rope loading at increasing lengths in a laboratory environment is not found in practice. In the vast majority of cases, ropes do not fail in use providing there has been no abuse or misuse. In field work in the mountains, I have experienced three large (unintentional) falls greater than fall factor 1.0. In none of these cases did visible damage of the rope occur, which was 8.8 mm in diameter.

There are few known incidents of rope failure, and those which have occurred are usually due to the rope being weakened by edge effects such as the rope running over sharp rocks or having been cut by stonefall [52]. It can be concluded that all ropes which bear the U.I.A.A. label are safe when new. If carefully looked after, they will retain this safety for a period of time, although its energy absorption and strength will deteriorate due to abrasion, ultra-violet radiation and, most importantly, falls. The safe life of a rope is impossible to predict. However, it is felt that the user should discard it when:-

1. Any visible damage is observed on the sheath resulting in the core being visible, or if any anomalies such as thin sections can be felt or seen.
2. Any serious fall is sustained (greater than or equal to a fall factor of 1.0).
3. A period of one years normal use has been passed i.e. most weekends and one or two periods of expedition work.

Finally from these tests comes basic information on the peak impact force in the rope at varying fall factors. From these and the preliminary work on shock absorbers, the table 6 relating force to fall factor has been drawn up, and is illustrated in fig.36.

6.8 Investigation into Factors Affecting Impact Force

Now that the basic level of impact force in the rope has been established under a precisely controlled and pre-tensioned condition, the effect of altering various experimental parameters can be examined. To find the forces imposed on the system in a real fall, it is necessary to find the reductions in peak impact force caused by knots, the runners, the harness and the human body.

6.8.1 Effect of the Harness System

To assimilate reality more closely, a harness was inserted into the system by replacing the barrel with a hollow metal dummy which represents a human torso (see fig.25). The dummy has attachment lugs on top and bottom, the former for hoisting the dummy prior to the drop, and the latter to attach the ballast weight to adjust the weight of the dummy to 80 kg. The centre of gravity of the dummy is slightly lower than in reality, as its weight is concentrated in the ballast.

The harness used in this case was a Troll Mk VI belt with adjustable Alpinist leg loops, as shown in fig.25. The rope sample with a free rope length of 1.0 m was pre-tensioned to 800 kgf and three drops of factor 1.0 were conducted. The results are shown in table 5 under 8.1 to 8.3 and the traces in fig.37. It can be seen from these results that these are very close to the results of the barrel, indicating that the

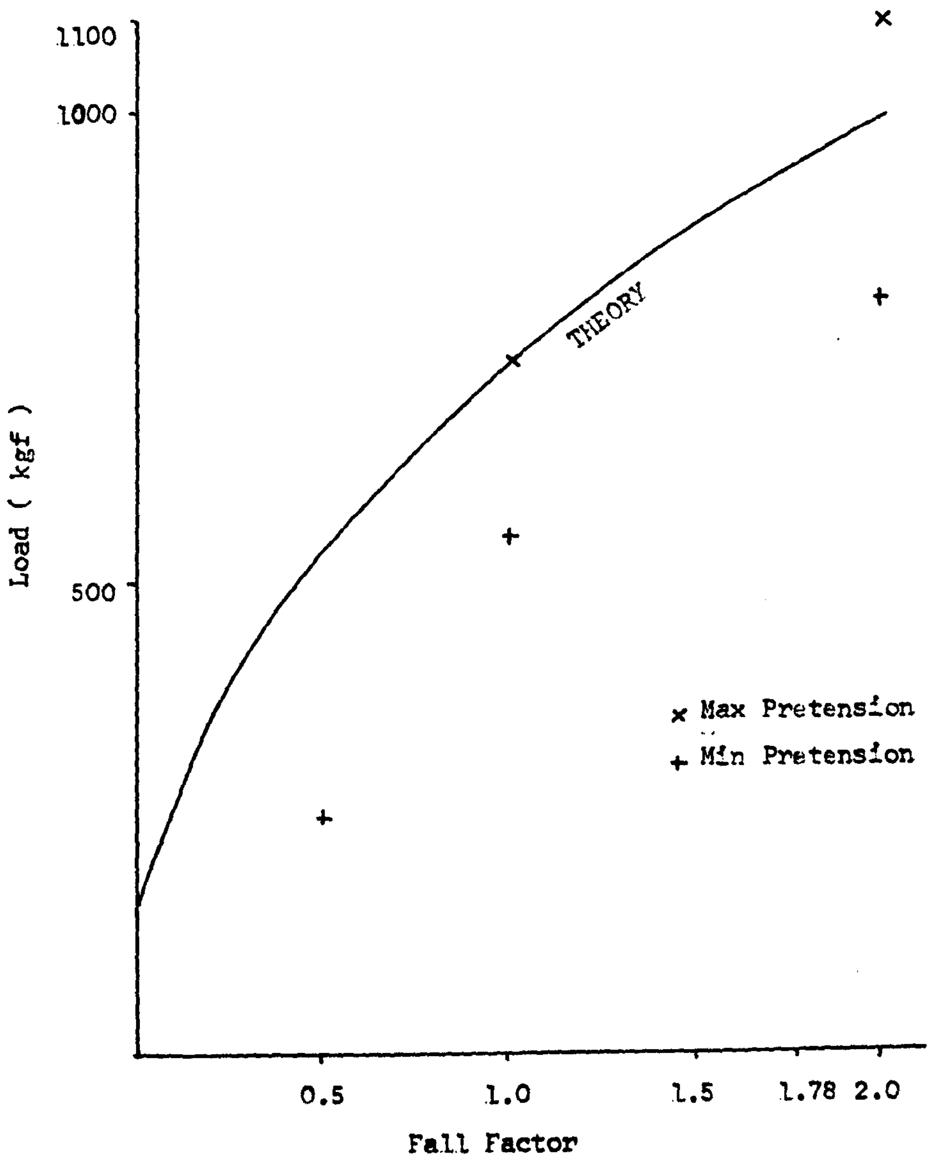


Figure 36: Graph of Force vs. Fall Factor

harness plays no significant part in reducing the impact force.

6.8.2 Effect of Pre-tension and Knots.

Although the procedure for obtaining repeatable results involves pre-tensioning to loads above those expected in the drop, it is necessary to examine the performance of a rope with no previous history of loading. Tests were conducted at fall factor 1.0 with reduced pre-tension and the results are shown in table 5 , 9.1 to 9.4 and the traces are in fig.38. Further, a test was also conducted on a used Beal 10.5 mm rope as part of an investigation into rope life for Mountain magazine[46]. Although these rope samples were of different quality to those used previously, the results are presented for completeness under 9.5 to 9.8.

In 9.1, the rope was pretensioned to 200 kgf before being used in a factor 1.0 test. In 9.2 to 9.4 an identical sample of rope was tensioned to 500 kgf. Comparing these results, the impact forces for the first fall are 545 kgf. This implies that pretensioning has no effect on the rope structure up to 500 kgf. The effect of the impact is to tighten the knots up and raise the peak impact forces on subsequent drops. Combining these results with those tests 1, 6 and 7 table 7 is produced. The minimum for fall factor 1.0 is thus 545 kgf compared to a maximum of 700 kgf, a reduction of 21%. The minimum for factor 2.0 is 800 kgf compared to a maximum of 1175 kgf, a reduction of 32%. Thus the larger the fall factor, the more effect the knot and the inherent elasticity of the rope will have. As a corollary to this, and important from the practical point of view,

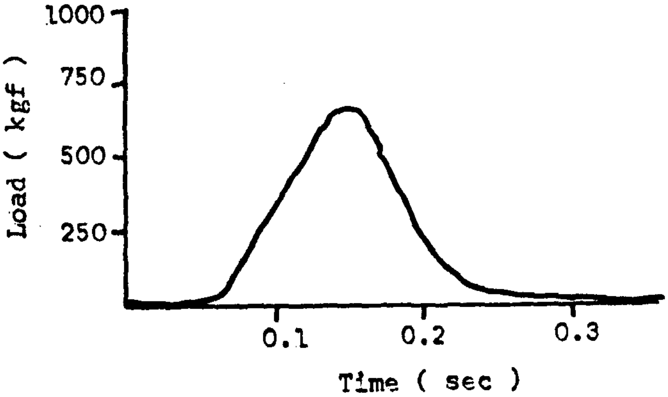


Figure 37: Effect of Harness on a Fall of Factor 1.0

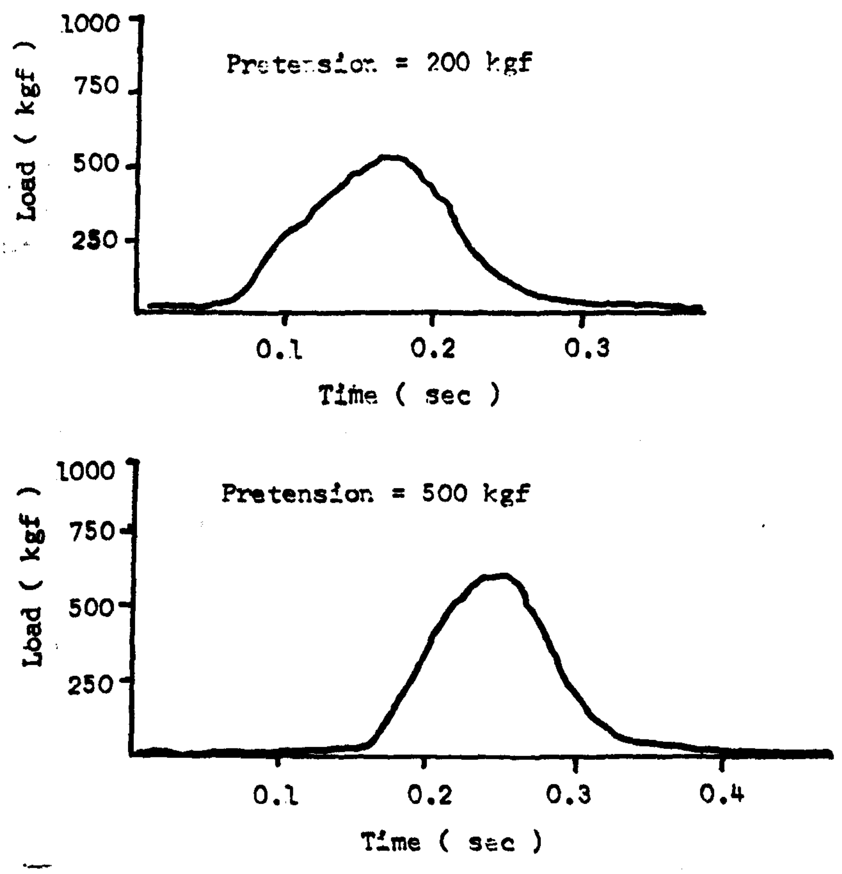


Figure 38: Effect of Pre-tension on a Fall of Factor 1.0

repeated falls above factor 1.0 will seriously impair the ability of the rope and knots to absorb the energy of the fall without damage. In fact , in the test after 9.8 on the used Beal 10.8 mm, the sample failed at a load of 800 kgf. Therefore, after any high factor fall, the user should consider discarding the rope, or at the very least loosening the knots back to their normal state.

6.8.3 The Effect of the Human Body on Impact Force.

These tests were considered very significant, as there is very little data available on drops using live human subjects. It was thought that the insertion of a flexible compressible human body into the harness in place of a rigid steel dummy would result in a decrease of the impact force. Apart from using live human subjects, the only other way to conduct this type of test is by using an anthropomorphic dummy, as used by the National Engineering Laboratory and the Road Transport Laboratory. Unfortunately these dummies are very expensive and not economically viable for a small company such as Troll. The human subject used was Paul Seddon, one of the directors of Troll, who weighed 68 kg at the time. He was therefore ballasted to increase his weight to 80 kg by using a weight belt. Because of the belt, the subject felt unstable and that he might invert in a fall. To avoid this, a chest harness was added to the harness system to raise the point of attachment of the rope. It was not felt that this would affect the impact force significantly, but would keep the subject upright and in a safe position after the impact had occurred.

Using rope samples pretensioned to 1000 kgf, three tests were conducted at factor 1.0 and three at 2.0, the results of which are shown in table 5 under 10.1 to 10.6. The results show a drop from 740 to 550 kgf for factor 1.0, a reduction of 27%. Similarly, for a fall of factor 2.0 the impact force drops from 1000 kgf to 750 kgf, a decrease of 25%.

Whether this reduction is maintained at higher fall lengths is not possible to determine on the Troll test rig. Useful information is, however, available from the sphere of parachute research where harnesses of a similar design are used. In particular, tests have been carried out by the military forces in America[53] where the difference in the impact forces on the parachute risers, equivalent to the rope force, was found to be 22%, although velocities and forces are much larger (around 50 m/s and 650 to 850 kgf).

6.9 Discussion of Drop Test Chapter.

6.9.1 Approximate Forces Developed in Drop Tests

Perhaps the most important feature of the results is the variation in impact force for nominally identical falls. At factor 0.5 , these vary from 250 to 350 kgf. At factor 1.0, the variations are from 630 to 850 kgf and at 2.0 from 850 to 1340 kgf. The cause of this is undoubtedly the varied test conditions, principally the history of the rope prior to the test. Pretensioning of the knots and the textile structure, whether by deliberate application or by previous falls , increases the effective stiffness of the rope and therefore the impact force as well.

The most important fall is naturally the initial one, as this is the most common occurrence in reality. Although repeated falls do occur, it is the single severe fall which is the most serious. Examining the results carefully, the impact force for a rope with little history of pretension is:-

Fall Factor	0.5	1.0	2.0
Impact on 1st Fall	250	500	800
Subsequent Falls	300	700	1000

This is a very rough approximation of the forces, and only applies to the 11mm rope of the type of construction used by Beal.

If the drop test data is inserted into the equation derived by Wexler, values for the rope stiffness, K, can be determined. As with the impact forces there is a large amount of scatter, but a mean value of 2.56 kN/unit strain can be calculated. Using this value of K, a continuous function of impact force against fall factor can be derived, and this is shown in fig 36.

Comparing the levels of forces in the above table with the forces produced by this theoretical value of K, the latter are invariably higher. This is due to the large number of tests conducted at a high level of pretension. This stiffens the rope and therefore increases the value of K.

If K is computed for the lowest pretension level at each fall factor, they are found to be 15.68 kN/unit strain at 2.0, 13.14 at 1.0 and 2.76 at 0.5. This variation of a supposed constant enhances the hypothesis that the fall factor breaks down at low levels.

The levels of force measured in this study are lower than those occurring in reality due to the breakdown of the Fall Factor Theory at low rope lengths. They are, however, higher due to the pretensioning imposed on the rope samples. Further, in the experimental procedure, there are no reduction effects such as belay plate slippage, belayer movement and leader compressibility, although some of these are now investigated.

6.9.2 Causes of Reduction of Impact Forces

Lack of pre-tension reduces the forces developed and if the relevant test series is studied, the effect is to reduce the force developed by 20%.

Insertion of the human body into the falling harness appears to reduce the load by at least 20% but this is not the only factor affecting the impact force in a real situation. These tests have been conducted using a rigid (static) belay. In practice, the belayer will move when the force is applied to him via the rope, particularly if he is standing on flat ground at the base of the crag. Even in cases where he is firmly attached to the ground or suspended in a hanging belay halfway up a crag, there will be absorption of energy through the belaying device. Quantitative assessment of this effect is difficult, although current belaying practices include bracing oneself for the impact or even jumping downhill which will increase the forces still further.The value of these techniques is debatable when using runners of low strength.

Other factors can contribute to the reduction of the peak impact force. Should a runner placement fail, the subsequent impact on the next runner will be reduced. Quantitative assessments are again difficult, but it is of value to place a series of runners close together, even if the first one is likely to fail.

A more frequent cause of reduction is the case in which the fall is out of line with the top runner. When the impact force is applied, the result will be a combination of a straight impact and a swing, more commonly known as a 'pendule' or 'pendulum'. Depending upon the proportion of pendule to straight impact, the peak force can be dramatically reduced. In the case where there is no straight impact, a simple calculation can be made. Observing fig.39, it can be seen that

Force $T = \frac{mV}{R}$ where m=mass
V=tangential velocity
R=radius = L

Now $V = 2gH = 2gL$ assuming conservation of energy

so $T = \frac{m.2gL}{L}$

$= 2mg$

So T is only equal to twice the weight of the mass and the force on the runner is 2T/ 2 = T 2 = mg.2 2. Assuming a climber of 80 kg, the runner force will be 225 kgf.

6.9.3 Conclusion

To conclude the chapter, the results from the preliminary research indicate approximate values for the maximum likely forces to be applied to a safety system, together with those more frequently occurring in practice.

Under repeated falls of factor 2.0, the forces have been measured as high as 1340 kgf although the maximum allowable impact force for a U.I.A.A. approved rope is 1200 kgf. This

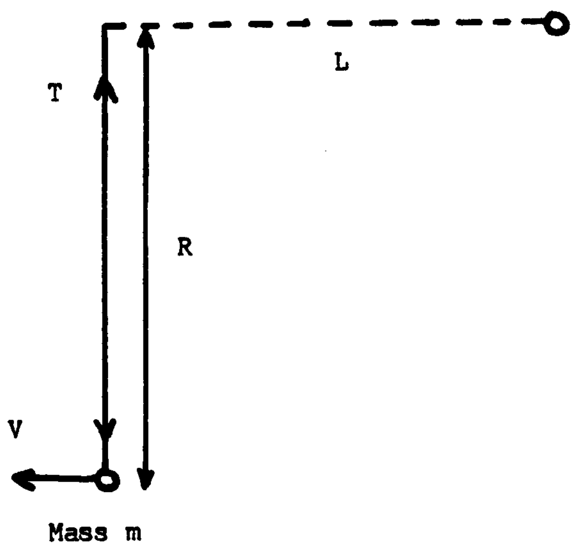


Figure 39: Diagram of a pendulum

discrepancy has occurred due to excessive pretensioning. In practice, the maximum likely force in the rope at fall factor 2.0 will be 1000 kgf when all components in the system except the rope are rigid. This will be reduced by at least 20% by the insertion of a human body into the system.

Falls of factor 2.0 occur very infrequently. In practice, the majority of falls sustained during climbing are of low fall factor (up to 0.5) with a small number between 0.5 and 1.0. The maximum impact forces developed at factor 1.0 have been found to be in the region of 550 kgf. These figures are susceptible to reduction by a number of factors.

In considering the design of safety equipment and the systems in which they are used, it is vital to consider both the likely maxima and the more frequently occurring forces on all components of the system to guard against failure and/or to minimise the consequences of any such failure.

Chapter VII

IMPACT ABSORPTION DEVICES

7.1 Introduction

This chapter deals with the development of a shock absorber or impact absorption device for use in industry. The problems encountered during its development include technical problems and constraints of production techniques as well as the difficulties of maintaining consistent testing standards and producing many different prototypes. However, a product has been developed as a direct result of this area of research and the author feels that this has been the most productive aspect of the work and a good example of cooperation between industry and the universities.

For the purposes of this study, the term shock absorber is not, as understood by the engineer, a fluid damper which provides a force proportional to the velocity with which it is compressed. A shock absorber or impact absorption device is a device whereby the maximum load on a safety system in arresting a fall is reduced.

The chapter is set out in the following way which approximates to the sequence of events in the development of the product:-

1. The need for shock absorbers in both climbing and industrial spheres is laid out.
2. The development of the cilmbing version is charted through many different prototypes, concluding that any

such design will be of limited technical effectiveness.

3. A section then follows on the development of the industrial version with an emphasis on the production problems of the device, concluding with the final design which is now a production item.

7.2 The Need for a Climbing Shock Absorber

As shown in the previous chapter, impact forces in the climbing rope can be high when a fall of high fall factor is sustained. In some cases, it is quite possible that the peak impact force on the runner, twice the tension in the rope, may exceed the strength of that runner. If this runner is the only one which will prevent the climber from hitting the ground, then the consequences of the fall will be very serious. There are two possibilities which can be used to remedy a potentially fatal situation:-

1. To increase the strength of the runner. Such a solution may not be possible or indeed desirable. Although this may seem contradictory, it may be preferable to maintain an element of risk. Further, it may not be practical from an economic or technical viewpoint as well as the ethical considerations to place strong permanent bolts for protection.
2. To reduce the impact force. The peak impact force calculated according to Wexlers Theory [49] assumes that all other parts of the safety system apart from the rope are rigid. Thus, in theory, all the kinetic energy of the fall is absorbed in the rope. If energy

can be absorbed elsewhere in the system, then the loads developed will be diminished. It is this purpose that a shock absorber serves in a climbing safety system.

7.3 The Need for an Industrial Shock Absorber.

The requirements of an industrial safety system are very different from those of a climbing system. There are always secure anchor points available which are used to secure the operator working on a high structure. Typical applications involve steel erction, tree surgery and steeplejacking. The operator is attached to the anchor by a lanyard to which he is permanently attached by a harness or a waist belt, so that no rope is used. Despite the anchor points being strong and the fall distances being low, it is still necessary to reduce the impact forces in a fall. As noted in the last chapter, the impact force is determined by the fall factor, not fall length. Even with correct working practice, a fall can be as severe as fall factor 1.0. Further, impact forces are higher than in the climbing situation because the lanyard material is generally stiffer than the climbing rope.

It is necessary to reduce this impact force, not because the anchor points may fail (as in the climbing situation), but to reduce the impact force on the operator. The maximum force acceptable is governed by safety legislation rather than strength of components in the system, and varies according to the type of belt or harness being used by the operator.

Thus, although shock absorbers for climbing and industrial applications have features in common, their end-uses differ distinctly. In climbing, long falls are held on a relatively extensible rope, with the shock absorber preventing failure of the runner. In industry, short falls are taken onto a stiff lanyard, and the main objective is to reduce the load on the operator. As the chapter proceeds, further differences in design criteria will become evident.

7.4 Test Methods for Shock Absorbers.

During the development of the shock absorber, three types of testing were employed:-

7.4.1 Simple Dynamic Testing

The main function of these devices is to reduce the impact force in a fall. The most directly applicable test is therefore a drop test in which a weight is allowed to accelerate under gravity for a fixed distance before being arrested by the safety system into which a shock absorber has been inserted. However, in order to isolate the effect of the shock absorber, it may be desirable to conduct a drop test on the sample alone, devoid of any other energy absorbing components. Thus the result of the test will be attributable only to the sample under observation. Further, as will be seen in the industrial section, there are applications where the shock absorber is the only component in the safety system and such a test will therefore simulate reality to a high degree. For the moment, a simple dynamic test can be regarded as the baseline method for determining maximum impact forces developed in the components of the safety system.

The tests were conducted using the drop test rig at the Troll factory and the testing procedure which is described in the previous chapter. The weight used was a barrel of 80 kg for the following reasons:-

1. Results from previous drop tests conducted with 80 kg could be compared with any drop tests conducted on shock absorbers.
2. Although shock absorbers are connected to a harness or belt when in use, it was necessary to eliminate all other energy absorbing components of the system.
3. From the drop tests already conducted, it was known that an 80 kg rigid specimen approximated to a 100 kg anthropomorphic dummy. The latter is the weight used to test industrial lanyards to British Standard[54]. It was therefore feasible to replicate, in an approximate manner, the B.S.I. tests and avoid the time and expense that would be incurred sending successive prototypes to the approved laboratory.

The fall factor used was 1.0 because:-

1. It is easy to set up in an accurate manner with the two linking karabiners level with each other prior to the drop.
2. At fall factors greater than 1.0, the weight must be displaced to one side to avoid striking the load cell during the fall. With a long rope sample, the resulting pendule is not of great significance, as shown in the 'Vertically Aligned Drop Tests'. However, the shock absorbers are short by comparison and are of the same order of length as the offset.

3. Any fall factor less than 1.0 cannot be regarded as a worst case.
4. In BS1397, the test procedure for industrial lanyards specifies a fall of factor 1.0. In order to ensure that any prospective industrial lanyard passes BS1397, it is essential to duplicate this test procedure as closely as possible.

7.4.2 Applied Dynamic Testing

Although simple dynamic testing is valuable in determining the independent performance of a shock absorber, it falls short of representing reality in a large number of cases. In a climbing situation, the shock absorber forms only one part of the safety system. As knowledge of the way in which the devices worked improved during development, it became evident that it was necessary to represent the climbing application more accurately.

A length of rope was taken which had been already used in a series of drop tests. This was done so that the knots would be tightened up and would no longer be capable of energy absorption by knot slippage, as shown in the slack knot drop tests. Thus repeatability between tests will be assured.

To represent the effect of a lead climber falling onto a running belay fitted with a shock absorber, the rope was anchored at one end to the cross-piece of the drop rig. The rope was then led through a karabiner attached to the lower end of the shock absorber sample which was in turn connected to the proof ring load cell in the normal way (see fig.40). Under tension, an angle was subtended between the anchored

Figure 40: Applied Dynamic Test Set-up

rope and the weighted rope. This reduced the tension applied to the runner which in theory would be twice the tension in the rope. However, to represent the lack of pre-tension in a real situation, this angle was adjusted by altering the height of the runner with respect to the anchor point, so that an angle of 70 degrees was produced between the anchored and weighted ropes. This reduces the tension on the runner by 20% which , as noted in the drop test discussion, is the effect of the lack of pretension. A barrel weighing 80 kg is used in these tests for convenience and comparison with the simple dynamic tests.

The fall factor used in these tests was reduced from 1.0 to 0.5. In the course of both drop testing and the simple dynamic testing of shock absorbers, it was found that the forces induced by fall factor 1.0 falls were high compared to those at which the shock absorbers were designed to operate. Thus, if a fall factor 1.0 drop was conducted when using a shock absorber, its presence made very little difference to the final maximum impact force. This is because such a fall is a very severe case and occurs less frequently in use than falls of lower fall factor. Further, it was hoped to show that the shock absorber might have some effect at these lower fall factors.

7.4.3 Static (Quasi-dynamic) Testing

During the dynamic testing, it became apparent that detailed knowledge of the operation of the devices was required. Specifically, the amount of energy absorbed by the sample was found to be a critical parameter. This can be determined by plotting the load on the device against the extension required to produce that load. The integral of force and extension, or the area under the force/extension curve gives the energy absorbed.

The static tests were conducted on an Instron 1122, an electronically controlled screw-driven machine with a maximum load capacity of 500 kgf. This was the only machine available which had the necessary extension available and also a high rate of extension of 1000 mm/min. Using this rate of extension does not equate to shock loading, but the machine was the most suitable one available for the rapid extension tests. To test at extension rates equivalent to shock loading requires technology as yet unavailable outside military research centres[55].

The samples were gripped in the machine by inserting silver steel pins of 10 mm in diameter into the holes in the spigot and stitched loop of the slings. In the later stages of the development , the samples were too long for load to be applied at both ends of the lanyard. In this case, one end was pinned as above, while the sling was gripped using rubber-faced jaws on the other side of the failure stitching in order to start with the shortest possible gauge length and thus obtain the highest possible extension.

7.5 The Development of a Shock Absorber for Climbing

With no practical designs to provide a starting point, the initial prototype was designed to be:-

1. Based on existing equipment. This means it will fit into the overall safety system with its other components. Further, the device will be acceptable to the

market as it will be recognisable as an adapted piece of standard equipment rather than an innovation.

2. Incorporated into the runner. The safety system consists of the leaders harness, the rope, the runner system, the belaying device and the belayer's harness. The shock absorber can therefore be inserted:-

a. in the leader's harness. Harnesses have been produced in the past with stitching that fails at a given load with full strength backup stitching[70]. However, it is difficult to predict load distribution in the harness and the device operates involuntarily.

b. between the leader's harness and the rope. The knot itself provides some absorption effect. The problem of load distribution is eliminated but the device still operates involuntarily when a fall occurs.

c. in the rope. Using a rope of reduced stiffness is a possibility, but this does not guarantee that the force will be kept to a fixed maximum. Further, extension of the rope must be kept to a minimum to prevent ground strike and to conform to U.I.A.A. standards.

d. in the belaying device. The most commonly used belay device in the U.K. is the Sticht brake plate, which has a slipping force of approximately 400 kgf[56]. This gives a load of 800 kgf at the runner, too high for this purpose (see below). Although the belayer can allow rope to slip through, it is difficult to controlthis correctly. This is an area for further development, as registered by the Antz-DBPA from Salewa[57].

e. in the runner. If the 'Safety Chain' of Schwartz [58]is analysed, the runner emerges as the most highly loaded and the weakest part of the system. It is therefore logical to place any shock absorber at this point to be effective. Further, by choosing whether to place each runner with or without a shock absorbing capacity, the leader has a more direct control over the safety system.

3. Triggering at 300 kgf. The <u>trigger load</u> of a shock absorber is defined in this case as the load at which the device starts to absorb energy in a manner which reduces the load compared to the normal system. For example, most designs will operate normally up to a predetermined load, at which further energy will be absorbed for no increase in load. The magnitude of this load is very important.

Consider a device whose trigger load, F, is variable but whose extension under load, d, is fixed. Its stiffness up to the trigger point is K, after which it is zero. A load extension curve as shown in fig.41 will be produced where the area under the curve is the energy absorption capacity, given by:-

$$E = \frac{F}{2K} + F.d$$

The higher the value of F, the greater the capacity E.

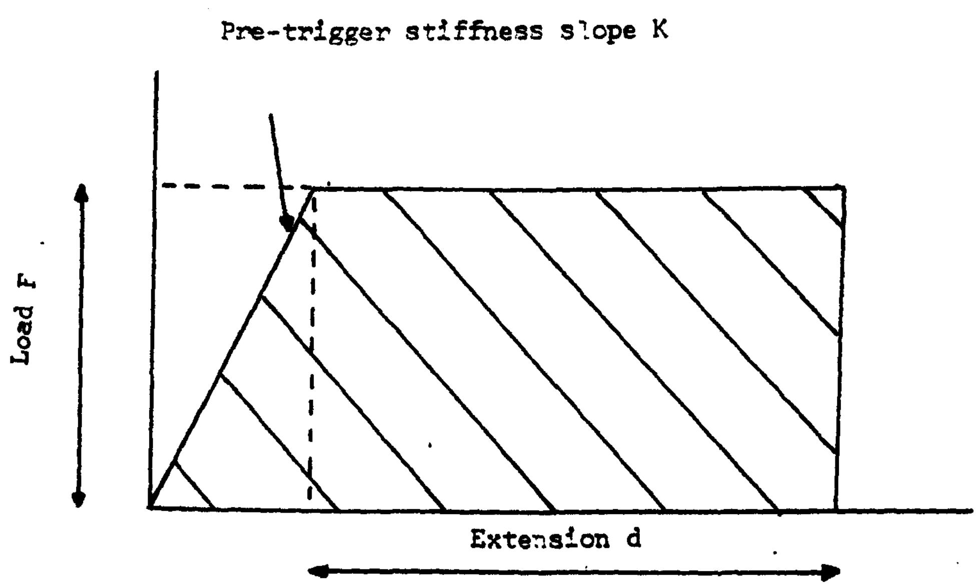


Figure 41: Idealised Force-Extension Curve of a Shock Absorber

However, the object of the device is to reduce the load on the system so that the runner, the component with the highest load and the lowest strength, does not fail. Therefore the level of F must be kept below this strength.

The minimum strengths of runners commonly in use can be found by examining a number of recent publications by independent sources. Strengths quoted by manufacturers are often a significant margin lower than the actual figures. Dickens[59]recently investigated the strengths of a comprehensive range of wired chocks available. The lowest figure found was of a brass chock with a loop of wire silver soldered into the brass, which failed at 240 kgf. This is an unusually low figure, and the more commonly used types constructed from swaged wire loops failed at 740 kgf. Schubert[14]conducted a survey of ice scews, often considered to be a weak link in mountaineering safety systems, and found that the weakest failed at 350 kgf

Other ways in which a safety system may be weak are:-

a. The medium in which the runner is fixed(rock or ice)may fail. Data on this is non-existent and in any case difficult to define.

b. Runners which have a high strength when new may deteriorate with use, particularly if left in-situ on the rock face. Data is similarly difficult to obtain, although in-house tests by Troll[60]indicate strength losses of up to 70% in 18 months of exposure to desert conditions.

The likely loads on the runner can be more accurately defined. The minimum load in a static situation will be twice body weight, that is 160 kgf. Concerning maximum load, it has been shown that the load at fall factor 2.0 will be 1600 kgf with minimum pretension which can be reduced to 1000 kgf when allowing for the effects of the human body. Falls of factor 2.0 are, fortunately, rare in a climbing situation and the more likely severe falls will be of the order of 0.5 in factor, where the load is approximately 600 kgf for a rigid dummy and 450 kgf for a human subject.

Summing up the above information, the trigger load of the device should not be more than 450 kgf (unlikely to trigger) or less than 160 kgf (certain to trigger), and slightly less than the weakest runners. While the weakest has a strength of 240 kgf, its counterpart in the size above has a strength of 400 kgf. With the energy absorption capacity directly related to trigger load, it was felt that a load of 300 kgf, the mean of the above two limits, was a suitable figure which would also be below the strength of most runners, thus ensuring a trigger should a severe fall occur.

7.5.1 SA1:High Extension Polypropylene Insert

The design of the first prototype, SA1, is shown in fig.42. A Troll snake sling is used as the basis for the design. It is 61 cm in length and constructed from 25 mm standard web [6]. At each end is a 5 cm loop, held in place with a 10 cm

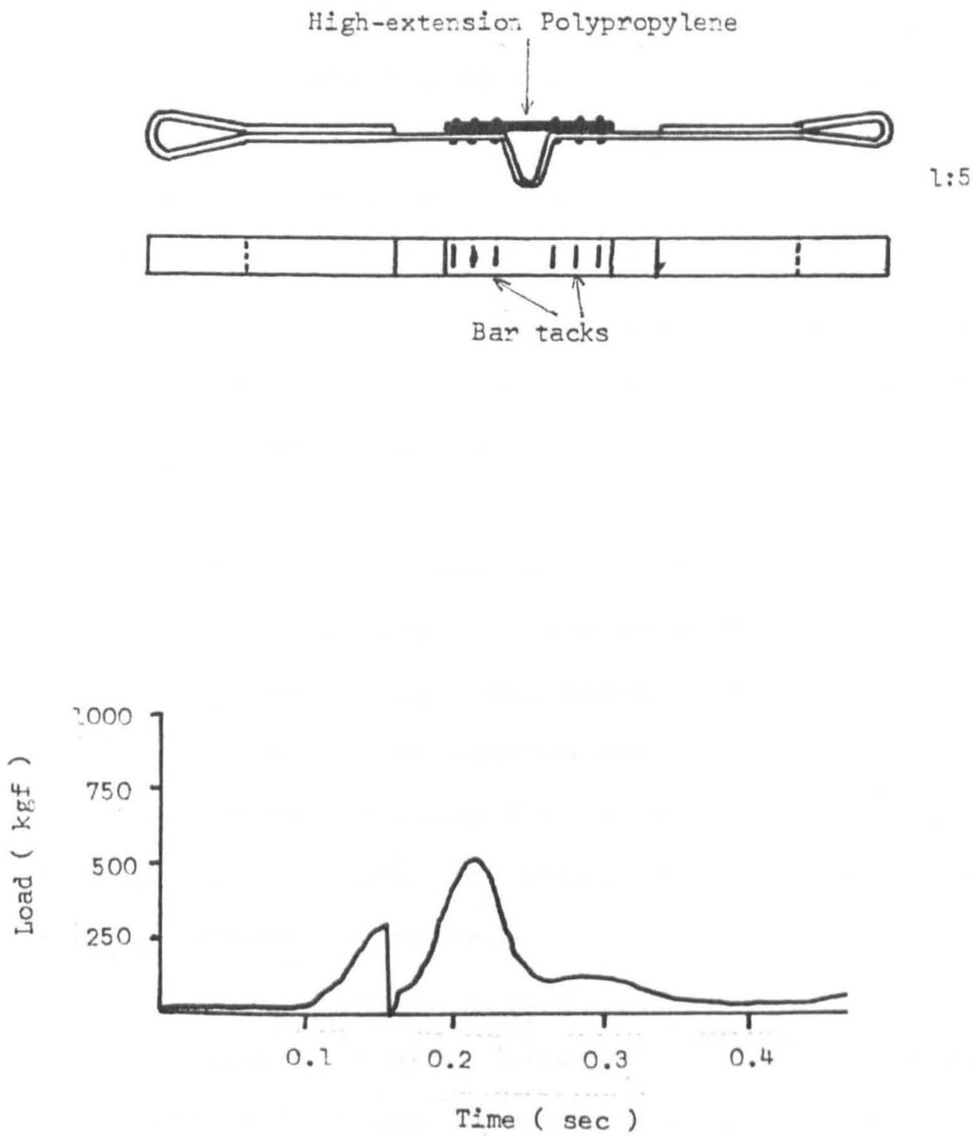


Figure 42: SA1: Design and Drop Test

sewn lap joint using 9 rows of 20's thread at a stitch density of 6 stitches per inch. (Unless otherwise stated, this is the form of sling used when referring to a standard short snake sling).

In the central section of this sling it was necessary to fit a component which failed at 300 kgf, yet after the failure left the snake sling intact to take the remaining part of the fall. As the project was based on tape and sponsored by Troll who use tape as a base material for most of their products, it was natural for this first design to use tape. A type of polypropylene tape, 25 mm in width, was identified as having a tensile strength of 300 kgf and an elongation at break of 80%.

The shock absorber was constructed by sewing a 110 mm length of polypropylene in place over the nylon of the standard snake sling using 3 bar tacks at each end. The free length of polypropylene between the two innermost tacks was 35 mm. In order to allow for the extension of the polypropylene before failure, an extra amount of nylon tape was included between the tacks.

$$\text{Predicted extension} = \frac{80 \times 35}{100} = 28 \text{ mm}$$

$$\text{Total length of nylon between tacks} = 35 + 28 = 63 \text{ mm}$$

In order to test the effectiveness of this design, a simple dynamic test was conducted. The fall length was equal to the length of the sling so that the fall factor was equal to 1.0

As a prelude to the testing of the shock absorber, a control test was conducted using an ordinary standard snake sling. The same sling was subjected to 3 consecutive impacts, with an interval of 5 minutes between each drop. The results of each test, recorded using the datalogger and plotted on the chart recorder are shown in fig.43. It was noted that the control sling had increased in length to 66 cm, a permanent extension of 5 cm due to weave deformation. Immediatly after these control tests, the prototype shock absorber was tested in exactly the same way. As expected, the polypropylene tape failed and the resulting force-time graph is shown in fig.42.

Examining first the results of the control tests, the maximum impact forces at a fall factor of 1.0 start at 700 kgf and increase to 875 and 900 kgf for each successive drop. This is due to a combination of plastic deformation of the yarns and tightening up of the internal structure of the fabric which results in an increase in stiffness of the web and a corresponding increase in impact forces.

Comparing these control results to the force-time graphs of the shock absorber, the most prominent feature to note is the clear effect of the polypropylene tape. The impact force rises to 300 kgf, falls rapidly to zero as it fails, and as the weight continues to fall and tension is applied to the backup nylon tape, the force rises to a maximum of 500 kgf. Thus the impact force has been reduced from the control value of 500 kgf but is still above the desired maximum of 300 kgf.

In order to gain an understanding of the processes involved, some simple theoretical analysis was conducted. Consider the amount of energy involved in the fall:-

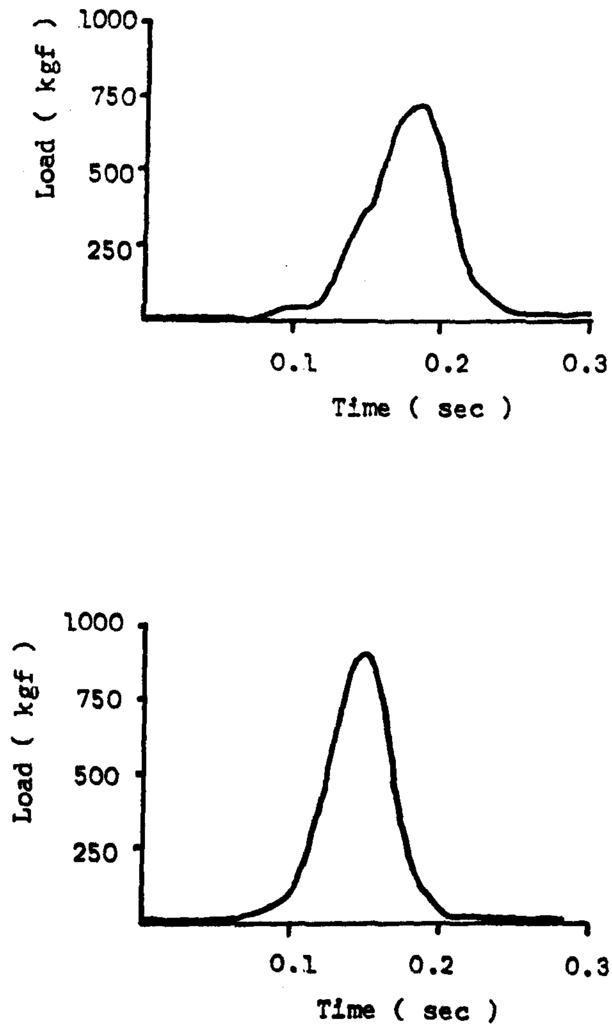


Figure 43: Pre-SA1 Control Drop Tests

Potential Energy, $E = MgH$ where M=mass of the falling body

g=gravity

H=length of the fall

=470 Joules

The amount of energy absorbed by the polypropylene can also be calculated. If it is assumed that it behaves elastically and that it fails at 300 kgf and 80% extension under dynamic as well as static loading, then the energy absorbed at failure

$$E = \frac{FxX}{2} = \frac{F \times 0.8 \times L}{2} \text{ where L=Length of polypropylene}$$

$$= \frac{300 \times 9.81 \times 0.035 \times 0.8}{2}$$

$$= 42 \text{ J}$$

The failure energy, E , is comparable in percentage terms to the reduction in impact forces. However, the impact force of 500 kgf was still too large. In order to reduce this, the energy absorbed by the polypropylene had to be increased. This was done by increasing its length.

7.5.2 SA2:Increased Length High Extension Polypropylene Insert

Similar to SA1 in construction, the change made to SA2 was to increase the length of polypropylene to the maximum possible. On a standard short snake sling, the distance between the two sewn blocks is 26 cm. Of this length, two 5 cm sections are taken up by the triple bar tacks, leaving 16 cm. This 16 cm has to accommadate the gauge length plus the extension. With an elongation of 80 %,

$$16 \text{ cm} = L\ (1+0.8)$$

$$\text{So } L = 9 \text{ cm}$$

These prototypes were constructed with 9 cm of polypropylene between the two innermost bartacks with 7 cm of excess nylon to allow for extension of the insert. Its construction is shown in fig.44.

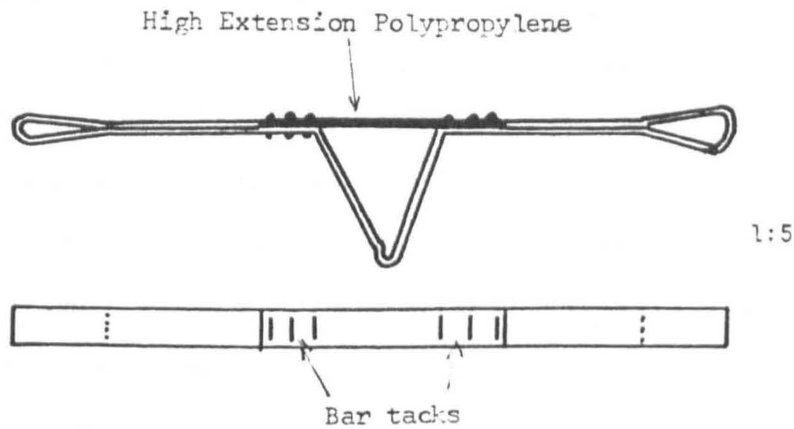
Tests were conducted on the three prototypes, and the insert was observed to fail in each case. The force-time graphs are shown in fig.44, where the insert failure at 300 kgf can clearly be seen followed by a subsequent secondary impact. These secondary impacts have maxima of 650, 700 and 600 kgf.

As these results are the opposite of that expected, the testing method has to be critically examined. Given the repeatability of the tests of SA2, it was suspected that the result from the test of SA1 was an anomaly. Examining the trace of SA1 in more detail , there is a plateau at approximately 100 kgf after the maximum of the secondary impact. This suggests that the test was in some way corrupted by, for example, the weight falling out of line.

However, it was decided not to research this more thoroughly, although the following points emerge from these two sets of tests:-

1. The shock absorber has a small but limited effect on the maximum impact force, the secondary maximum being slightly lower than the control test data.
2. This being the case, the aesthetic properties of the device will be more important than the technical effect on the impact forces.
3. To examine the small effects of these samples, a rigorous testing procedure will have to be followed.

Therefore this style of prototype was rejected in favour of a more compact version, and further prototypes were tested in both simple dynamic and static(quasi-dynamic) modes.



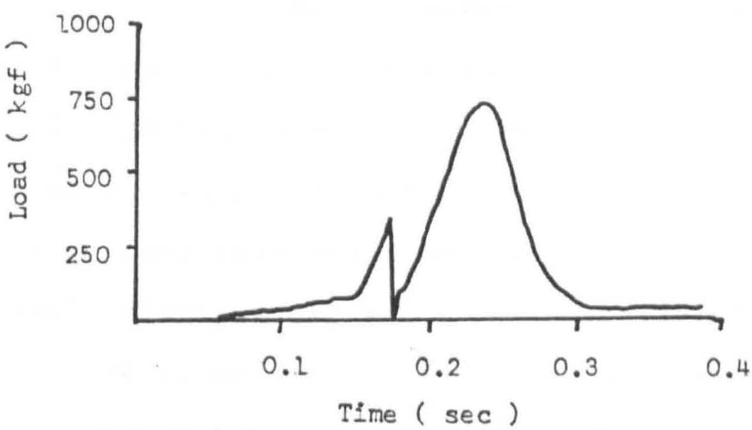


Figure 44: SA2: Design and Drop Tests

7.5.3 SA3:14 mm Inserts in Snake Loop

Having accepted that the device would have little effect on the impact forces, these three prototypes were produced with the object of making the device more aesthetic. They were more rigorously tested to establish the processes occurring during fall arrest. This was the first prototype to be tested using applied dynamic methods and a series of control tests were conducted beforehand to establish impact forces at fall factor 0.5 using this method.

Three drop tests were conducted using a standard short snake sling, a rope length of 2.0 metres and a fall length of 1.0 metre and the results are shown in fig.45. The peak impact loads on the runner are 700, 700 and 750 kgf for each test, slightly lower than the figure predicted from the previous drop tests. This was expected to be 870 kgf, and the discrepancy is due to the control snake sling which will:-

1. elongate and thus subtend a greater angle between the anchored and weighted ropes, and
2. absorb energy, thus reducing the load on the rope.

A standard short snake sling was assembled with an inserted loop of 14 mm twill tape with a strength of 150 kgf. This loop was 7 cm in length from the main sewn block to its fold, giving it a potential extension of 2 cm (see fig.46).

Static tests were conducted on the prototype with the result that the insert extended so far as to place tension on the main loop of the snake and the maximum capacity of the load cell was exceeded before any failure occurred. An applied dynamic test with a fall length of 1 metre and rope

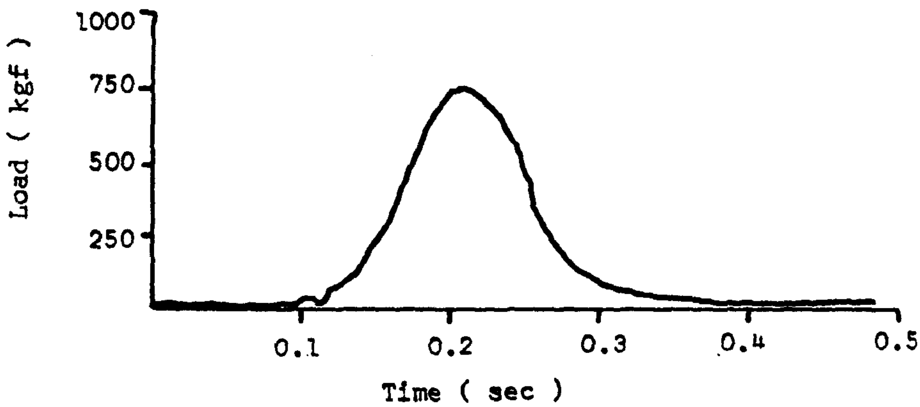
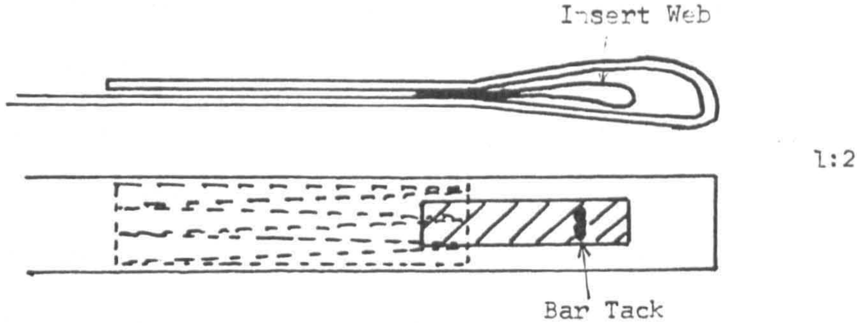
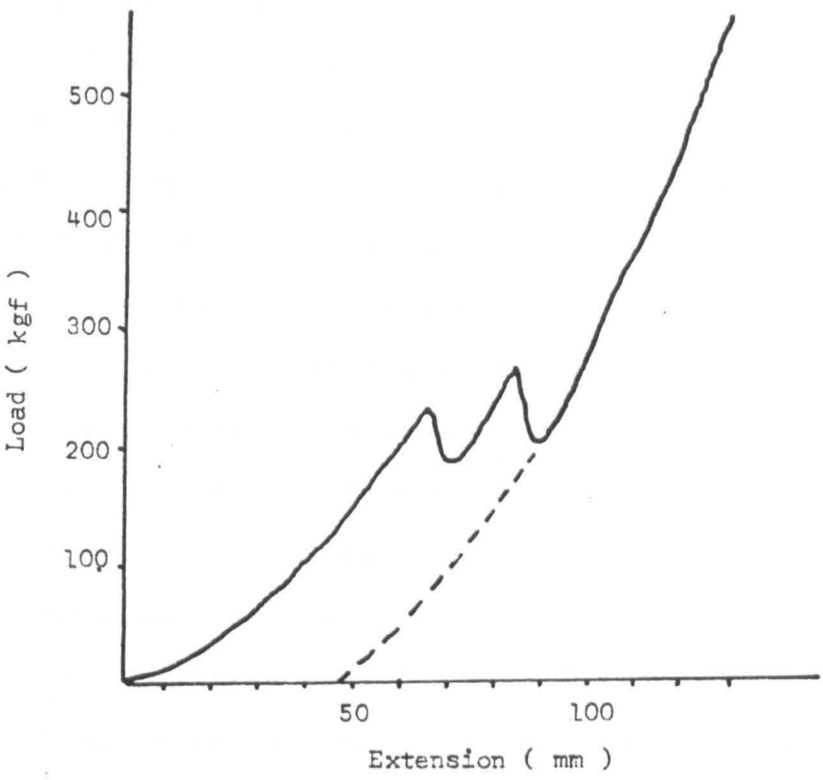


Figure 45: Applied dynamic Control Drop Test at Fall Factor 0.5





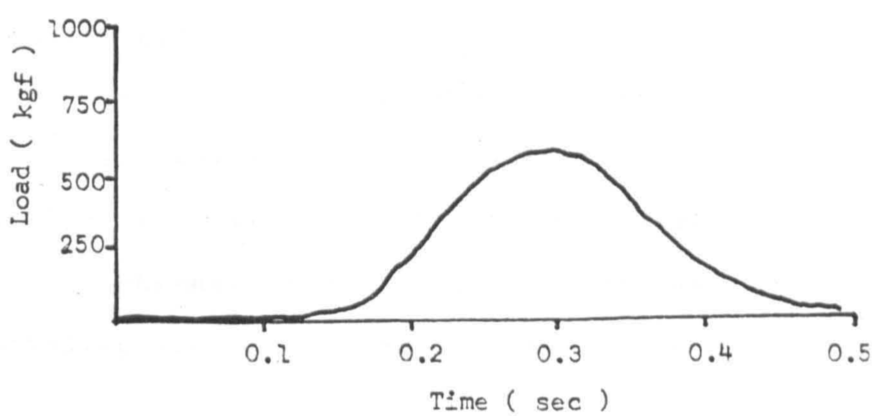


Figure 46: SA3: Design, Static and Drop Tests

length of 2 metres was also conducted on the sample and the insert did not fail.

The remaining two samples were altered by placing 10 mm bar tacks in 40's thread across their width approximately 1 cm from the fold(see fig.46) and the tests were re-run. In the static tests (fig.46), the failure of the tacks at each end of the sling can be seen at 110 and 120 kgf. The net amount of energy absorbed by these tacks is derived by constructing a line parallel to the trace back to the axis of zero load. The area between these two lines corresponds to the energy absorbed and is equal to 18 Joules. Clearly, compared to the potential energy of 80 kg falling through 1 metre, 800 Joules, this energy is small and there will be little effect on the final impact force, as shown in fig.46.

It will be noted that the force has in fact increased with the insertion of these tacks. This is due to a slight change in test method. Previously, the trigger bar was activated from in front of the rig, and this causes the weight to be pulled out of line with the anchor point immediatly before the drop causing a pendule. To eliminate this, the trigger was activated from behind the rig, pulling the weight into line immediatly beforethe drop. Using this optimum trigger position, the maximum impact force rises from 425 to 550 kgf.

Thus SA3 has a negligible effect on the impact force. Further, it was rejected on the basis that it might be possible to clip into the insert without clipping the main nylon loop. Whether done by accident or deliberately by misunderstanding of the mode of operation of the device, the effect of this would be disastrous. In a fall, the insert would fail at the comparatively low load of 300 kgf which is unacceptable, and the design of SA3 was therefore rejected.

7.5.4 Development of Impact Absorption Theory

At this stage, a more detailed analysis of the fall arrest system was required. If the fall factor theory is studied, it is seen that the potential energy of the fall is absorbed in the rope in the form of strain energy. When using a shock absorber, this condition is altered so that the potential energy is split between the shock absorber and the rope. Given an energy absorption capacity of E_A, the theoretical impact force can be recalculated.

$$mg(H+X)=\frac{PX}{2}+E_A$$

and $$P=\frac{KX}{L}$$

So $$mg(H+X)=KX^2/2L+E_A$$

$$KX^2/L-mgX-mgH+E_A=0$$

Solving this quadratic equation,

$$X=\frac{mgL}{K}+\frac{mgL}{K}.\sqrt{1+\frac{2KH}{mgL}-\frac{2E_A K}{m^2 g^2 L}}$$

So $$P=mg+mg.\sqrt{1+\frac{2KH}{mgL}-\frac{2E_A K}{m^2 g^2 L}}$$

The corollaries of this equation are:-

1. As the energy absorption capacity, E , increases, the maximum impact force, P, decreases
2. As the mass, m, is increased, the maximum impact force, P, increases.
3. If the fall length, H, is increased with constant rope length, L, the force, P, rises
4. However, if both H and L are increased while maintaining their ratio (the fall factor) constant, then the negative coefficient of E decreases in magnitude and the force, P, increases.

5. If E =mgH, then P=2mg, which is equivalent to a fall factor of zero. This means that the load on the runner will be 4mg. If the trigger load of the device is less than 4mg, then the load on the runner will be reduced to that level.

Evidently , it is necessary to maximise E without increasing the trigger load above 300 kgf. Ideally, the load-extension curve of such a device should be as in fig.41 with the load maintaining a plateau at the level of the trigger load. Rather than one component failing, this can be done by many smaller components operating in progressive failure.

This can be done by using a sewn joint. In such a joint, the individual looped threads will fail gradually, compared to a web insert where the loading is much more even and results in a single high strength failure. In addition to this theory, Troll Safety Equipment had the facilities to produce different types of sewn joint. Thus the development of the device from this point onwards is dominated by sewn joint progressive failure.

7.5.5 SA4:Double Fold, Single Bar Tack in 20's

This was the initial device using stitching, which tested the feasibilty of the concept rather than the practicality of this design as a production item. A standard short snake sling was folded into an'S' configuration in between the two blocks so that the length of the 'S', three layers of tape deep , was 15 mm long (hence the expression 'double fold';see fig.47).

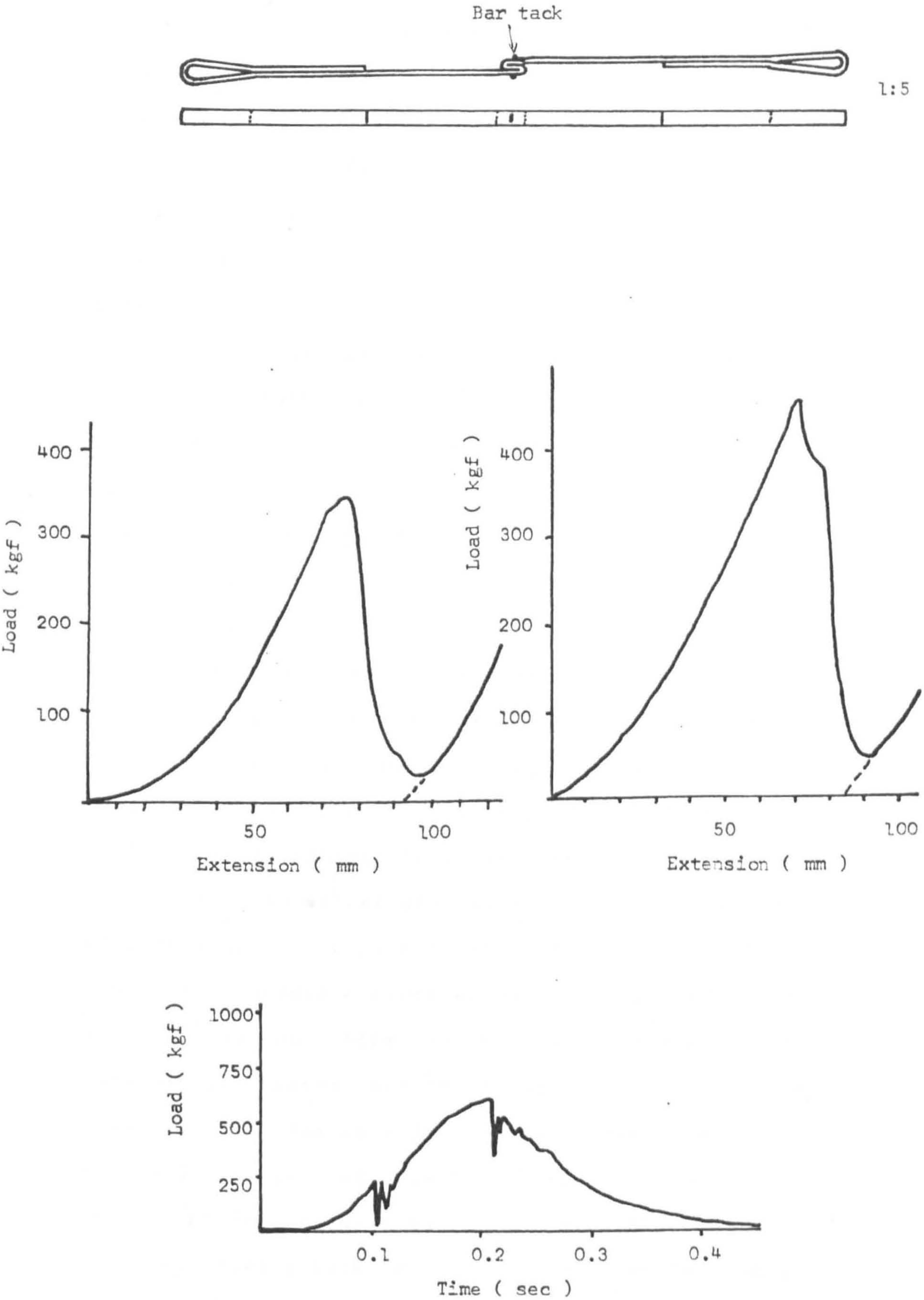


Figure 47: SA4: Design, Static and Drop Tests

A bar tack was then sewn through all three layers of tape. This and all subsequent bar tacks in 20's were inserted using a Brother Industries machine, no.LK3-B430, with 42 stitches [61]. The tack stitch length was set at 5 mm and the width at 23 mm. 20's thread in nylon (the thread used for the majority of applications at Troll) was used for compatibility purposes.

A static test was conducted on the sample and the results of seperate tests are shown in figs.47. The failure of the bar tack can clearly be seen and the energy absorbed was calculated by measuring the area under the trace. This was found to be 88 and 56 J with trigger loads of 228 and 175 kgf respectively. The reason for the large discrepancy between the two results lies in the second test where the bar tack was inserted off the centre line of the tape. Damage to the weft yarns on the edge of the web was observed before the test , the tack triggered gradually at a lower load and thus had a lower energy absorption capacity(EAC).

An applied dynamic test was then conducted with a rope length of 1.85 metres and at a fall factor of 0.5. The stiffness of the rope was checked by conducting a control test with a standard short snake sling , and a peak of 710 kgf was observed. After an interval of 5 minutes, the shock absorber was tested and the result of the test is shown in fig.47. The bar tack failure is clearly seen at 220 kgf followed by a gradual rise to 600 kgf. At this point a discontinuity in the curve is seen, with the load dropping to 350 kgf, rising back to 500 kgf and then falling gradually as expected.

Analysing the results of these tests in terms of the energy involved, the total amount of energy involved in the fall is 80x9.81x0.9=700 J. Thus the effect of the shock absorber is to reduce the energy absorbed in the rope to 610 J, a reduction of 12.5% equivalent to a decrease in fall length of 0.11 m

Comparing this with the results of the applied dynamic test, there is a corresponding fall of 110 kgf or 15.5% in peak impact force. However, the force involved is still higher than 300 kgf and the EAC must therefore be increased

7.5.6 SA5:Double Fold, Double Bar Tack in 20's

To increase the EAC, the number of tacks holding the device together was increased to two. The fold length was increased to 25mm. Studying fig.48, both tacks will be loaded evenly thus increasing the trigger load and, by implication, the EAC. The trigger load of SA4 has been measured at 220 kgf and so it was possible to increase this. Further, the development of this prototype would expand the knowledge of the operation of this style of shock absorber.

As in SA4, two static tests were conducted and the results are shown in fig.48. The trigger loads were found to be 495 and 425 kgf with crresponding EAC's of 201 and 192 J respectively. The source of the slight discrepancy between the results is again uneven failure of the second sample, shown by the inflection immediatly prior to failure. Thus the effect of doubling the number of bar tacks is to increase the trigger load by 100% and the EAC by 120%. Studying the applied dynamic trace in fig.48, the load rises to 525 kgf, falls to zero and then rises to 500 kgf to break

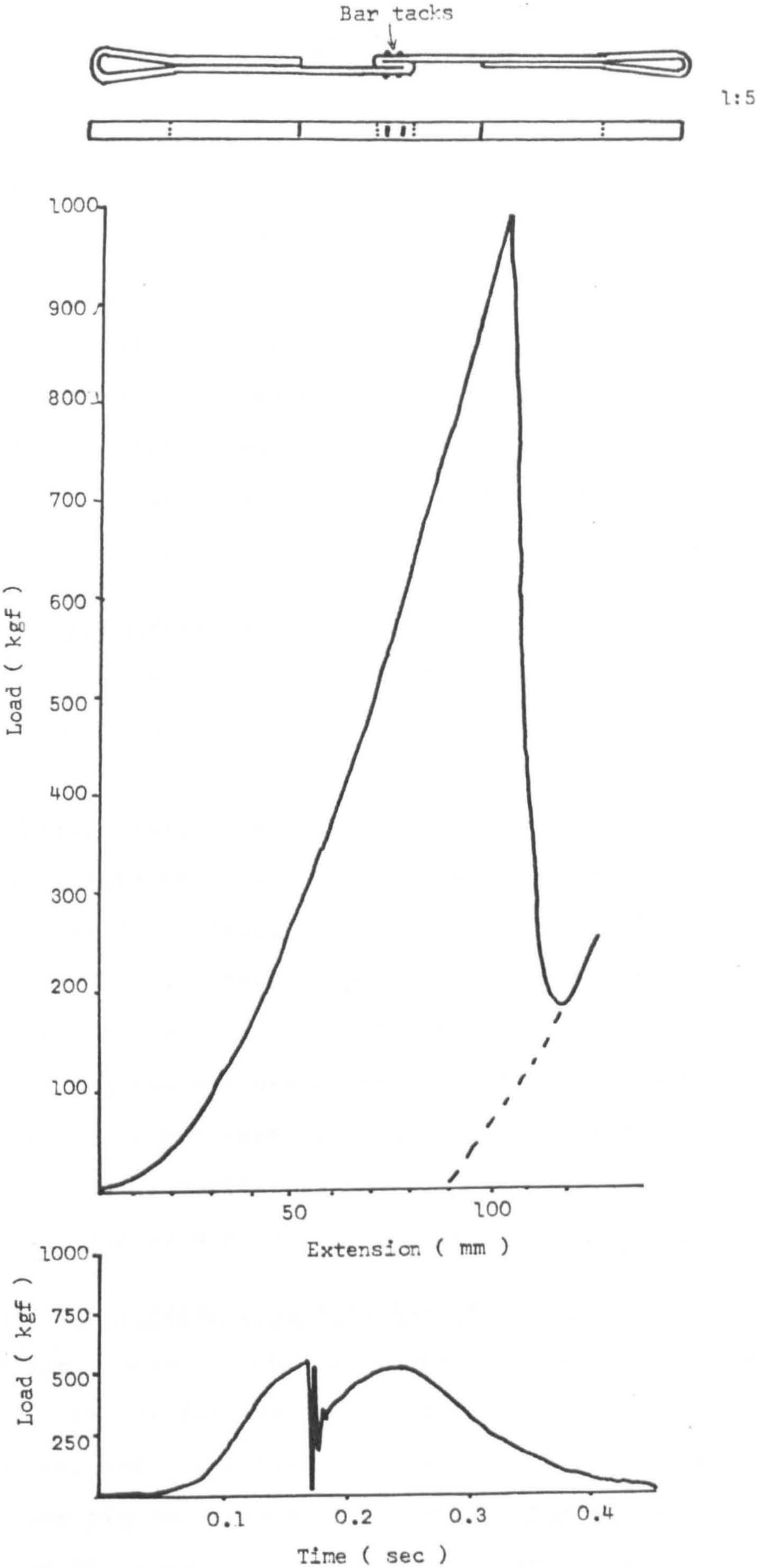


Figure 48: SA5: Design, Static and Drop Tests

the second tack. There is a secondary impact of 500 kgf following this.

Comparing the results of the static and dynamic tests, the EAC compared to the overall potential energy is 28.5%, which is very similar to the drop in peak impact force of 29.5%. Thus the correlation is excellent.

Unfortunately, the trigger load is now too high, although the quantities of energy are becoming more comparable to the potential energy in a short fall.

7.5.7 SA6:Double Fold, Triple Bar Tack in 20's

To complete this set of tests, the length of fold was increased to 40 mm and the number of bar tacks increased to 3.

In the static test, the upper limit of the test machine was exceeded before the trigger point was reached, and the device also failed to trigger in a fall factor 0.5 applied dynamic test(fig.49). Extrapolating the results of the two previous test sets, it would be expected that SA6 would have a trigger load of 840 kgf and an EAC of 300 J. This theory is not disproved by the tests conducted, but it was not felt necessary to conduct further tests, as the device would not be a practical one with such a high trigger load.

7.5.8 SA7:Double Fold, Single In-line Bar Tack

At this stage, none of the prototypes had kept the peak impact force to the desired limit of 300 kgf. To induce progressive failure, the bar tacks were reorientated by 90 degrees. (see fig.50) Thus the bar tack is In-line with the warp yarns of the tape. The mode of failure, it was hoped,

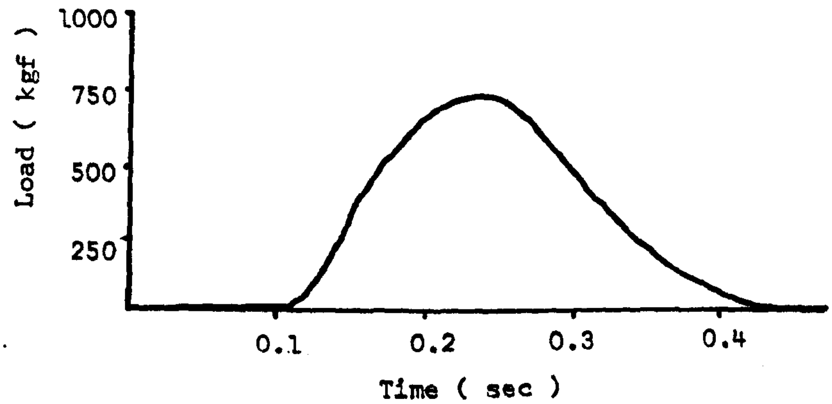


Figure 49: SA6 Drop Test

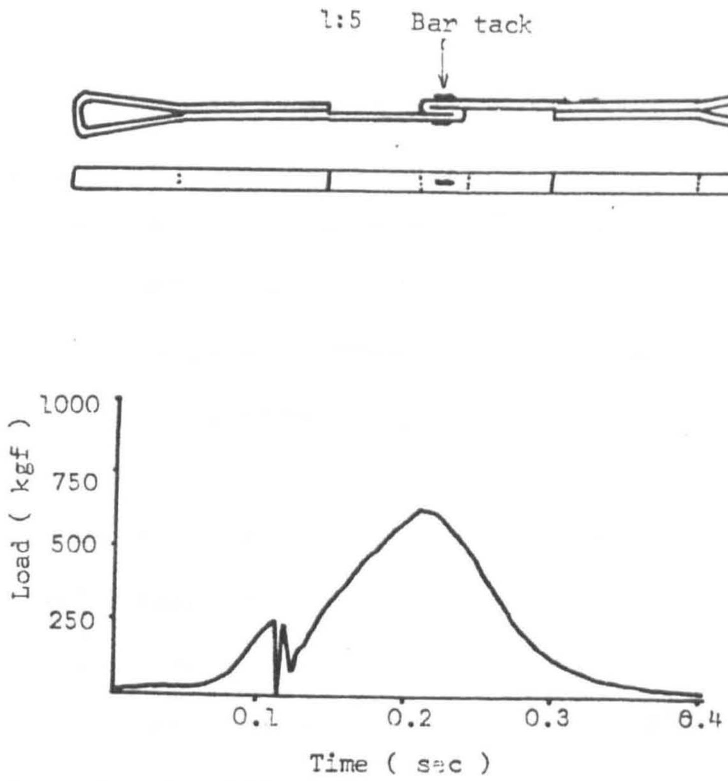


Figure 50: SA7: Design and Drop Test

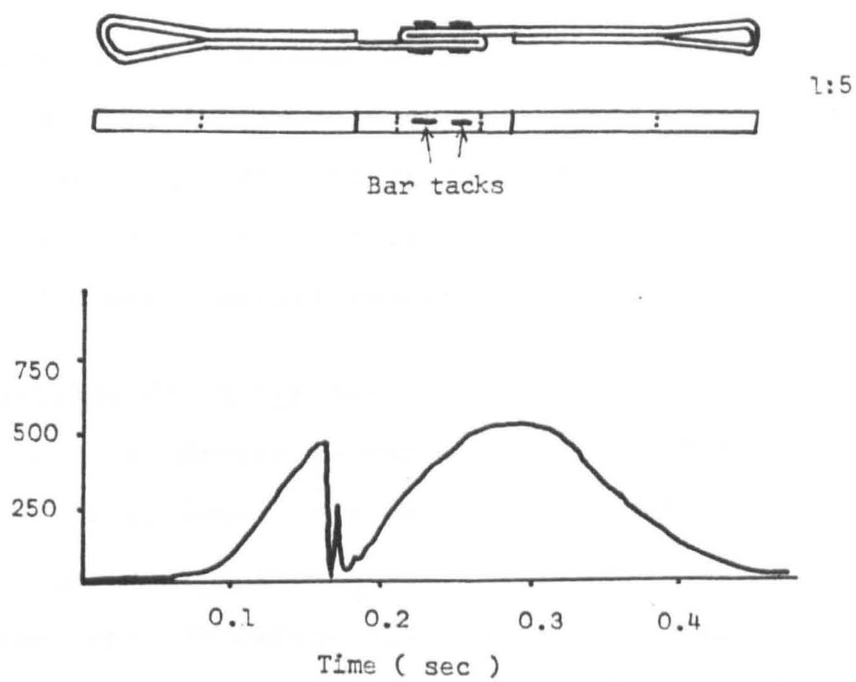


Figure 51: SA8: Design and Drop Test

would be by individual failure of the stitches rather than by rapid failure of the entire tack.

Examining the results of the applied dynamic test in fig.50, there is no significant difference between this and SA4. It would therefore appear that loading in the dynamic situation is not progressive and the difference in peak impact force is small.

One important difference between SA4 and SA7 is that , in the latter, web damage was much more noticeable. Weft yarns were torn out, leaving the sling with an unacceptable appearance and , presumably, a lower strength. For this reason, the design of SA7 was rejected.

7.5.9 SA8.Double Fold, Double In-line Bartack in 20's

THis prototype was simply a doubled up version of SA7 with two bar tacks in series down the length of the folded web.

As in SA7 there was unacceptable web damage when an applied dynamic test was conducted. Further, the trigger load remains above the desired level of 300 kgf (see fig.51)and SA8 was therfore rejected.

7.5.10 SA9:The DMM Shocktape

At this time, a device appeared on the market for shock absorption in a climbing situation. Denny Moorhouse Mountaineering are traditionally associated with metallic equipment. Their DMM Shocktape was a snake sling in 25 mm web with an overall length of 62 cm. The end loops are secured with gate blocks in 20's thread and between these two blocks lie 48 cm of web. This free length is folded double, as shown in fig.52, with the length of each fold being 25mm.

Six of these double folds are inserted along the free length and each is secured with a gate block in 40′s thread. Hence there are two important differences between SA9 and the previous designs:-

1. A number of folds, rather than just one, is inserted. This should lead to an improvement in EAC, as the failure will be spread over a greater length, thus failure will be more progressive.
2. A gate block in 40′s is used in place of a bartack in 20′s. This means that the trigger load of each block will be significantly different. Although the number of stitches inserted in each block type is approximately the same (50 in a gate block, 42 in a bar tack) the loading of the block in the former is spread over a greater area. Further, the individual strength of each stitch will be reduced due to the lower thread weight. A benefit of lower thread weight is that web damage should be eliminated.

The accompanying literature with this device stated that it "absorbs a considerable proportion of the dynamic load". Given the difficulty already experienced in absorbing more than a small proportion of the potential energy in the fall, it was difficult to see how a similar device could warrant such a claim. A quantity of DMM Shocktapes were therefore purchased and tested in the usual way, both statically and in applied dynamic mode.

In the first test, the maximum crosshead limit of the test machine was reached before the sixth and final gate block failed. Studying fig 52, the blocks did not fail in

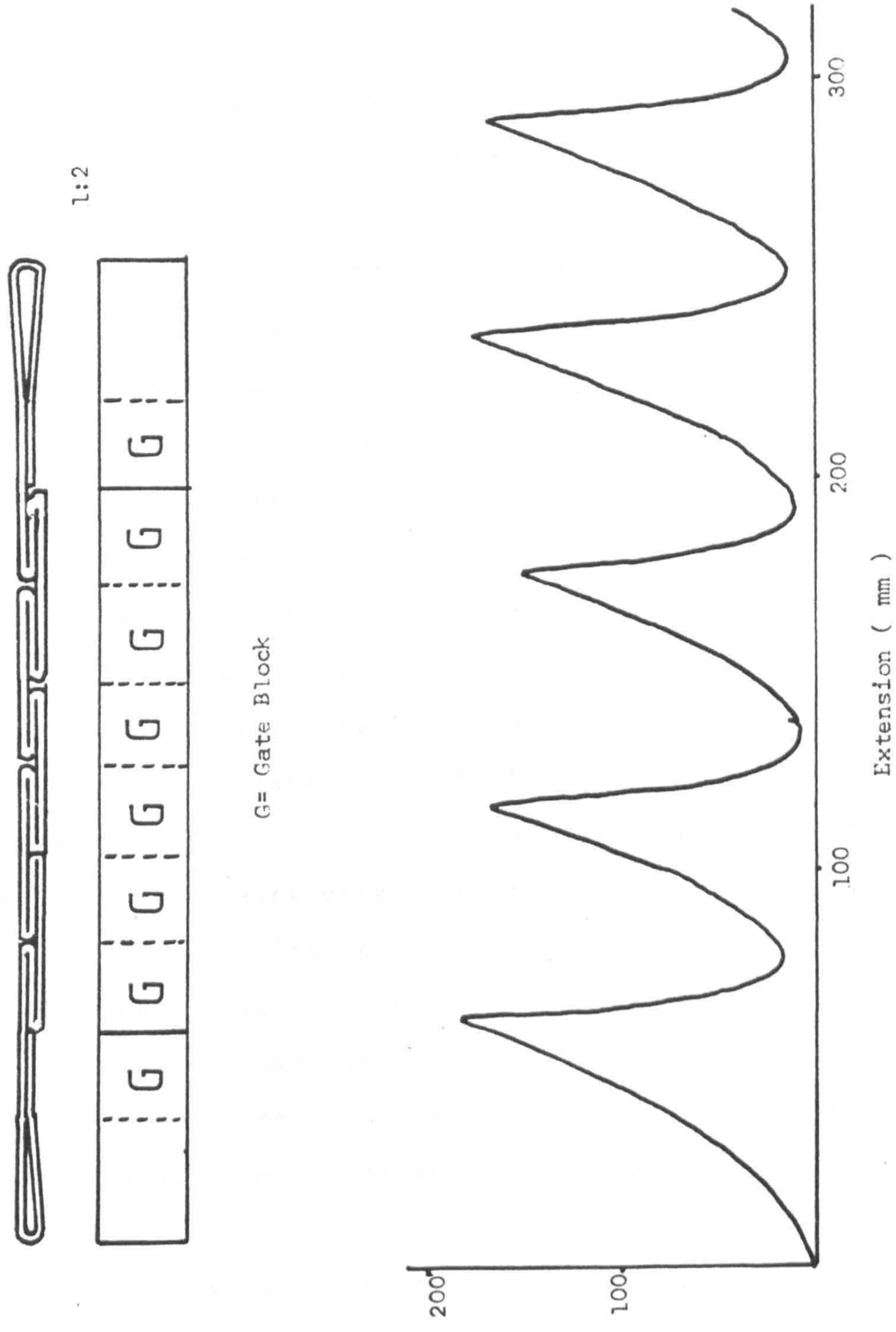


Figure 52: SA9: Design and Static Test

order of increasing magnitude, as might be expected, with the trigger loads being 185, 165, 150, 175 and 170 kgf. However, these failure loads are closely related to the EAC's of each block, which are 51, 36, 22, 40 and 36 J respectively, derived by measurement of the area under the curves. Thus an average EAC of 37 J/block is obtained and, adding this to the total of the measured EAC of 5 blocks, a predicted total EAC of 222 J is obtained.

In the second static test, all six blocks triggered, thus giving a complete picture of the operation of the device. The trigger loads were 155, 160, 155, 170, 140 and 160 kgf with EAC's of 43, 36, 32, 38, 29 and 37 J respectively. Thus there is once again no evidence of triggering in increasing order of magnitude, but the EAC of each block is closely related to its trigger load. The mean EAC of a gate block is 36 J and a total EAC for the device is measured as 215 J, comparable to the first test and to the EAC of SA5. Therefore it was expected that the magnitude of the secondary impact force, 500 kgf, would be similar when the applied dynamic tests were conducted on SA9.

Because of the claim to "absorb a considerable proportion of the dynamic load", a number of applied dynamic tests were conducted rather than the single ones conducted on the Troll prototypes. The results are shown in fig.53 and a table of trigger loads, times and secondary impact forces shown in table 8.

There are several features of these results worth noting. The trigger loads are significantly higher in the dynamic than in the static situation, a phenomenon which is absent

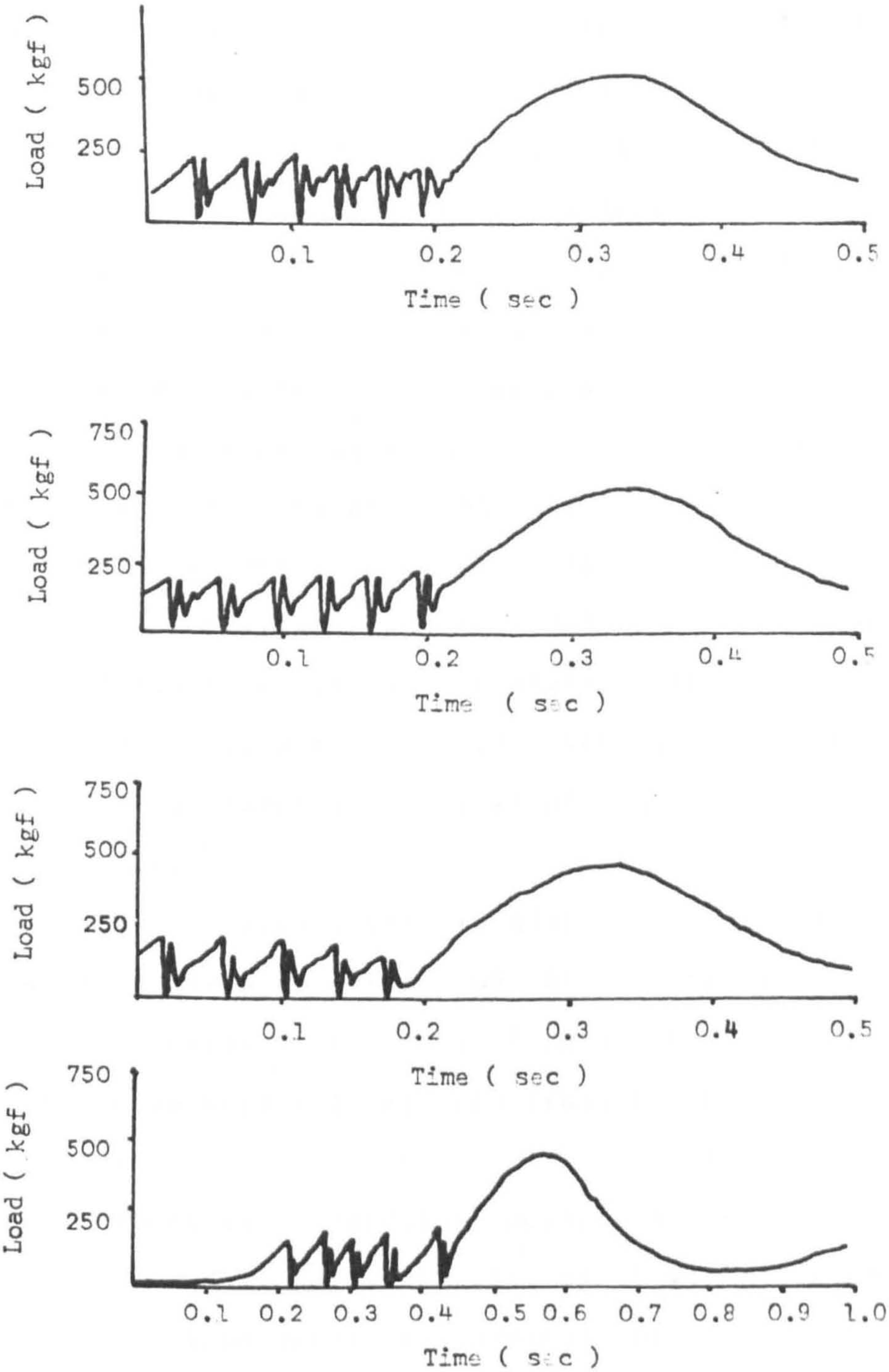


Figure 53: SA9: Drop Tests

in the bartacked prototypes. The dynamic trigger loads vary from 150 to 225 kgf compared to 140 to 185 kgf in the static case. This is due to the difference in extension rates. In the static case, the extension rate is 1000 mm/min and the test takes approximately 20 seconds. Studying fig.53, complete triggering takes place in less than 0.3 seconds. In the static case, the triggering process will therefore be more progressive, leading to lower trigger loads. Each trigger pulse is characterised by a gradual rise from zero to the trigger load, an instantaneous drop to zero followed by a secondary pulse at between 125 and 175 kgf, after which the load drops to about 50 kgf before beginning to rise to the next trigger. This two-stage trigger of the block is a marked charateristic of the double-fold configuration, but is not reproducible in the static test. Any data on this would be difficult to obtain without a tensile test machine capable of comparable rates of extension to the dynamic situation.

As stated above, the secondary impact forces are expected to be comparable to those of SA5. Observing the traces in fig.53, these forces range from 475 to 500 kgf. This connection between SA5 and SA9 leads to two important conclusions:-

1. There is a definite connection between EAC and the secondary impact force, as it was possible to predict the load based on knowledge of the EAC, even though the trigger loads and the designs of the devices are radically different.

2. From a practical point of view, this device falls short of the necessary requirement in a typical fall situation. The claims of "a considerable proportion of the dynamic load" are unsupportable, particularly if the rope and fall lengths are increased to levels commonly experienced.

Nevertheless, SA9 is comparable to SA5 in terms of EAC with a much smaller trigger load. At this point in the development, it was necessary from a commercial angle to produce a device equal to SA9 in terms of both EAC and trigger load, although the latter could be slightly higher. However, the design had to appear different from SA9 to avoid accusations of copying the rival manufacturer's design.

7.5.11 SA10:Loop Sling, Double Fold, Single Bar Tack in 20's.

The other common configuration of sling apart from the snake is the loop sling. This has three advantages over the snake:-

1. Given a certain width of tape, the loop is twice as strong as the equivalent snake.
2. The loop is far more popular with climbers for the purpose of attachment to small wire runners.
3. Using a loop gives a greater degree of product differentiation between the final Troll version and the competing SA9 from DMM.

SA10 was constructed by cutting a piece of standard web 40 cm long. A 15 mm double fold was placed in it and secured using a 20's bar tack, as in SA4. A loop was then formed with a 7cm overlap and secured with 5 bar tacks in

20's thread. This change in the construction of the joint from double-W to bar tacking was done so that the sling would be flexible enough to be used on small wire runner placements. Previously, bartacking of slings had been avoided because of their greater susceptibility to surface abrasion, but in this case it was necessary to compromise this in order to retain sling flexibility.

The sling in this form was tested statically and the result is shown in fig.54. As expected, the trigger load of the sling, 485 kgf, was approximately twice that of SA4 as the total load is split between the two halves of the sling.

The EAC is derived by extending the post trigger trace back to the axis of zero load parallel with the original trace as described in SA3. The area between the real and constructed traces is measured and represents the EAC of 66 J. This is very similar to the EAC of SA4, and this is because the free length of tape under tension is similar in these two cases. In the snake, the length of web beween the lap joints is 250 mm, minus the length involved in the fold which is 75 mm, giving 175 mm. In the loop, the free length is 400 mm minus the tape in the tape in the joint, 140 mm, minus 75mm for the fold gives 185 mm. Thus, the length and type of the tape in the device determines the EAC, with the thread weight, joint type and fold configuration governing the trigger load.

Having establshed a correlation between the prototypes, it is still evident that the EAC is below that required for a significant effect on the secondary impact force. Further, the trigger load of SA10 is too high. Two seperate

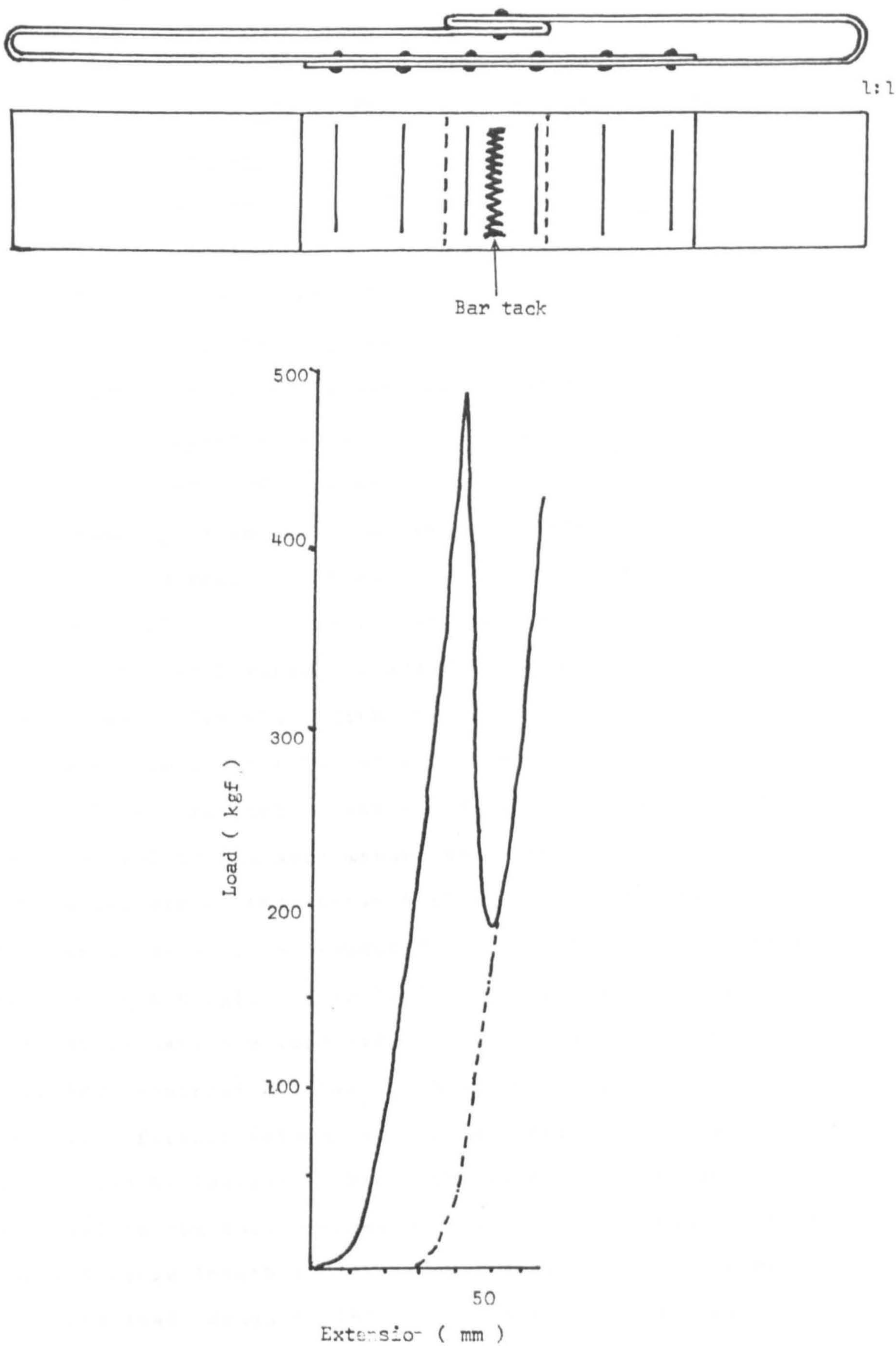


Figure 54: SA10: Design and Static Test

problems have to be solved, and these are tackled in the next two prototypes.

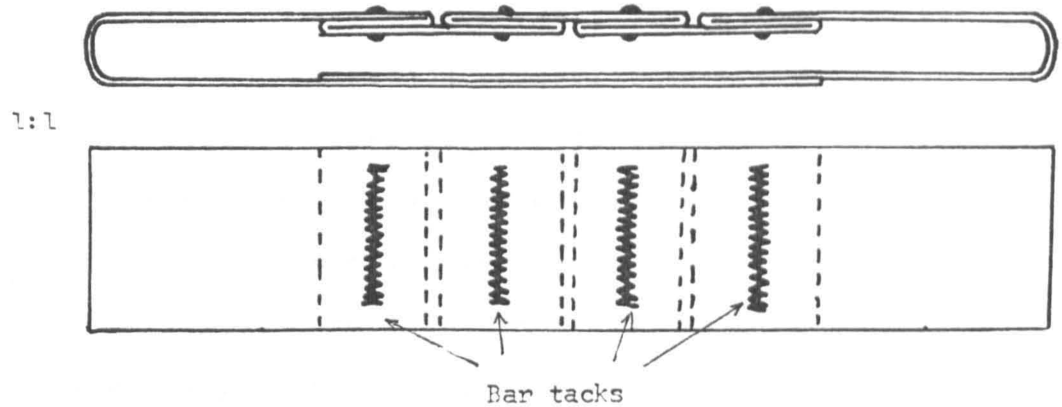
7.5.12 SA11:Loop Sling, Four Times Double Fold, Single Bartack in 20's

In order to increase EAC, two changes can be made to the basic loop design:-

1. The free length of web in the system can be increased, limited by the fact that this will increase fall distance and that the user will not accept a sling for this purpose above a certain length.
2. The number of bartacks can be increased and their spacing decreased in order to maintain a load plateau with increasing extension as shown in fig.41.

Accordingly, the basis for SA11 was a loop, 60 cm in circumference, with extra web added to form four double folds, each 15 mm in length. With the 7 cm required for the five bar tack joint, the total length of web cut was 85 cm, which also allowed for web shrinkage during sewing. The folds were secured in the same manner as those in SA10.

The results of the static test are shown in fig.55. The trigger loads are, as expected, twice those of SA4 with a maximum of 450 kgf. This load is still too high, although the EAC is markedly improved, with 317 J being the highest capacity achieved so far. Studying the graph in more detail, further information about the operation of the device can be derived. When the first tack triggers, the material in the fold becomes part of the loop, thus increasing its gauge length and reducing its extension by 30 mm, so that the load drops to 185 kgf. With repeated failure of



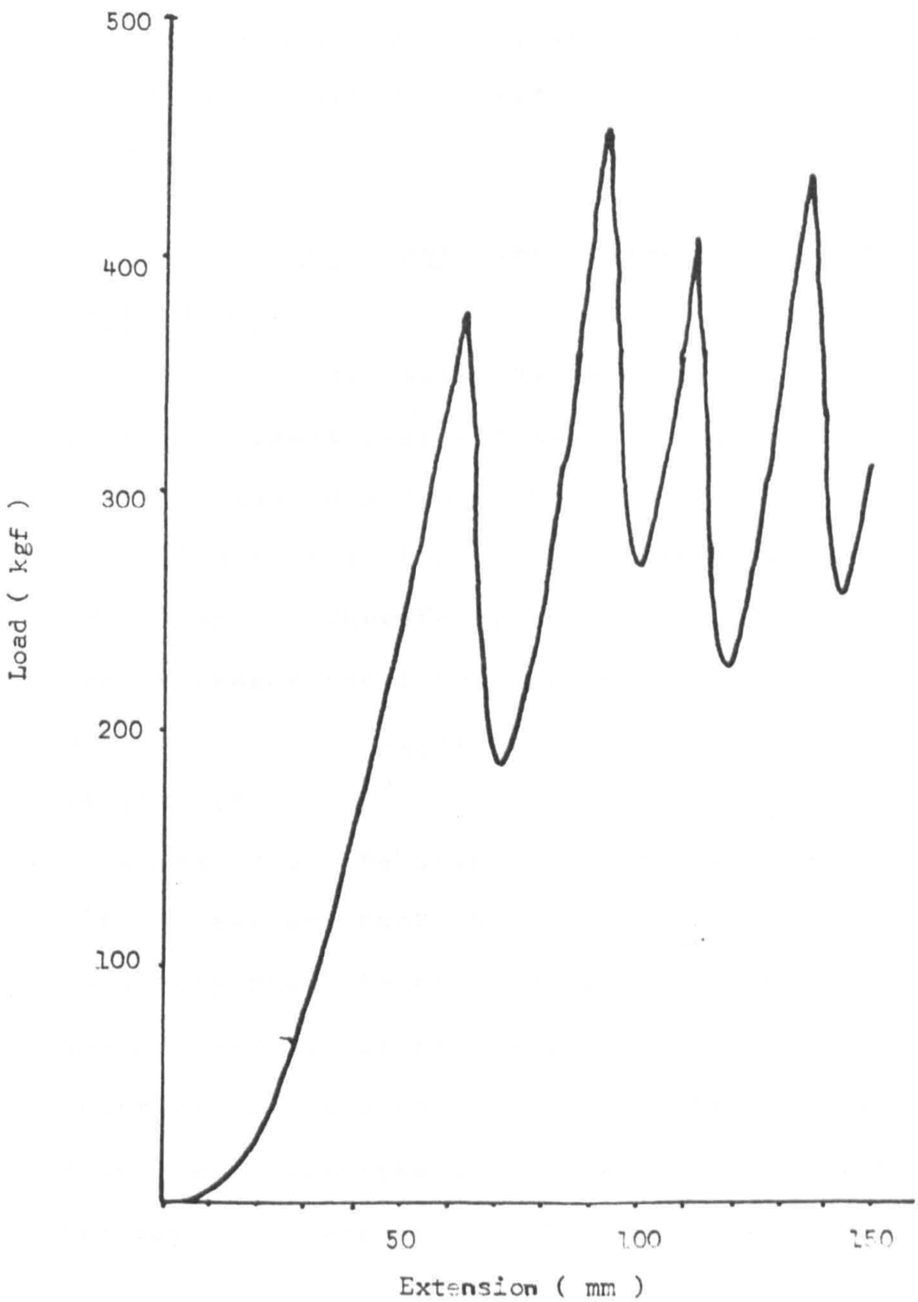


Figure 55: SA11: Design and Static Test

the tacks, the post trigger minima are 270, 220 and 255 kgf after which the loop is loaded normally. In order to maintain as level a plateau as possible, the amount of material involved in each fold has to be minimised. In this respect, the minimum fold length attainable is governed by production criteria. The minimum fold length is 15 mm given current technology and using that thickness of web.

The problem of a high trigger load remains and, to reduce this, it is necessary to change either the thread weight and/or the configuration of the folds or the sewing. The next prototype was therefore constructed using 40's thread instead of 20's.

7.5.13 SA12:Loop Sling, Four Times Double Fold, Single Bar Tack in 40's

Until now, all the bar tacks had been inserted using a thread supplied by James Pearsall and Co. of Taunton, code no. T336, with a quoted strength of 9.6 kgf[62]. The 40's thread used by Troll is a bonded nylon thread with a quoted strength of 4.3 kgf. Therefore, assuming the strength of the tack to be proportional to the strength of the thread used, the resultant trigger load of SA12 should be 400x4.3/9.6=200 kgf.

If the traces from the static tests are examined (see fig.56), it is evident that this prediction is not valid. Trigger loads vary from 355 to 410 kgf, scarcely less than the previous prototype. It is possible that the two different manufacturers quote strengths with different margins, although such a wide difference is unlikely to be accounted for in this way. Tests were therefore conducted on the

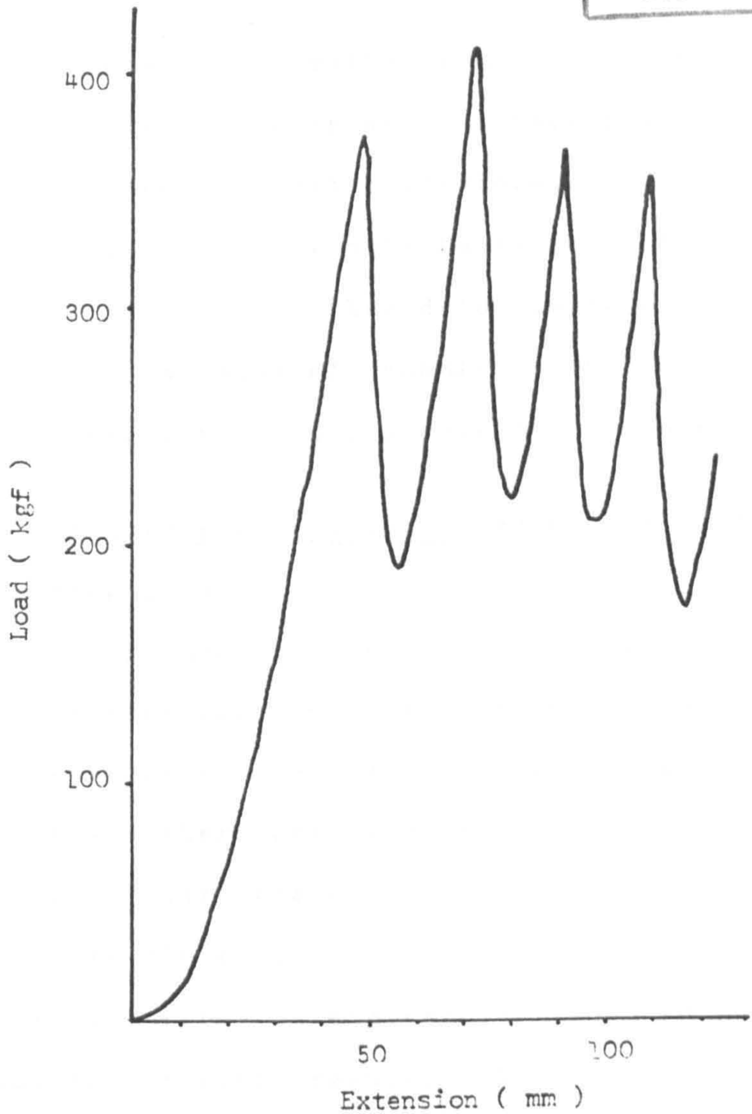


Figure 56: SA12: Static Test

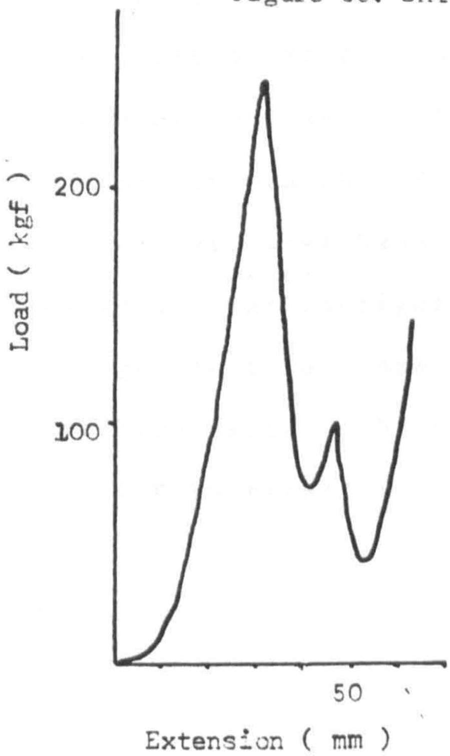


Figure 57: SA13: Static Test

threads to check the validity of the quoted data and the results are given in Appendix A rather than interrupting the flow of the shock absorber development with a large amount of test data. Further, more tests would be conducted using slings sewn with 40's thread to check the consistency of this result. No applied dynamic tests were conducted from this point until the EAC was markedly improved.

7.5.14 SA13:Loop Sling, Two Times Double Fold, Single Bar tack in 40's

By reducing the number of tacks, it was hoped to isolate the effect of the triggering of 40's tacks. Hence SA13 had just two double folds but in all other respects was identical to SA12. It was therefore expected that this prototype would produce a similar trace to SA12 with a trigger load of approximately 400 kgf.

The result of the static test is shown in fig.57 and differs from the expected result. The initial trigger is at a level of 240 kgf, more in line with the result expected before the testing of SA12. However, the second tack triggers at a load of 100 kgf. There is evidently some factor playing a major part in the loading of the sling when nominally identical bar tacks have trigger loads which vary from 100 to 400 kgf. The configuration of the loading of the tack was thought to be a possible cause for this variation. To test this hypothesis, the fold configuration was changed from double fold to single fold.

7.5.15 SA14:Loop Sling, Four Times Single Fold, Double Bar Tack in 40's

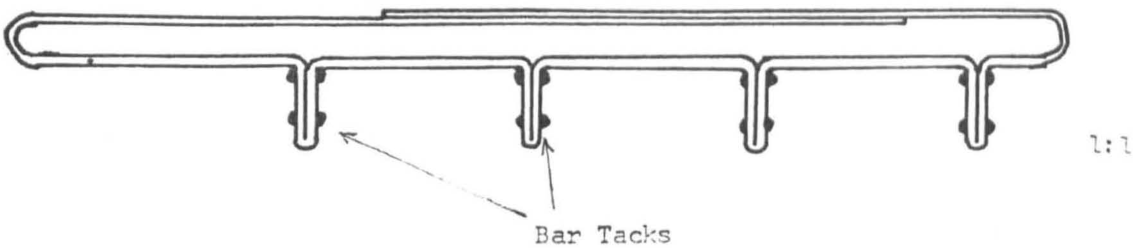
To decrease to a single fold is a simple operation which had been avoided in the past because it produces a 'tag' of doubled web which is less tidy than a double fold which produces a flat compact section of three layers of web. For the purposes of experimentation, however, the single fold is a useful design which was adopted for the next series of prototypes.

SA14 was a 30 cm loop sling as in previous versions, but the 40's bar tacks were placed through two layers of material to each fold, with 10 mm between each tack and a 10 mm gap between the tack and the fold (see fig.58). Thus each fold was effectively 20 mm and each set of tacks was seperated by 25 mm in order to fit successive folds under the presser foot of the bar tack machine.

The result of the static test is shown in fig.58, with the trigger loads varying from 225 to 290 kgf. This increased consistency of the trigger loads suggests a more uniform loading method, which is discussed in more detail after the testing of SA15. The EAC of SA14 is 240 J which is no improvement on any prototype so far, although the trigger load is of the correct order.

7.5.16 SA15:Loop Sling, Single Fold, Eight Bar Tacks in 40's

In order to investigate the effect of having a larger number of bar tacks in the same fold, SA15 differed in appearance from the prototypes constructed so far (see fig.59). By placing all eight tacks in the same fold, a predictable



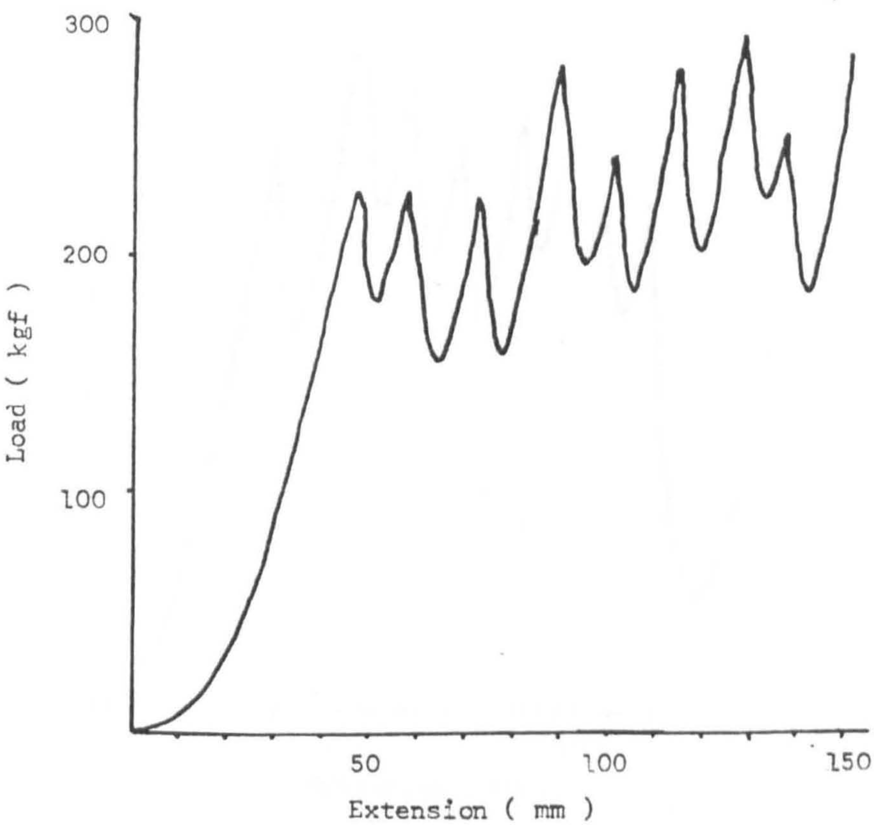
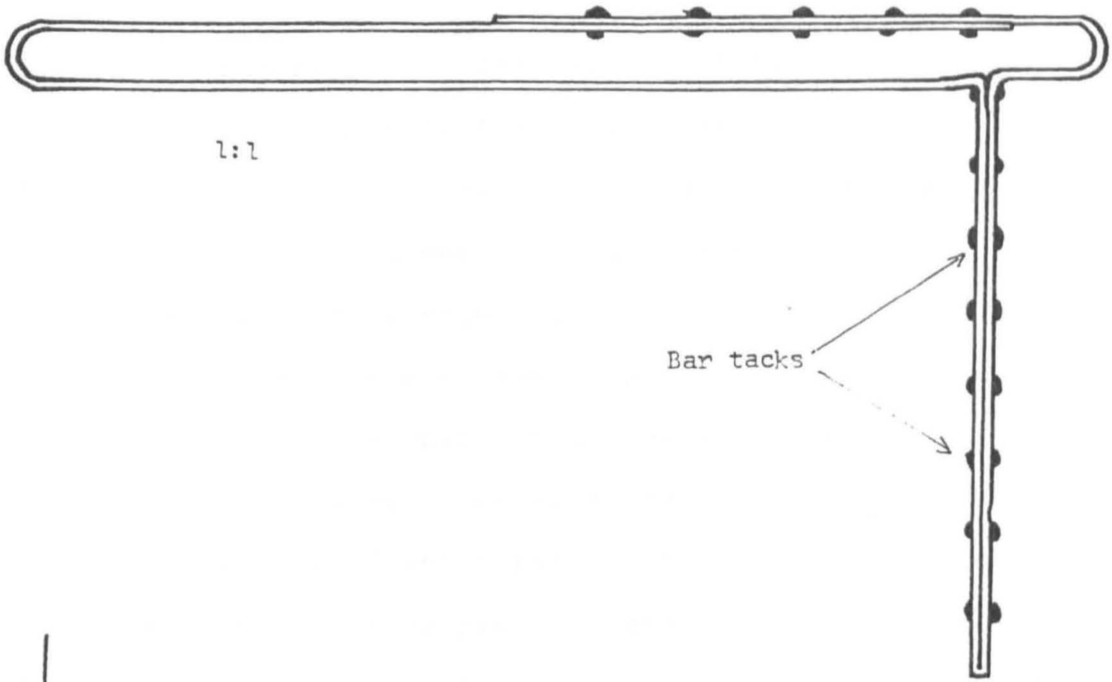


Figure 58: SA14: Design and Static Test



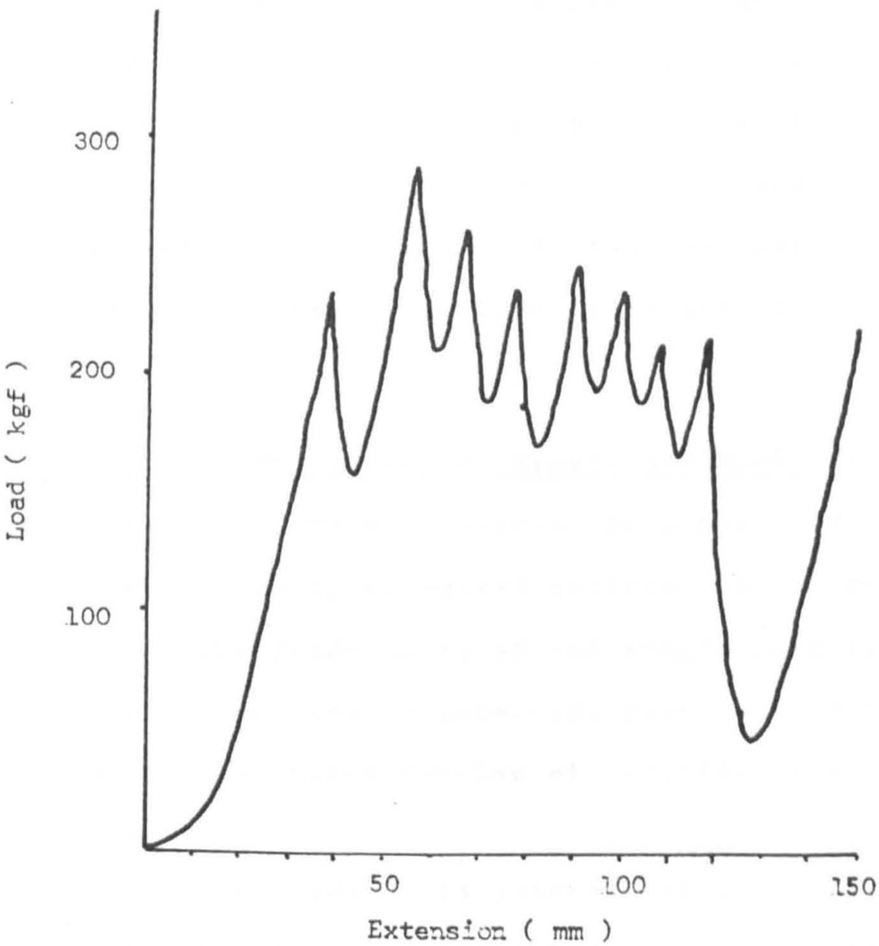


Figure 59: SA15: Design and Static Test

sequence of triggering is assured, with the tack furthest from the fold triggering first and each tack triggering individually. Further, SA14 and SA15 have the same number of tacks, so any difference in performance can be isolated to the difference in configuration.

Studying fig.59, the trigger loads from the static test are between 215 and 290 kgf, thus confirming the consistency of this type of loading configuration. As each tack triggers, the section of web between the former and the next tack becomes part of the gauge length, thereby decreasing the strain and therefore the load. Thus the drop after each trigger is dependent on the tack spacing and the ratio of that spacing to the current gauge length. The difference between the trigger load and the post trigger minimum in load decreases as triggering progresses and the gauge length increases.

7.5.17 Evaluation of Single and Double Fold Construction

Comparing the performance of double fold shock absorbers with single fold, marked differences can be seen between the two. The performance of the single fold is much more reliable and behaves as expected, given the information collected during extensive testing of double-folded joints using 20's thread.

If the loading is examined at a fundamental level, the differences bnetween the two configurations are clear.

7.5.17.1 Single Fold

When load is applied to the two ends of web leading from the fold, the means by which it is held together is the interlacing of the two threads to form a stitch, repeated 42 times in a set pattern to form a bar tack.

In order to trigger, the loop between the two must fail, a direct result of uniaxial tension on the joint. Therefore, assuming constant thread quality, and that the loop is formed between the two layers (see fig.60A), the load at which the loop fails will be constant. Although nominally identical, each bar tack will be formed with slight differences and, within each tack, each stitch will have a slightly different configuration. Thus load distribution will vary producing the differences which are evident in fig.59, for example.

7.5.17.2 Double Fold

In a double fold, the stitch is formed as in fig.60B. Ideally, the loop is positioned in the middle of the joint, that is <u>inside</u> the middle layer of web. In order for the joint to fail, both threads must fail so that the web can assume uniaxial tension. After failure of one thread, one loop is left inserted through one and a half layers of web(see fig.60C). This version of a single fold has to be subsequently loaded in order for complete failure to occur.

Further problems cause the situation to become more complicated. As the joint is loaded, a moment is exerted due to the axes of the tensile load being displaced by a distance equal to 3 thicknesses of web. The folded section is therefore twisted until the stitch loops are in line

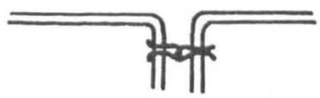


Figure 60A: Single Fold Stitch

Figure 60B: Double Fold Stitch

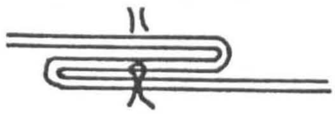


Figure 60C: Partial Failure of Double Fold Stitch

Figure 60D: Double Fold Stitch under tension

Figure 60E: Unevenly Balanced Double Fold Stitch under tension

Figure 61: Comparison of Loop and Snake Design for Shock Absorbers

(assuming there is no bending moment exerted by the web itself to resist this twisting). As in fig.60D, the joint is in shear and tension rather than straight uniaxial tension. Thus the mechanics of stitch failure become more subject to variation.

The position of the loop between needle and bobbin thread with respect to the three layers of web is critical. In an ideal situation, this loop is formed in the middle layer. However, this does not occur in practice, particularly as the sewing machine will be set up to sew double rather than triple layers of tape. If, for example, the loop occurs between the top and middle layers, as shown in fig.60E, the upper thread will fail first, leaving a complete single fold joint to be subsequently loaded. Furthermore, if the loop is positioned inside the web then the thread may tear yarns from the web rather than thread failure occurring. This will depend on the thread weight and the type of web in use. From both a practical and theoretical point of view, it has been established that a single fold joint performs consistently compared to the double fold. The manufacture of a single fold is much simpler than a double fold, and less prone to variations in fold length and alignment of the layers of web on the bar tacker. Subsequent prototypes were therefore restricted to single fold construction.

7.5.18 SA16:Snake Sling, Single Fold, 22 Bar Tacks in 20's

The change back to a snake sling using 20's thread was based on a number of factors. It had become apparent by this stage of the investigation that the device would have little actual effect on the secondary impact force, so aesthetic considerations took precedence over the technical performance of the device. Nevertheless, the maximising of EAC was still an important factor.

Reduction of bulk and weight was of great importance, as there is currently great pressure on equipment manufacturers to do so from the leading exponents of the sport. Light weight equipment enables the latter to push the limits of the sport further, both in gymnastic rock climbing and in the exhausting environment of high altitude mountaineering.

In order to reduce the weight of the device, the length of cut web must be minimised. If a loop and a snake are compared, the snake will use less tape than the loop as its central section is composed of single rather than doubled web. Further, if the construction of the shock absorber is studied, the snake offers a more flexible design when the tacked section is secured to the main body of the sling, as it must be for aesthetic purposes. In the loop, the tacked section is strapped to the main block, forming a solid unbending section. In the snake , although the tacked section is secured to one of the blocks, the sling remains flexible as the other free block can bend and twist. This can be seen in fig.61.

Having selected a snake sling as the basis for the shock absorber, the thread weight is predetermined. In SA15, a single fold in a <u>loop</u> produced a trigger load of between 215 and 290 kgf. Assuming that the load is split evenly between each half of the loop, this implies that the actual load on the tack at the trigger point is between 110 and 150 kgf. In a snake sling/single fold construction, the load on the runner with 40's thread would therfore be 150 kgf, which is too low. If 20's thread is used it would be expected that the trigger load would increase by a factor of 9.6/4.3, the ratios of the quoted thread tensile strengths. Expected trigger loads are therefore between 245 and 335 kgf.

Thus the concept of a snake sling, single-folded, with 20's bar tacks is defined. The base sling was a medium snake sling in tubular web, as this has more warp ends than the standard web and was therefore less prone to web damage. The sling was 90 cm long with the standard 5 cm loop and 10 cm lap sewn double-W block at each end. The free length of single thickness between the web was therefore 60 cm and this was folded in its centre and bar tacks placed all down its length from the fold to as close to the sewn block as possible. Having no information on the effect of bar tack spacing, the tacks were spaced by sliding the double thickness web until the last bar tack was no longer covered by the bar tacker presser foot. This was done in this way to facilitate consistent production rather than for any particular technical purpose. Using this spacing criterion, 22 bar tacks were inserted.

The static tests were conducted on a 5-ton RDP tensile test machine in the Physics Department of Leeds University, as this was the only machine capable of accommadating the large extension of this prototype. The results are shown in fig.62 and are approximately as expected. The individual trigger points of the 22 bar tacks vary between 330 and 245 kgf, apart from the 14th tack. This tack was incomplete due to the bobbin thread on the bar tacker being exhausted, and the tack had approximately half the normal number of stitches. The tack therefore failed at 150 kgf. However, as each tack constituted less than 5% of the EAC, it was felt that the results of the test could be used to evaluate the device's performance.

When the area under the curve is measured, the EAC is found to be 980 J. This is the highest EAC achieved so far, compared to SA11 which has an EAC of 317 J, and the trigger load of SA16 is far more applicable. SA16 is therefore the best device produced so far in terms of technical performance, and is also acceptable from the point of view of weight, bulk, flexibility, extension and user acceptance.

To pursue this avenue further, the effect of bar tack spacing was investigated by manufacturing two further prototypes, one with the spacing halved and one with the spacing doubled. The base length of the slings was held constant so that the actual number of tacks changed in inverse proportion to the spacing.

7.5.19 SA17:Snake Sling, Single Fold, 38 Bar Tacks in 20's

Although the intention was to halve the spacing and therefore double the number of tacks inserted, this was not possible because:-

1. The tacks would have overlapped and

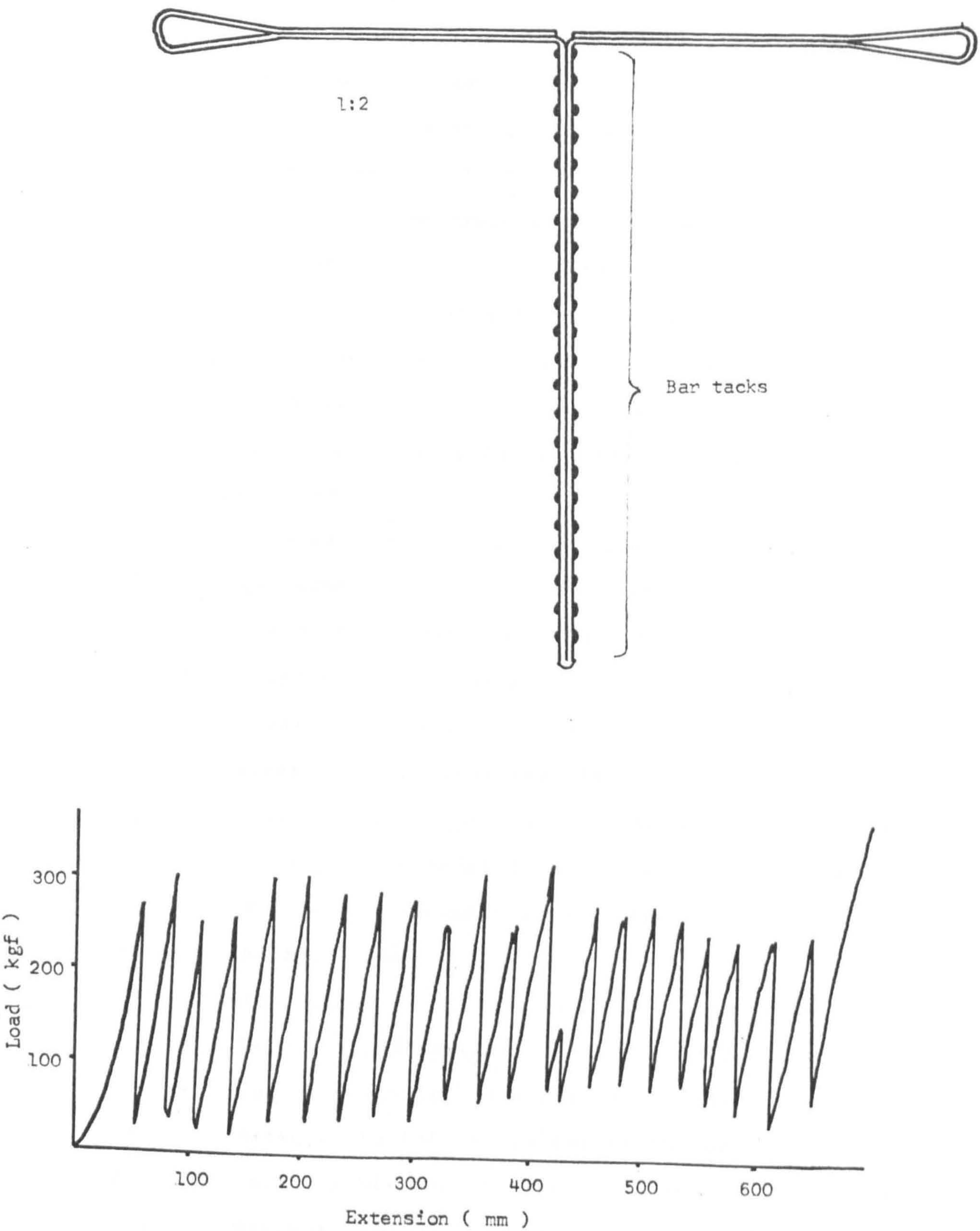


Figure 62: SA16: Design and Static Test

2. Web shrinkage during tacking means that, the more tacks that are inserted, the less length is available.

Examining the result of the static test in fig.63, the trigger loads are in the range of 320 to 260 kgf. Comparing the results of SA16 and SA17, the most noticeable difference is the decreased amount of extension between each trigger. In the latter, the peaks are seperated by a mean of 16 mm compared to 28 mm in SA16. Thus these peak spacings are proportional to, but much greater than, the nominal bar tack spacings quoted above.

The post trigger minimum in the case of SA16 is between 20 and 82 kgf, compared to 66 and 130 kgf for SA17. This is because the amount of material added to the gauge length when the trigger occurs is dependent upon the tack spacing. Thus, the closer the spacing, the less the current gauge length increases, and the less the drop in strain and therefore load. As triggering progresses, the proportion of the gauge length change with respect to the actual gauge length decreases, so the post-trigger drop is reduced and the post trigger minima increased.

The overall effect of closer spacing is to maintain a higher mean load, which results in a higher EAC. SA17 has an EAC of 1160 J, showing the merits of closer bar tack spacing. However, the EAC is limited by the product of the trigger load and the maximum extension. For example, the theoretical maximum EAC of this sling is 3000x0.6=1800 J, which can only be achieved by having a constant load exerted by the device from zero to maximum extension. This ideal is difficult to realise in practice, although devices using ply

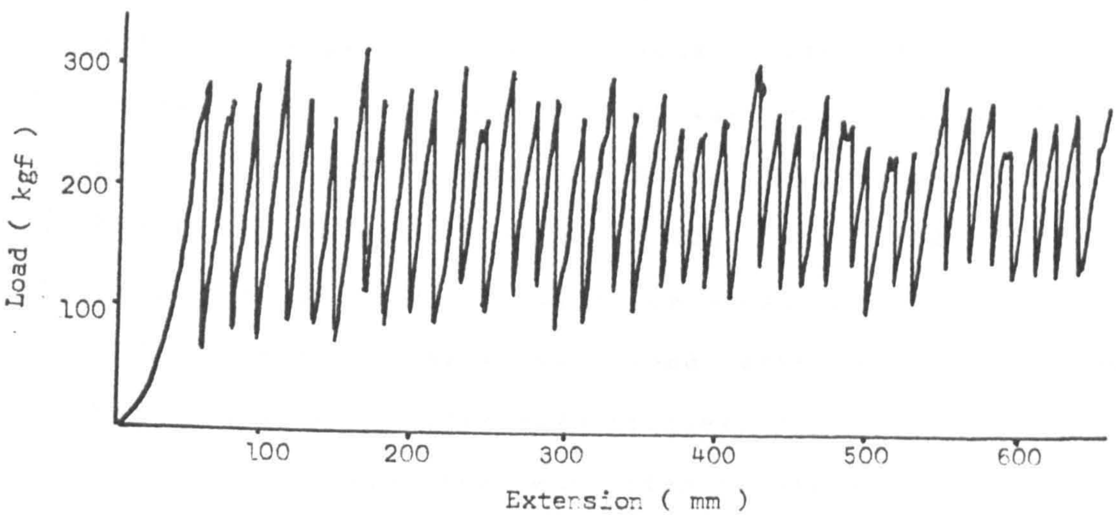


Figure 63: SA17: Static Test

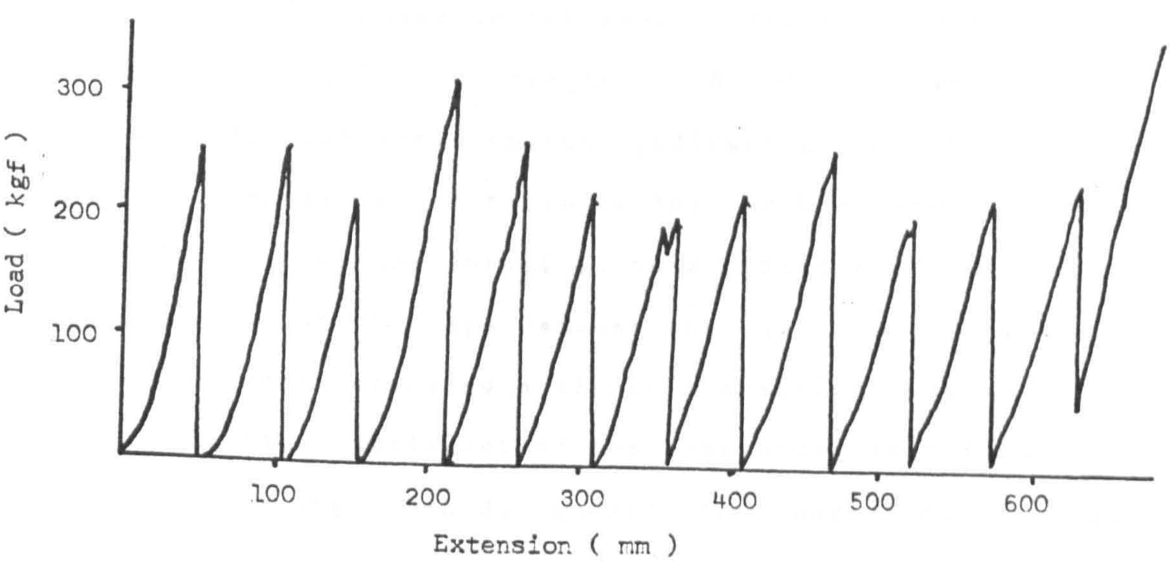


Figure 64: SA18: Static Test

tear webbing[63] are the best solution. Tearweb is, unfortunately, heavy, bulky and expensive and not appropriate in the climbing situation.

7.5.20 SA18:Snake Sling, Single Fold, 12 Bar Tacks in 20's

To obtain a more complete picture of the effect of bar tack spacing, a prototype with a wide spacing of approximately 2 cm was produced, although it was recognised even before testing that there would not be an improvement in EAC. SA18 had 12 bar tacks in its 23 cm fold length and, when statically tested, produced the trace shown in fig.64.

As expected, the trigger load varies between 220 and 335 kgf. Immediatly after each trigger, the load drops to zero. This implies that the extension required to load the bar tacks to the trigger point is less than the extra tape added to the gauge length immediatly after trigger. In the latter stages of the triggering sequence, the extension required increases as the gauge length increases. For the last two tacks to trigger, the post trigger minimum is slightly positive, thereby indicating that the extension is approximately equal to twice the tack spacing. Examination of the trace in detail at this point confirms this:- the extension of the tape between the last two trigger points is 54 mm, which produces a slightly positive load.

The EAC, while not of the same order as the two previous tests, is still 590 J, greater than any other previous prototype.

7.5.21 Discussion of the Effect of a Climbing Shock Absorber

From the test of SA17, it appears that the maximum EAC obtainable is limited to 1100 J, given the other limits of the specification and production criteria. To examine the effect of this in a real situation, it is necessary to study the equation developed:-

$$P = mg + mg\sqrt{1 + \frac{2KH}{mgL} - \frac{2E_A K}{m^2 g^2 L}}$$

To predict the effect of SA17, the following values are assumed:

m=80 kg
g=9.8 m/s
K=13 kN/unit strain
H/L=0.5

P is then computed for varying L, and the results of the calculation are shown in table 9 and fig.65.

At a rope length of less than 4 m at H/L=0.5, the argument of the rooted term is negative. In a practical sense, this means that the EAC of 1100 J exceeds the potential energy involved in the fall, and the load on the runner will be restricted to the trigger load of the device.

Above this point, however, the impact force rises rapidly. The normal practice at rope lengths of less than 5 metres would be to rely on jumping safely to the ground rather than on the security of a dubious runner.

At 6 metres, the load is reduced from 415 to 330 kgf which will produce an impact force at the runner of 660 kgf. In a situation where a runner of 700 kgf was being used, this device would therefore prevent a ground fall. However, once above this rope length (and therefore height above

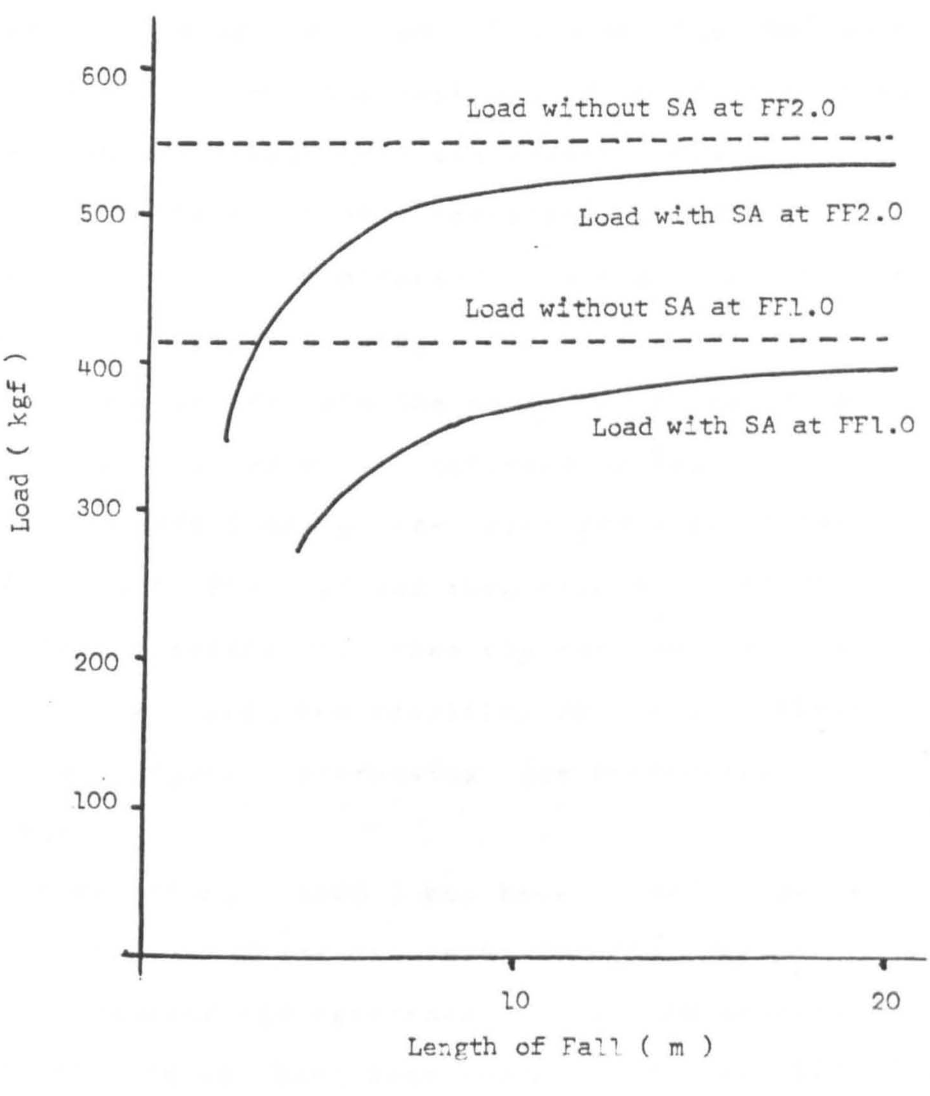


Figure 65: Effect of 1100 J Shock Absorber

ground) the reduction becomes less and less until, at 20 metres, the rope load is 392 kgf giving a runner load of 784 kgf.

This illustrates the limited technical effectiveness of such devices in a climbing situation. As a result, although Troll have the capability to produce the devices, this is done only to retain a reputation as state-of-the-art manufacturers in all fields of tape products, rather than as a profit-making product line. The company have issued a publicity circular based on this work for the user and the retailer[64], but the emphasis of the device is very low in the company's catalogues and advertising.

To achieve comparable reductions at higher rope lengths, the EAC's must be increased. A realistic target might be 300 kgf at 10 m rope length and a fall factor of 0.5. Putting these values into the equation gives an EAC of 2370 J, substantially above that achieved so far.

If an ideal design was produced whereby the force rose instantly to 300 kgf and then held a constant plateau with increasing extension, then the necessary extension would be 0.8 metres, and the resulting fall would therefore be 1.6 metres longer, increasing the possibility of a ground strike.

In practice, 1100 J has been found to be the limit in this study. There are several other designs of climbing shock absorber in existence. The DMM Shocktape has been investigated and has been shown to have an EAC of approximately 220 J. There are other designs on the market which are reviewed in the final discussion of this chapter.

The device developed represents the best from a technical point of view available in the U.K.

7.6 The Development of a Shock Absorber for Industry

As has been shown in the development of the climbing shock absorber, the amounts of energy absorbed by the prototypes are limited. In practice, the amount of energy absorbed equates to a reduction in fall height of 1.4 metres. Generally, this is small when compared to the fall length and the rope length involved in a climbing safety system. The effects of the shock absorber on the secondary impact force are therefore negligible, as it is rare that short falls of high fall factor are experienced.

There is, however, an area where short falls of high fall factor can occur, and that is in industrial applications. Operators working as tree surgeons, steel erectors and steeplejacks will be attached to a secure anchor point by an Industrial Safety Lanyard. This lanyard is fitted with a karabiner at one end which is used to clip the lanyard either to its anchor or to itself, having been wrapped around the anchor point. At the other end the lanyard is attached to the wearer via a buckle which is integrated into a belt or harness system.

Because of their method of use and the environment in which this use takes place, there are a number of factors affecting the design of industrial safety lanyards:-

1. Under normal use the lanyard acts in a static and/or passive way, that is the operator is partially or wholly supported by the lanyard or that the lanyard is

slack and the operator is standing on a part of the working structure such as a tree branch or girder. Under static use the material of the lanyard should therefore be of low elongation under body weight so that the operator can remain in a fixed position.

2. An increased degree of robustness is required compared to the leisure field. The limits on weight and bulk are not so stringent, although the smaller and lighter the safety system is, the greater likelihood it has of acceptance by the workforce. Nevertheless, the device has to be bulky enough to engender confidence.

3. The nature of the application is such that the dimensions of the components and their location with respect to the worker are fixed. In an industrial situation, the anchor is fixed and the operator alters his position with respect to that anchor (compared to climbing where the rope length alters). The fall factor is limited to 2.0 in theory, but in practice should never exceed 1.0 as correct working procedure dictates that the anchor point should be level with or above the point of attachment to the harness/belt.

4. The length of the lanyard is balanced by two conflicting requirements. The longer the length, the greater degree of freedom is given to the worker to move around without changing his anchor point. However, his potential fall distance is increased.

In practice, some of these design criteria are fixed within limits by the British Standard covering Industrial Safety Lanyards, BS 1397. This standard lays down the maximum initial length of the lanyard, the harness or belt to which it should be attached, the maximum load to which the wearer should be subjected under fixed test conditions and the maximum extension of the shock absorber in absorbing the energy of the fall.

There are two categories of lanyard under the standard:-

1. A short lanyard designed for use with a waist belt and
2. A long lanyard for use with a full body harness.

The initial length of the short lanyard must not exceed 1.2 metres, its final length must not exceed 1.85 metres and the impact force must not exceed 5 times gravity. The long lanyard must not exceed 2.0 metres in initial length and 2.65 metres in final length and the maximum impact load must not exceed 10 times gravity.

Comparing these two specifications, the short lanyard is the 'worst case' problem. Although the length of the lanyard is lower, the maximum permitted force is lower. When a low stretch material is required to fulfil the role of a static lanyard, this presents more of a problem than the climbing situation where rope is used.

Rope is not used because of the problems of attaching the rope to any other part of the device. Splicing ropes is very expensive and can only be done with hawser laid rope. Kernmantel rope can only be knotted and these knots can form a weak link in the chain and are susceptible to misuse, far more so than a sewn joint. It was therefore decided that a lanyard made from sewn tape would be desirable.

Troll Safety Equipment were already at this time producing an industrial safety lanyard with a shock absorber[65].

A tear web pack, purchased from an ouside source, was sewn to a karabiner and buckle and the device, while performing impeccably, was expensive and bulky.

It was felt that the work applied to the climbing shock absorber could be used in the development of a device which would equal the performance of the tear web pack. During discussion of SA17, it was noted that an EAC of 1100 J equated to a height reduction of 1.4 metres, which is comparable to the length of the lanyard and therefore of the fall length involved.

The tear web pack measures 20 cm by 5 cm by 2.5 cm whereas any device made from sewn tape will be based on a width of 2.5 cm and could be much shorter and therefore less obtrusive than the tear web pack. Further, the cost of purchasing the packs from an outside source was high compared to the manufacturing cost at the Troll Factory. It was hoped that a device could be produced which would be the technical equal of the existing technology but better in terms of weight, bulk and cost.

7.6.1 Initial Design of an Industrial Safety Lanyard

It was decided that the design of the lanyard should be based on a type of web known as 'Supertape', a standard Troll stock item. All the previous work had been conducted on 25 mm web and 25 mm Supertape was the only web capable of supporting the tearing action of 20's bar tacks without web damage due to its greater bulk and number of warp yarns.

Further, Troll were at this time producing a basic safety lanyard without a shock absorber using 25 mm Supertape. In the interests of product continuity, the design of the prototypes was based on this design.

7.6.2 The Technical Specification and the B.S. Test Method

The technical criteria of the lanyard are laid down by BS1397, and it is therefore necessary to examine the test methods from which these criteria are derived.

The core of the standard is the drop test, equivalent to the simple dynamic test method described in 'Test Methods for Shock Absorbers'. In this test, the belt/harness is attached to a 100 kg anthropomorphic dummy and, via the safety lanyard, to a fixed anchor point. Immediatly prior to the test, the point of attachment to the belt/harness is raised to a height level with the anchor point, thus giving a potential free fall distance equal to the length of the lanyard. The dummy falls for this distance and is then arrested by the shock absorber, during which time the extension of the shock absorber must not exceed 0.65 metres. The deceleration measured at the anchor point must not exceed 5g in the case of the belt and 10g in the harness. Effectively, this deceleration is derived by measuring the force and dividing by the mass of the dummy. Thus, 5g equates to 500 kgf and 10g to 1000 kgf.

This test can be represented by the simple dynamic test developed at Troll with the exception that an anthropomorphic dummy is not available. These dummies are very expensive and it is not practical for Troll to purchase one for in-house testing purposes. The dummy at Troll is a rigid specimen with a mass of 80 kg. Now it has been established in the drop test programme that the harness absorbs little or no energy during the drop. Further, the impact forces produced by a live human specimen are 20-25% lower than those produced by a rigid dummy. Thus, in place of the 100 kg anthropomorphic dummy, an 80 kg dead weight can be used. Although it will not be an exact replica of the test, the conditions are similar enough for in-house testing purposes. Nevertheless, to ensure that the force would not be exceeded in the B.S. test, the limit for the impact force during development was set at 5g and 10g for an 80 kg mass, that is 400 kgf and 800 kgf for the short and long lanyards respectively. The upper limit for the trigger load is therefore fixed at 400 kgf. To ensure that this limit is not exceeded by variations in thread properties, tack structure etc., it was decided to aim for a nominal trigger load of 300 kgf.

7.6.3 The Basic Design

Troll were already producing a basic safety lanyard at the time of this development. Shown in fig.66, this was essentially a loop of web joined together with two double-W 13 row 20 cm blocks in 20's thread. The two halves of the loop were then sewn together, leaving small loops at either end containing the karabiner and the buckle.

These lanyards were tested dynamically to ascertain the base level of impact force before attempting to reduce it using a shock absorber. The results of these tests are shown in table 10. Comparing these to the maximum deceleration allowed, the 1.2 metre is the 'worst case'. The device was therefore designed using the 1.2 metre lanyard as the vehicle for development

The Troll lanyard was a loop of 25 mm Supertape. Folded lengths of tape had to be incorporated into this on the basis of SA14 to 18. However, these could not be copied exactly because the symmetry of the device demands a loop on both sides of the sling. Therefore, if 20's thread were to be used, then each arm of the sling would exert 300 kgf with a resultant trigger load of 600 kgf. The solution to this is to sew up just one half of the sling, or to halve the trigger load of each arm by using 40's bar tacks. The latter option was taken first to avoid the design changes involved in tensioning only one side of the loop.

7.6.4 ISA1:1.2 metre Industrial Safety Lanyard; 2 Parallel Single Fold, 16 Bar tacks in 40's

The first prototype industrial lanyard was therefore a loop sling with an 'arm' on each side, each containing a number of bar tacks in 40's. To set the number of tacks, the previous prototypes using 40's thread, SA14 and SA15, were examined. The static tests of these produced EAC's of 240 and 200 J respectively using eight tacks. In a 1.2 metre fall, the amount of energy involved is 940 J. It was thought that 4 times the number of tacks in SA14 would therefore be required. 16 bar tacks were inserted into each arm to give a total of 32 tacks and the device was tested using the simple dynamic method.

Fig.66 shows that the device does not fulfil its function. The bar tacks can be seen producing a trigger load of 300 to 350 kgf. There is a large secondary impact force of 800 kgf, which means that this device would fail BS 1397. The correlation between SA14, SA15 and this device is not accurate because it is the properties of the tape which determine the EAC rather than the tack properties.

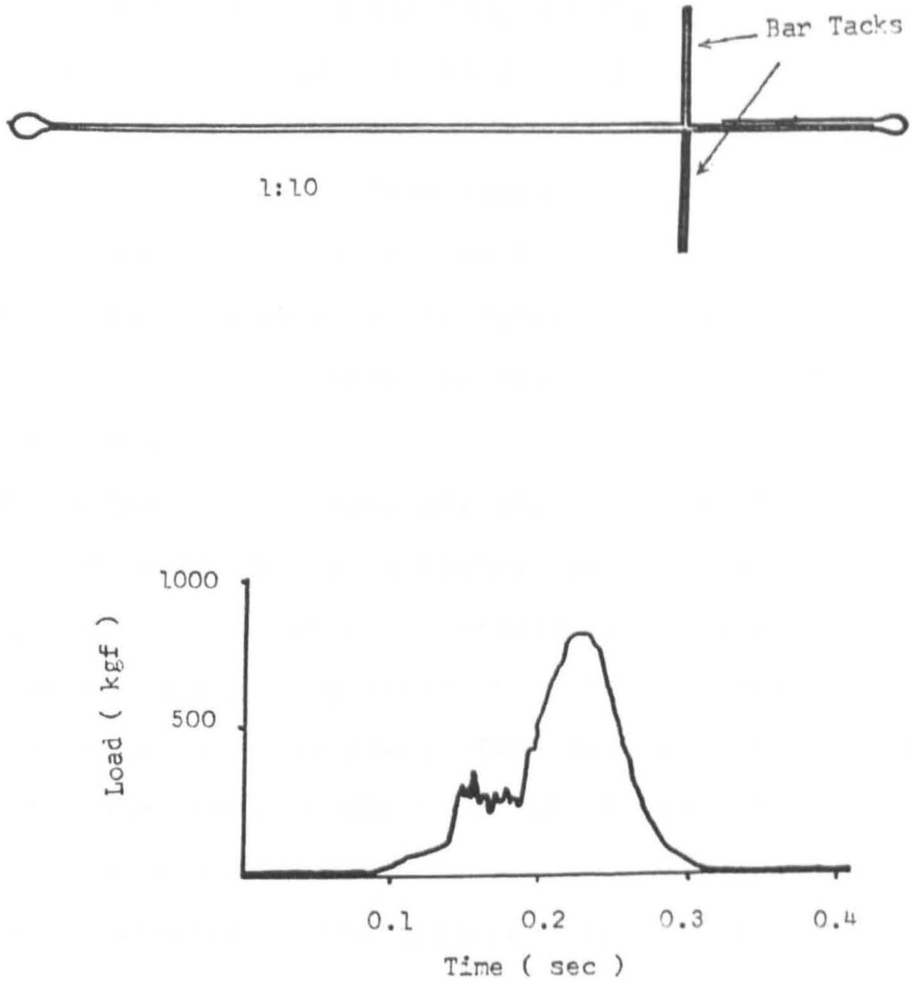


Figure 66: ISA1: Design and Drop Test

7.6.5 ISA2:1.2 metre Industrial Safety Lanyard; 2 Parallel Single Fold, 32 Bar tacks in 40's

Knowing that ISA1 was inadequate but not having any data other than SA14 to base development on, an arbitrary decision was taken to double the number of tacks and observe the effect on the secondary impact force. A static test of ISA2 would also provide further information on the behaviour of the prototype.

The results of this test are shown in fig.67. The trigger load remains at approximately 300 kgf and the EAC is found to be 890 J. In this static test, the sample is so long that the sling is gripped in ordinary rubber faced jaws rather than using 10 mm pins. Thus the measured EAC is lower as the elongation of the tape in the body of the lanyard is not taken into account.

When the results of the dynamic test are studied, it is observed that the secondary impact force is still very large. Peaks of 550 and 630 kgf are seen in two seperate tests after the complete triggering of all 64 tacks implying that not all the potential energy of the fall has been absorbed and that this residual energy causes a large peak in secondary impact.

Considering that the static test predicted an EAC of 890 J out of a total potential energy of 940 J, the correlation between static and dynamic tests with this configuration of sling is not very accurate. The series of tests were continued using simple dynamic methods until the secondary peak was eliminated.

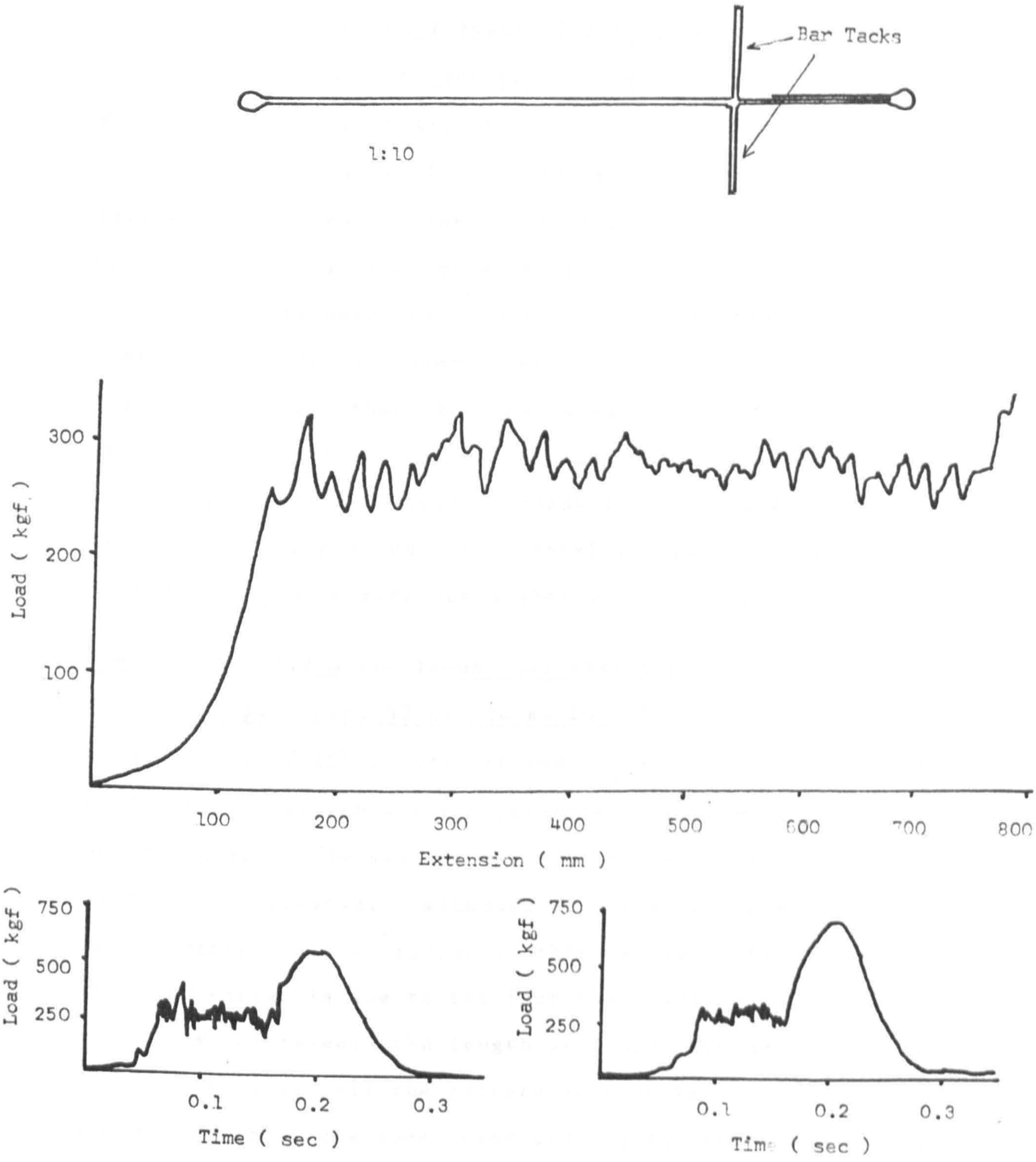


Figure 67: ISA2: Design, Static and Drop Tests

7.6.6 ISA3:1.2 Metre Industrial Safety Lanyard;2 Parallel Single Fold, 40 Bar tacks in 40's

With a total of 80 tacks, it was expected that the size of the secondary peak would be reduced still further. From fig.68, the secondary peak is still present, although it has been reduced to a level equal to the trigger load. There is therefore still potential energy to be absorbed after complete triggering has taken place. Because the tape is of a higher stiffness than the rope used in the climbing situation, any small increase in the residual energy will cause a disproportionately large increase in the secondary impact. It is therefore desirable to totally eliminate this secondary peak by increasing the number of tacks still further.

7.6.7 ISA4:1.2 metre Industrial Safety Lanyard; 2 Parallel Single Fold, 50 Bar Tacks in 40's

With a total of 100 tacks, it was thought that this version would finally absorb all the potential energy without a secondary impact. As seen in fig.69, the secondary impact is virtually eliminated, although it is still present to a small degree. In retrospect, this inability to absorb all the fall energy is due to the fact that, while the number of tacks was increased, the length of loops remained constant. This was because all the prototypes from ISA1 to ISA4 were cut to length at the same time and the significance of tack spacing was not appreciated at the time. The effect of spacing is examined more fully in Appendix B where a computer model is used to duplicate the static test.

It was felt at this stage that the maximum practical number of tacks had been reached, and it was decided to produce

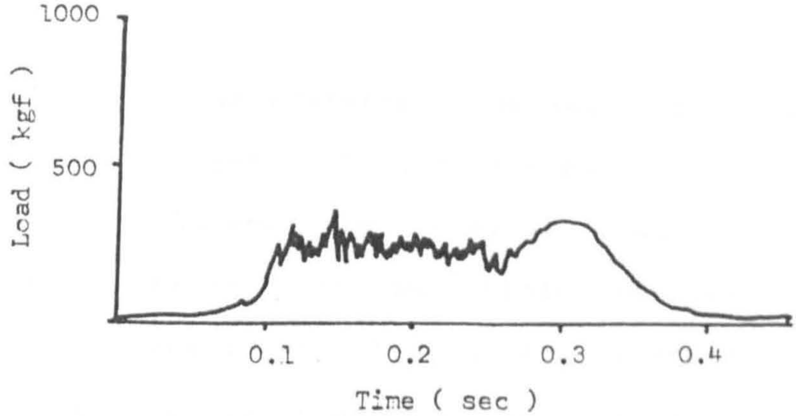


Figure 68: ISA3: Drop Test

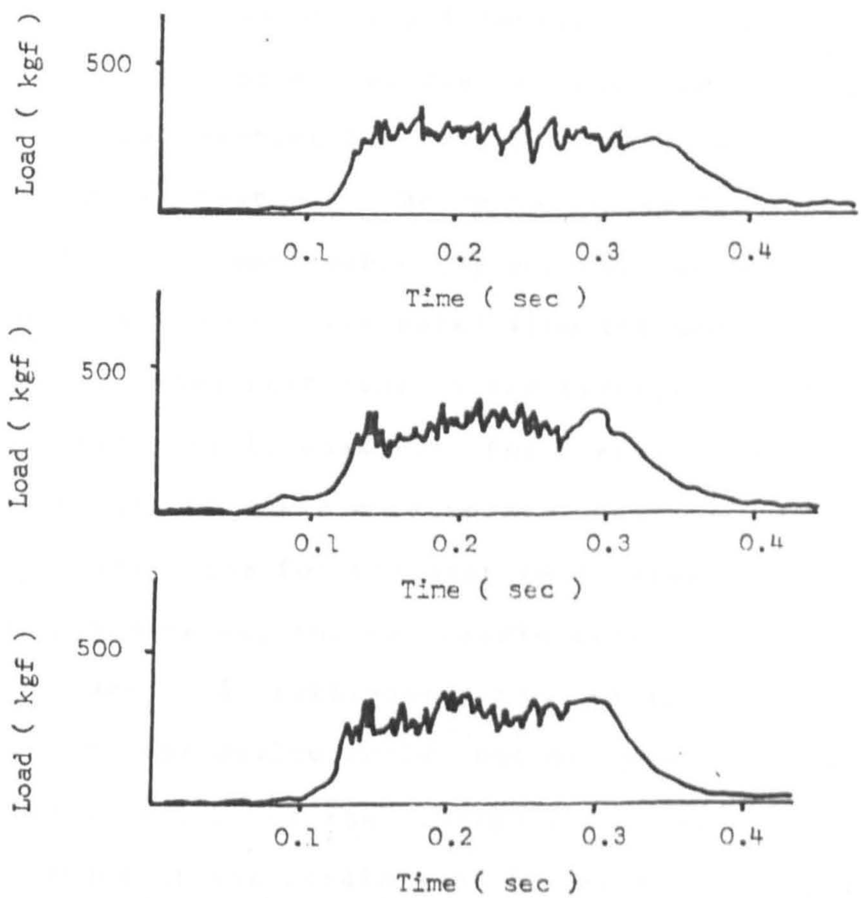


Figure 69: ISA4: Drop Tests

a small number of prototype ISA4 under factory conditions. Up until this point, all the prototypes had been sewn up by the author. However, when ISA4 was manufactured under production conditions, a serious problem emerged.

The bar tacks in 40's thread are inserted using an automatic machine which is operated by two foot pedals: one to lower the presser foot and the other to insert the stitches. The entire process of tack insertion takes about 2 seconds, during which time the needle is inserted approximately 40 times. The friction between the needle and the web causes the needle to heat up. Under normal production where there is a small but noticeable gap between each tack insertion, the heat is rapidly dissipated from the needle.

However, when inserting 50 bar tacks into a straight section of web, it is possible for a skilled machinist to cut the time gap to half a second. Under these conditions, there is less time for the heat to dissipate so that, after every 3 or 4 tacks, the hot needle melts through the thread. The necessity of rethreading the machine this frequently meant that the device could not be produced economically. Extra lubrication of the thread was tried but had little effect since it was needle/web friction rather than needle/thread friction which was causing the problem. A fan blowing cold air over the working area also had no effect.

The only viable solution was to persuade the machinist to leave a small time gap between each bar tack insertion. However, with 100 tacks this increases the manufacturing time significantly. Further, the bar tack machinists are on a piece-work rate, so that the instruction to wait after each tack insertion was difficult to implement.

Therefore, although a viable prototype had been designed, it was impossible to mass produce it. As mentioned in the initial design, the other possibility was to use 20's thread in one arm of the sling. The overheating problem would not occur because the machine used for 20's bar tacking operated at a lower speed and was fed by compressed air with more effective cooling of the needle. Further, the presser foot operated more slowly than that of the 40's machine, so that there was an enforced time gap between each tack insertion. In trials, it was not possible to cause thread melting, even operating at maximum speed. It was not practical to thread this machine with 40's thread since it was being used for more urgent production jobs involving 20's thread, and rethreading such a machine is a time consuming process.

7.6.8 Industrial Safety Lanyard with Shock Absorber in 20's; The Basic Design

FRom SA16 to SA18, it was known that the trigger load of a single fold 20's bar tack is 300 kgf. Thus, to have a device with a trigger load of 300 kgf demands that only one joint be peeled apart, rather than two as in the previous ISA's.

At first sight, a snake sling could be used, as in SA16 to SA18. However, such a sling would fail the ultimate tensile strength requirement of BS 1397 which requires the sling to withstand a load of 2000 kgf after triggering. The quoted strength of a 25mm Supertape snake sling is 1800 kgf [19]. To increase the width of the tape would increase the bulk of the finished device to an unacceptable degree.

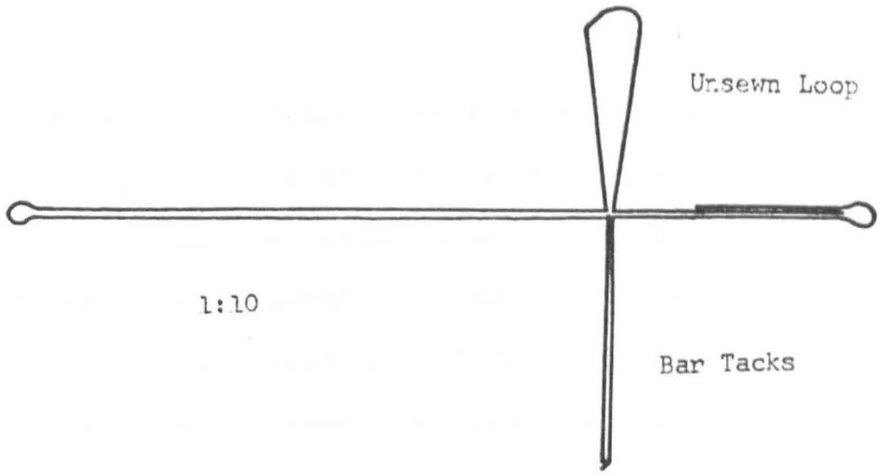
Therefore the solution is to have a loop sling, based on the original design of the lanyard with a spare unloaded arm as shown in fig.70. To ensure that the load does not equalise on each half of the loop, it is essential that the main block is sewn through all 3 layers of tape, and that the two halves of the lanyard are stitched together. This corresponds to the design of the Troll lanyard without any form of incorporated shock absorber.

7.6.9 ISA5:1.2 metre Industrial Safety Lanyard; Single Fold 40 Bar Tacks in 20's with Unsewn Loop

Having established the basic form of the device, the next stage of the design was to establish the precise dimensions and the number of tacks to be inserted. The latter was done by examining previous work carried out on 20's tacks. The potential energy to be absorbed is given by a 100 kg mass falling through 1.2 metres, that is 1170 J. In SA's 16, 17 and 18, each tack absorbs approximately 44, 30 and 49 J respectively. Previous work conducted in America[66] records that a 20's tack absorbs 26.5 J. If, however, 30 J is taken as the lowest, then the number of tacks required is 40.

This takes no account of tack spacing, but the EAC will be maximised by increasing the extension during triggering. Under BS 1397, the maximum allowable extension is 65 cm, so the length of the folded section must be half this, 32.5 cm, with a matching loop on the other side (see fig.70).

In fig.70, the standard Supertape block of two 20 cm 13 row double-W lap joints are sewn with a 5 cm loop at one end, into which a buckle would be sewn in normal manufac-



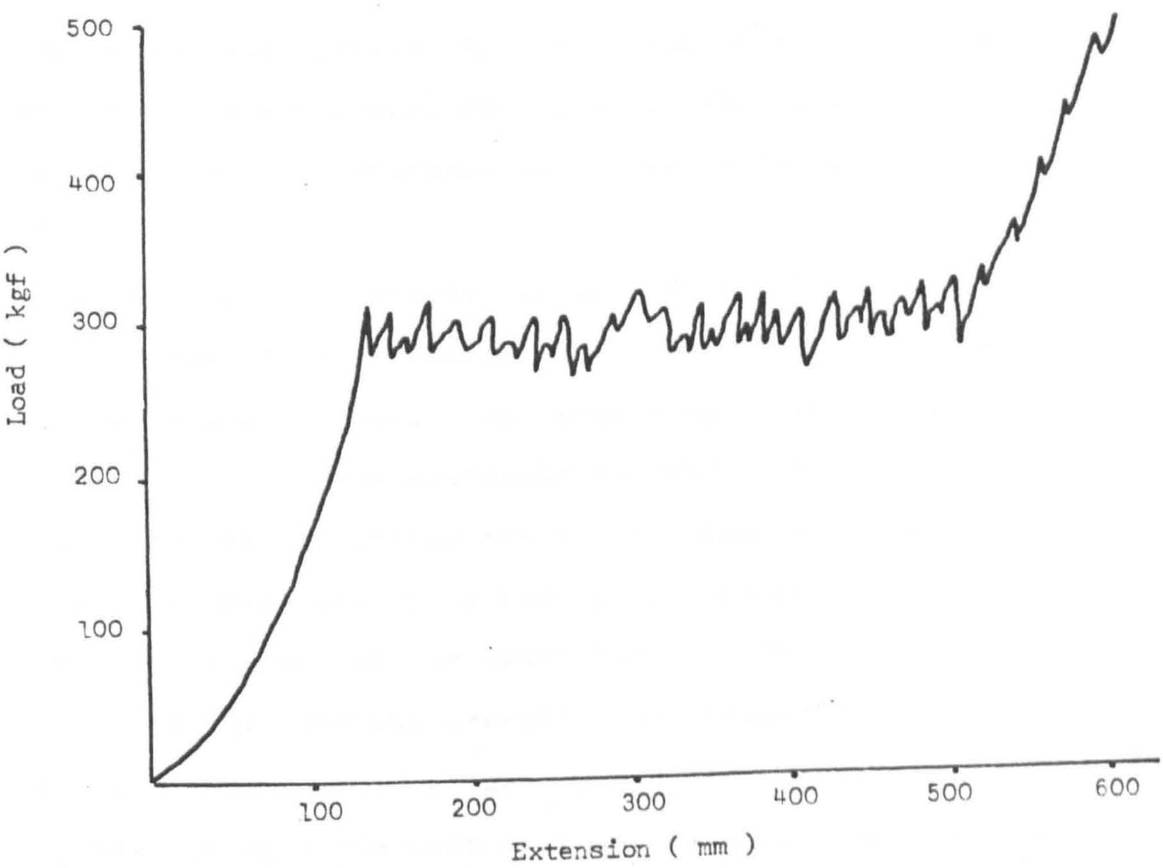


Figure 70: ISA5: Design and Static Test

ture. A 10 cm gap is left after the joint, followed by the two 32.5 cm loops. Thus the two loops will fold flat onto the block and the entire stitched assembly, 32.5 cm long, is covered in heat shrink tubing. The remainder of the sling is stitched together, leaving a 5 cm loop at the end for a karabiner. For the correct function of the device, this stitching must not shear under a load of 300 kgf. The number of stitches in this section is computed by taking its length and multiplying by the stitch density. This gives 360 stitches which will easily hold 300 kgf, as a 9-row 20 cm block has 213 stitches and holds loads far in excess of 300 kgf.

When a static test is conducted on the prototype, two minor flaws become evident, both resulting from the extension of the sewn loop. As tacks trigger individually, more gauge length becomes available so the extension required to cause subsequent triggering becomes greater. At the 30th tack, the extension plus the gauge length becomes equal to the gauge length of the spare loop. Tension is therefore placed on this and the overall load required to cause triggering of the remaining tacks gradually increases. When it reaches 500 kgf, the test self aborts as the maximum load of the cell has been exceeded and five tacks are left untriggered (see fig 70).

When the lengths are measured, it is found that the extension of the device at the end of the test is 67 cm and there is still 10 cm of web stitched together in the remaining tacks. The lengths of web have to be altered, and this new design was designated as ISA6.

7.6.10 ISA6:1.2 metre Industrial Safety Lanyard; Single Fold, 40 Bar tacks with Asymmetric Spare Loop

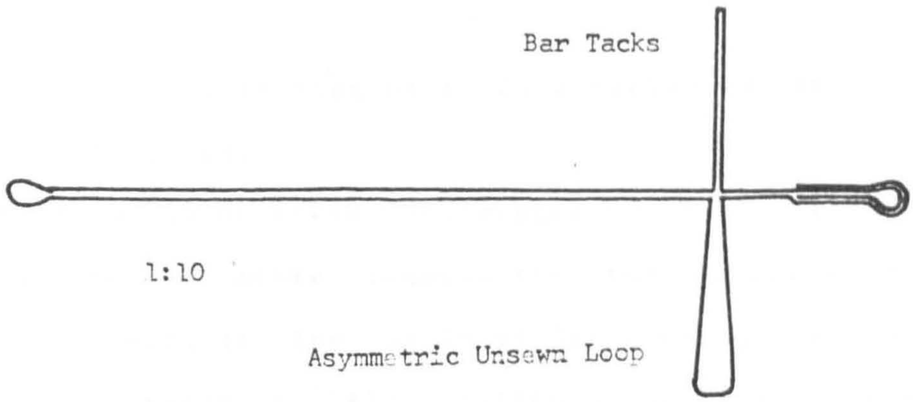
The reduction in extension was calculated from the levels measured in ISA5.

Extension of sample	67 cm
Length of web still stitched	10 cm
Max allowable extension	65 cm
Reduction	12 cm

To ensure that the BS specification would not be exceeded, the reduction was set at 15 cm. To complicate matters further, factory procedure works in dimensions of inches, so an extension of 50 cm corresponds to a doubled length of 10 inches (see fig.71). To ensure that the spare loop did not take any tension, the length of web on that side was increased by 10 cm (4 inches). Thus the stitched loop was 10 inches long and the unstitched loop was set at 12 inches.

In order to increase the working length of the lanyard, the double 20 cm block was moved to form the buckle loop and a 7.5 cm (3 inch) gap was left between that and the folds. Thus the doubled sections could be folded into this gap and the entire assembly covered in heat shrink tubing.

When a full production model of ISA6 was tested in a simple dynamic way, the trace shown in fig.71 was produced, which is in many ways a perfect result. The triggering of the tacks can clearly be seen, with the time intervals between each trigger increasing later in the sequence as the velocity of the falling mass is reduced. The maximum load occurs during mid sequence at 390 kgf. The last trigger is only partial, as is shown by the jagged crest of the final pulse, which is effectively the secondary impact, even though 3 tacks were left intact after the test. Thus all



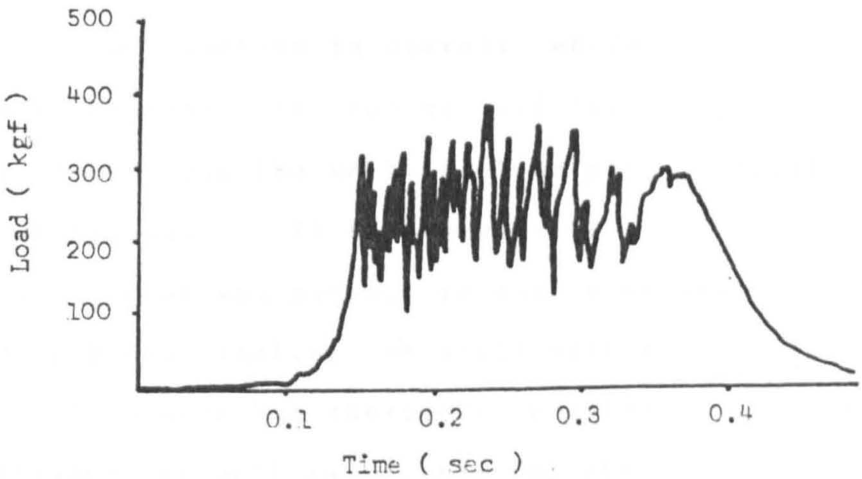


Figure 71: Design and Drop Test

the energy of the falling mass is absorbed by the tearing action of the tacks.

A small batch of these prototypes was then produced in both 1.2 and 2.0 metre lengths for testing according to British Standard at the National Engineering Laboratory. Both lanyards passed[67][68], although the final lengths of the lanyards were still very close to the allowable maximum. The lengths of cut web were therefore reduced by 10 cm to give a 5 cm reduction in overall length.

In conclusion, it can be said that a production device has resulted from the work carried out on impact absorption and bar tacking. If this device is compared with similar ones using tear web packs, it can be readily seen that ISA6 is cheaper and smaller yet still performs to British Standard. This work has therefore resulted in a useful practical advance as well as furthering the knowledge of energy absorption.

7.7 Discussion of Impact Absorption Chapter

The most important point to emerge from this chapter is that any impact absorption device works by absorbing all or part of the potential energy of the fall. This EAC is determined in a static test by the integral of the force and the distance moved through by that force, which is equivalent to the area under the load-extension curve.

The maximum capacity is therefore limited to the product of the maximum permissible force and the maximum permissible extension. This ideal situation would occur if, with increasing extension, the force rose instantly to its maximum permissible level and thereafter maintained a level plateau until maximum extension had been reached (fig.72A). In practice it is not possible to achieve this maximum because instant rise and the maintenance of a plateau are difficult to build into a design. The proximity of these two factors to their ideals will determine the 'efficiency' of the device. The rate of initial rise to maximum force depends on the elasticity of the components of the device before triggering. This factor is less important than the maintenance of the plateau because the extension of the device during subsequent triggering is greater than that during the initial rise.

To maintain the constant level of force through a range of extension is therefore a critical aspect of the design. The methods by which this is achieved are examined below. The most obvious method by which this can be achieved is that of friction, where the load is dependent upon the force perpendicular to the plane of movement. Thus the load will be constant with increasing extension as $F=k.R$ where F=Friction force, k=coefficient of friction and R=Reaction force. However, the manufacturing problems in setting up such a device to give an accurate force preclude it.

In a mechanical damper, the passage of fluid through small orifices in a plunger passing through a cylinder gives a force proportional to the rate of extension. Thus, although the force can be constant with increasing extension, the extension rate must also be constant and, in a dynamic situation, this does not occur.

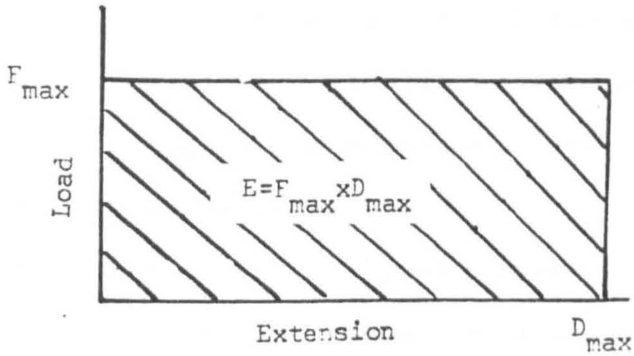


Figure 72A: Idealised Maximum Energy Absorption Capacity

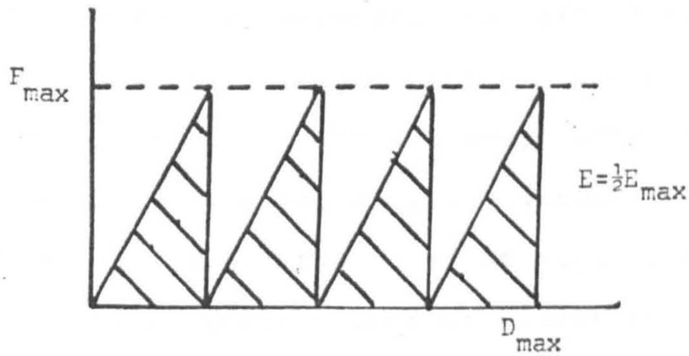


Figure 72B: Repeated Failure Shock Absorber

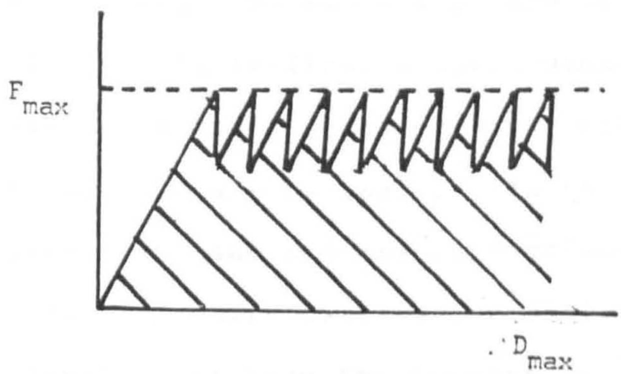


Figure 72C: Improved Repeated Failure Shock Absorber

Maintaining a constant load is difficult to fulfil in practice. If, however, the force which it is possible to place on the device is limited, then practical solutions start to appear. The design ideal consists of loading a component in the device until it fails, which is followed by loading on another until all these components have failed, whereupon a backup comes into operation(fig.72B). This design lends itself readily to manufacture from textiles. In the theoretical version, the efficiency of the device is only 50% as the sawtooth pattern drops to zero after each failure or trigger. If the drop after each trigger can be reduced, then the EAC will be increased (fig.72C).

In a tear web, two plies of high strength web are held together by a large number of binder threads. As the two plies are pulled apart, the binder threads fail, giving the appearance that the two plies are being pulled apart gradually [63]. In reality, a large number of failures are taking place as each binder thread fails and thus the drop after each failure is small. In the industrial field, tear web packs are used and are appropriate to the application of short falls at high fall factor [65].

A development from the concept of tear web has been pursued in the U.S.S.R. [69] where two individual plies of tape have been knitted together by hand. When the plies are placed in tension, the knitted loops fail one by one, giving an exaggurated saw toothed pattern similar to SA16. The major problem with this system is that it is bulky, heavy and expensive. Further, the large gaps between each knitted loop mean that the drop after each trigger is quite large, so efficiency is lost. From the traces in the reference, it can be calculated that an EAC of 675 J will be gained from 225 mm of extension. A production model was shown to the author with a length of 250 mm, which would give an EAC of 1500 J. It would therefore have a larger EAC than any of the prototypes developed, but its size and weight are prohibitive for the U.K. climbing market.

Devices similar to the SA versions developed in this project have been tested in the U.S.A. The only data available is from the manufacturer. The 'Air Voyager' developed by Wild Things of New Hampshire [66] is effectively a single fold snake sling with either 8 or 30 tacks in 20's. Trigger load is set at 320 kgf and EAC is claimed to be 30 J per tack.

The only other shock absorber for climbing purposes based on the principle of tearing stitching is the DMM Shocktape, as replicated in SA9. The device is shown to have an EAC of 220 J and the claim to 'absorb a considerable proportion of the dynamic load' has to be viewed with caution.

Finally, the Forrest Fall Arrest functions by individual lengths of tape and the only data available gives a trigger load of 800 lb. No data is available on the EAC, but it is claimed that the FA 'reduces the force of a fall held by conventional methods by as much as 300 %'[70]. The ambiguity of this claim perhaps sums up the lack of knowledge in this field.

The device developed at Troll has an EAC of 1100 J with a trigger load of 300 kgf and an extension of 0.5 m which gives a possible maximum EAC of 1500 J. In order to improve the EAC, the solution is to reduce the spacing of the tacks. As this cannot be done in practice because the tacks start to overlap, this effect has been investigated using computer prediction. Correlation between experiment and theory is not perfect, but indicates that the EAC is indeed increased with closer tack spacing.

In the final analysis, it is the effect on the peak impact force which is the major concern. Given a limited EAC, the effect of the device on this force will be governed by the other factors involved in the fall arrest system. Specifically, the length of the fall and therefore the amount of potential energy has to be compared to the EAC, together with the other components of the safety system such as the compressibility of the leader, the belayer, and belay plate slippage.

In an industrial situation, the lengths of the falls are short and the device is designed to absorb all the potential energy of the fall.

In a climbing situation, however, the fall lengths are higher and the amount of potential energy is large compared to the EAC's available with current technology. The effect of the shock absorber on the secondary impact force is therefore reduced and their technical value is therefore questionable. As a psychological aid, however, in allaying anxiety when making difficult moves above poor runners, there may be some value to shock absorbers.

In practice, falls do not result in failure of components in the fall arrest system, even in falls of nominally high fall factor. This is because the system is effectively not as stiff as measured in the laboratory environment. The knots, the human body and the action of the belayer all absorb energy. Apart from these involuntary reductions, there are also techniques available to the belayer to reduce the impact force, principally by allowing rope to slip through the belay plate.

To keep the runner force below 500 kgf, the belayer has to let rope slip through at 250 kgf. If potential energy is compared with the energy absorbed in plate slippage, it can be seen that:-

$$F.d = m.g.H$$ where d=slippage, H=fall length

$$\text{so } 250g.d = 80g.H$$ F=slip load, m=mass

So the amount of slippage has to be approximately one third of the fall distance to keep the force to this limit. In practice the belayer will not be able to accurately exert 250 kgf, but if the runners are suspect he would be well advised to allow rope slippage if there was sufficient fall distance available to do so. This is likely to have a far greater effect than any shock absorbing device.

7.8 Conclusion

The technical value of shock absorbers is limited. In an industrial application, where short falls of high fall factor are encountered, the impact force can be reduced significantly, and a lanyard has been designed which conforms to the relevant British Standard.

In a climbing situation, however, there are far larger fall lengths and therefore quantities of energy involved. The rope and ancillary components of the fall arrest system play the major part in the absorption of the energy and the value of the shock absorber lies to a great extent in the field of psychology rather than technology. Despite this, a great deal of research has been conducted in an attempt to produce an effective climbing shock absorber because of external market forces.

Appendix A

THREAD TESTS ALLIED TO SA12

A series of tests were conducted on the threads used in the shock absorbers. These tests were carried out on an Instron 1026 with a 2512-109 load cell with a maximum load capacity of 10 kgf. The method of gripping was by two manually operated jaws measuring 15 by 10 mm as this gave a sufficiently high contact pressure to prevent slippage. Tests were carried out at a variety of gauge lengths and the results are shown in table 11. Failure occurred at either jaw on every occasion. Thus the effect of jaw failure cannot be discounted when considering these results.

However, if they are compared with the quoted strengths, it can be seen that the mean UTS of 40's in natural is 4500 g and 40's orange is 5000 g compared to a quoted strength of 4300 g. 20's in natural has a mean UTS of 9200 g, off-white a UTS of 9650 g and blue a UTS of 9200 g compared to a quoted value of 9600 g. Hence there is a good correlation between these results and the quoted strengths.

Extension was also measured and the elongation and EAC of the threads computed from these. Although elongation levels at failure are similar, the higher UTS of 20's thread means that it absorbs approximately twice the energy of 40's for a given length. EAC for 10 cm of thread yields approximately 0.41 J for 40's and 0.9 J for 20's.

To return to the original point of the test series, that is to establish the validity of the quoted strengths and thus eliminate thread strength as the cause of the discrepancy between SA11 and SA12, it can be said that this has been achieved. The root cause of the differences therefore lies in the following possible areas:-

1. Experimental error due to inconsistent testing methods
2. Some factor other than thread strength playing a part in the strength of the bar tack, which is related to:-
3. The structure of the tack and its loading configuration in particular.

Consistent testing methods have been used in the previous eleven tests. All slings have been loaded in the same way at the same extension rate and the instrumentation has performed satisfactorily and accurately. 1. can therefore be discounted as a source of error. More tests were therefore necessary to check the consistency of the result from SA12.

Appendix B

THEORETICAL PREDICTION OF THE EFFECT OF SPACING ON EAC

The problem of isolating the effect of tack spacing is that there are so many other variables which affect the system. It was therefore decided to use computer prediction to observe the effect of altering various parameters by simulating the static tests of SA's 16 to 18.

The following assumptions were made:-

1. The load and the extension of the web were linearly related and were independent of extension rate.
2. The extension of the stitching in the tack was negligible compared to the extension of the web.
3. Bartacks will fail at an identical load obtained from previous experimental work.

Examining the theory behind these assumptions, it can be seen that the web extends elastically under increasing extension by the simple equation:-

$F = \frac{KX}{L}$ where F=Tension in web, K=Stiffness of the web, X=Extension and L=Gauge length

Incrementing the extension by dX, the new load F′ is given by

$$F' = \frac{K(X+dX)}{L}$$

until F′ exceeds FT, the strength of the tack. At this point, the tack fails and immediatly the gauge length of the web is increased by twice the bar tack spacing in a single fold situation. Thus the load can be calculated by incrementing the extension and increasing the gauge length each time the loads exceeds the tack strength. Further, the EAC is calculated by multiplying the force level at each increment by the extension increment to give an energy increment. The Fortran programme to perform this calculation is shown in Appendix C. The Amdahl system run by the University of Leeds Computing Service was used to implement the programme.

To obtain numerical values for the force, the following initial variables were set up.

1. Initial Gauge Length: Assuming all the single web between each block of the sling is tacked together, the initial gauge length is represented by the two sewn blocks and the loops of the snake, plus a small amount between the block and the first tack. The loops, each of length L are equivalent from an extension point of view to a single length of web, also of length L , which in the case of the snake sling is 7 cm. It is assumed that the blocks are inextensible because the web structure is tightened up by the stitching process, and there is approximately 3 cm between the blocks and the first tack. Thus the initial gauge length is 10 cm.
2. Displacement Increment: The smaller this is, the more accurate the prediction will be. An arbitrary value of 0.1 cm was selected, as the error due to displacement increment is likely to be negligible compared to errors in other variables or the assumptions made.

3. Tack strength: This is one variable which will be altered for differnt runs of the programme. To replicate SA's 16,17 and 18, spacings of 1 cm, 0.6 cm and 1.7 cm were selected.

4. Number of Tacks:As with the tack spacing, the total number of tacks in SA's 16, 17 and 18 were copied, that is 22, 38 and 12 tacks.

5. Stiffness of Web: This was found by conducting a small number of tests to determine the elongation properies of the 25 mm tubular web used in the samples. Three sample lengths were taken and placed in the Instron 1122 tensile test machine. Traces of load against extension were produced and, from points on the curve, the load/unit strain value was calculated and is shown in table 12. It will be noted that the value of K is not constant, particularly in the lower ranges of strain, which denotes a non-linear relationship. Nevertheless, a value of 21.2 kN/unit strain was selected to represent a linear relationship between zero and 300 kgf load.

B.1 Comparison of Experimental and Theoretical Results

The results are shown in graphical form in fig.75 and the table 13 compares the theoretical with the experimental results.

The theoretical extensions are uniformly too low, by between 21% and 31% whereas the EAC's are too high by between 10% and 22%. Further, it can be said that the errors are larger for greater tack spacing. These errors arise from two sources:-

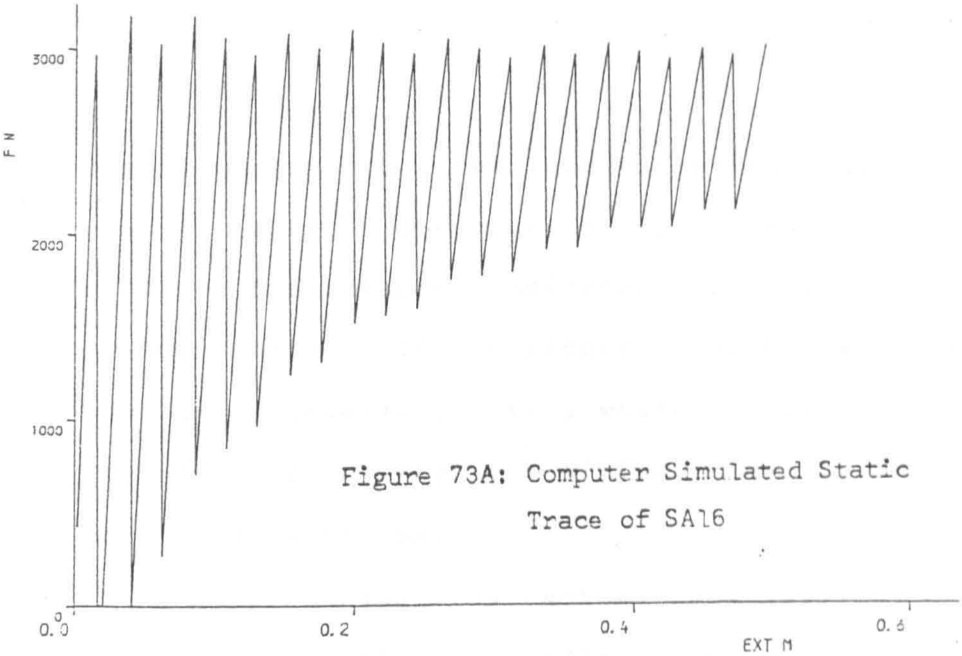


Figure 73A: Computer Simulated Static Trace of SA16

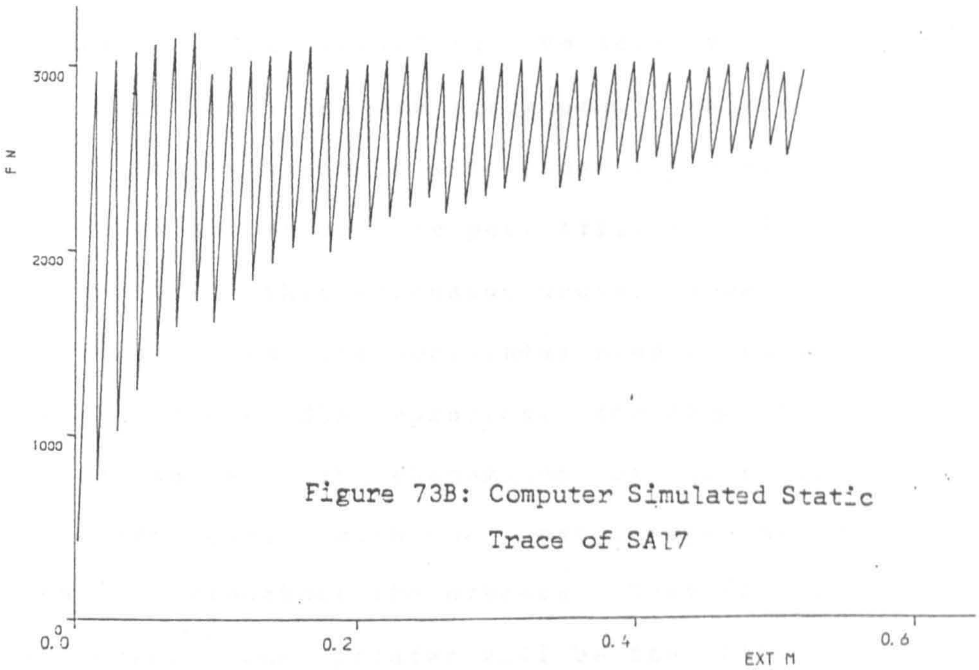


Figure 73B: Computer Simulated Static Trace of SA17

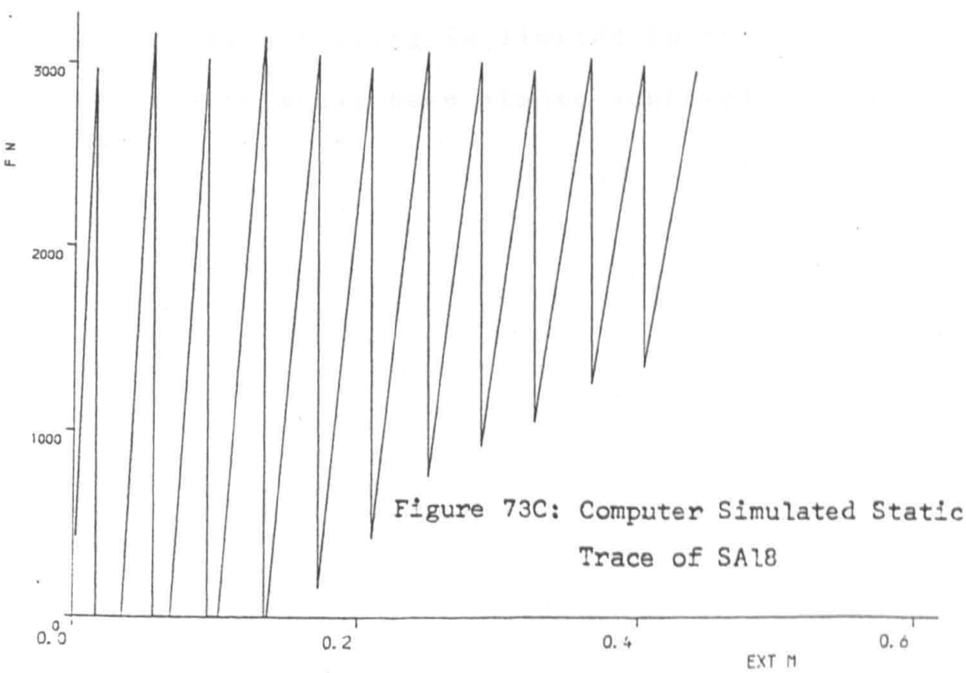


Figure 73C: Computer Simulated Static Trace of SA18

1. The assumption that the load extension property of the web is linear. Observation of the performance curve of SA17, for example, indicates that extension is high at low loads. If the property of the web was more accurately modelled, this would increase extension. Further, the post-trigger minimum would be lower which would reduce the EAC.
2. The assumption that the tack is inextensible. Observation of a static test indicates that this is not the case. The thread in the tack visibly extends and sinks into the web structure, causing the joint to 'grin'. This will also cause the overall displacement to be larger and the post trigger minimum to be lower. Modelling this extension would, however, be far more complex than the non-linear properties of the web.

Despite these discrepancies, the theoretical work does have some value. The phenomenon of the triggering process is clearly seen, with the post-trigger minima gradually increasing throughout the process. Therefore the closer the tack spacing, the greater will be the EAC. In practice, however, the tack spacing is limited to the stitch length of the tack, and this has been almost achieved in SA17.

Appendix C

PROGRAMME FOR THEORETICAL PREDICTION OF SHOCK ABSORBER PERFORMANCE

```
C A SIMPLE PROGRAM TO PREDICT THE RESULTS OF A QUASI-DYNAMIC
C TEST ON A SINGLE FOLD BARTACKED SNAKE SHOCK ABSORBER 10/4/86
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION FD (1000),XD(1000)
      REAL AX(2),AY(2)
C READ IN INITIAL VARIABLES
C INITIAL GAUGE,EXT INCR,TACK UTS,SPACING,NUMBER,TAPE STIFFNESS
      READ (5,*) RL0,X,F1,X1,N,RK
      N1=1
      W=0.0
      I=0
      D=RL0
      RL1=RL0
C SETUP COLUMN HEADERS AT START OF NEW TACK
 10   PRINT *, 'STEP      LOAD       DISPLACEMENT'
      PRINT *, '          NEWTON     METRES      '
C INCREMENT EXTENSION
 20   D=D+X
      X2=D-RL1
      S=X2/RL1
      F=RK*S
      IF(F.LT.0.0)F=0.0
      X3=D-RL0
      I=I+1
      IF(I.GT.1000)GO TO 500
      FD(I)=F
      XD(I)=X3
      DW=F*X
      W=W+DW
      WRITE (6,200) I,FD(I),XD(I)
      IF (F.LT.F1) GO TO 20
      PRINT *, ' WARNING, TACK NUMBER ', N1,' JUST FAILED '
      RL1=RL1+(2*X1)
      N1=N1+1
      IF (N1.LE.N) GO TO 10
      IMAX=I
      XMAX=X3
      PRINT *, ' PROGRAM ABOUT TO HALT, N1=',N1,'  N=',N
      PRINT *, ' FINAL DISPLACEMENT=',X3
      PRINT *, ' APPROX ( VERY APPROX ) ENERGY ABSORBED =',  W
C END OF ITERATIVE CALCULATION
C
C START OF GRAPH PLOT CALLS
      AX(1)=0.0
      AX(2)=1.0
      AY(1)=0.0
      AY(2)=5000.0
      CALL JBAXES(AX,2,30.0,'EXT M',5,
     1           AY,2,20.0,'F N',3           )
C     CALL NEWPLT (0.0,0.5,25.0,0.0,5000.0,25.0 )
      DO 300 I=1,IMAX
      CALL JOINPT (XD(I),FD(I))
 300  CONTINUE
      CALL ENDPLT
      GO TO 400
 500  PRINT *, 'WARNING STEP TOTAL EXCEEDING ARRAY SIZE'
      PRINT *, 'PREMATURE HALT'
 400  STOP
 100  FORMAT (4D10.2,I13,D10.2)
 200  FORMAT (I3,F10.0,F10.3)
      END
```

Appendix D

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Appendix E

TABLES

TABLE 1

Particle Size Analysis of Abrasion Sediment

Size Interval	Mass (g)	% by mass
d > 2 mm	0.1	0.21
2 mm > d > 1 mm	0.4	0.34
1 mm > d > 500 μm	1.2	2.52
500 μm > d > 250 μm	4.4	9.24
250 μm > d > 125 μm	20.9	43.91
125 μm > d > 63 μm	13.4	28.15
63 μm > d	7.2	15.3
	47.6	

TABLE 2 Results of Tumbler Tests
Ultimate Tensile Strengths (kgf) and Percentage Loss

Abrasion Time	50 mm Seat Belt No P.U.	50 mm Seat Belt Soft P.U.	50 mm Seat Belt Medium P.U.	50 mm JC - HS	50 mm WW - 11	50 mm Polyester	50 mm H.T. Polypropylene Olympic WW	25 mm Nylon Coreweb
Control	2350 -0%	2280 -0	2580 -0	3170 -0	3380 -0	3750 -0	2000	2100 -0
2 hours	1825 -28	1730 -24	1620 -37	1955 -38	2070 -39			
4 hours	1775 -30	1665 -27	1725 -33	2030 -36	2170 -36			
6 hours	1545 -39	1370 -40	1475 -43	1670 -47	1890 -44			
8 hours	1730 -26	1750 -23	1900 -26	1870 -41	2120 -37			
24 hours	1530 -35	1550 -32	1650 -36	1885 -40	1920 -43			
48 hours	1760 -30	1710 -25	1605 -38	1710 -46	2290 -32			
104 hours	1555 -38	1610 -29	1650 -36	1685 -47	1985 -41			
200 hours						1830 -51		
300 hours		1030 -54	1355 -47	1255 -60	1430 -58		1100 -45	950 -55
400 hours	1375 -46	1260 -45	990 -61	1305 -59	1465 -57			
500 hours	860 -66	1080 -52	945 -63	1165 -63	1055 -69			
600 hours	880 -65	645 -72	610 -76	1185 -62	1345 -60			
Clearwater 104 hours	2285 -2	2467 +8	2500 -3	2880 -9	3205 -5			
Wet					2800 -17		2100 +5	1925 -8
200 hours Wet						1900 -49		

TABLE 3

Ultimate Tensile Strength of Sewn Slings after Abrasion by a Hexagonal Steel Bar

No. of Cycles of Abrasion	Strength of Standard Joint (KN)	Comments	Strength of Bar Tack Joint (KN)	Comments
0	24.5	From Troll Tape Booklet	23.5 Tape Failure	Sample (8). Brand new sling. Failure at endge of joint
10,160	17.97 Joint Failure	Sample (7). Air-coded sample. Tape is worn but not yet at retirement stage		
10,200	19.4 Joint Failure	Sample (1). Nearing retirement	18.72 Joint Failure	Sample (5). Furry stitching, but not yet due for retirement
21,60			12.55 Joint Failure	Sample (2). Badly worn, definite retirement, 98 stitches left
29,300	16.8 Joint Failure	Sample (3) would be considering retirement		
30,000			7.67 Joint Failure	Sample (6). Badly worn, definite retirement, 69 stitches left
31,000	18.5 Tape	Sample (4). Surface of joint polished hard by deposit of oil and aluminium		
There are a further two standard samples, as below:-				
10,200	17.48 Joint Failure	Sample (9), low result expected, as load was taken on unsewn part		
25,000	16.7 Joint Failure	Sample (10). Invalid after 17,500 cycles		

TABLE 4

Harness Comfort Results

Harness Type	Subjects														
	A			B			C			D			E		
	I	E	C	I	E	C	I	E	C	I	E	C	I	E	C
1		8	6		8	7		9	7		9	7		8	7
2		6	5½		7	7		6	6		8	8		6	6
3		7	6½					8	8						7½
4		5½	7½		5	6		6	7		6	7		5½	7
5		5	5		8	8½		6½	7½					7½	9
6		6½	4					7½	6½					7	4½
7	8	7	6				8	8	8				6	7	7
8	6	6	4				8	8	4½				7	7	3
9		7	8		6	8		7½	6½					8	8
10	6	6	2				3	3	0				3	7	2
11	5	6	6½				7	8	9				7	7	7
12		7	7					9	8					7	9½

TABLE 5

Drop Test Results

Test Series	Pre-tensioning (kgf)	Rope Length (m)	Fall Length (m)	Fall Factor	Weight Configuration and other Notes on Test Method	Peak Impact Forces (kgf)
1.1	800	0.9	0.9	1.0	Initial tests: 80 kg Barrel	630
1.2						650
1.3						650
2.1	800	0.9	1.8	2.0	As 1, maximum fall factor tests	850
2.2						1000
2.3						1000
3.1	1000	2.0	1.9	0.5	Barrel	350
3.2						300
3.3						350
3.4	500					250
3.5						350
3.6						300
4.1	1000	2.0	2.0	1.0	As 1, but longer rope and fall lengths	1175
4.2						1340
4.3						1300
5.1	1000	2.0	4.0	2.0	As 3, but at fall factor 2.0	1175
5.2						1340
5.3						1300
6.1	1000	0.5	0.5	1.0	Vertically aligned drop	625
6.2						640
6.3						650
6.4		1.0	1.0	1.0		700
6.5						725
6.6						725
6.7		1.7	1.7	1.0		775
6.8						790
6.9						800
7.1	1000	1.1	1.1	1.0	Identical pre-treatment of rope samples	735
7.2						740
7.3						745

Continued ....

TABLE 5 (Continued ...)

Test Series	Pre-tensioning (kgf)	Rope Length (m)	Fall Length (m)	Fall Factor	Weight Configuration and other Notes on Test Method	Peak Impact Forces (kgf)
7.4		2.0	2.0	1.0		855
7.5						860
7.6						850
8.1	800	1.0	1.0	1.0	Harness (Mk VI/Alpinist) instead of barrel	650
8.2						700
8.3						700
9.1	200	1.0	1.0	1.0		545
9.2	500	1.0	1.0	1.0		545
9.3						650
9.4						630
9.5	80	1.0	2.0	2.0	Used	800
9.6						800
9.7						800
9.8						800
10.1	1000	1.0	1.0	1.0	Human subject ballasted to 80 kg, wearing sit and chest harness	535
10.2						550
10.3						560
10.4	1000	1.0	2.0	2.0		725
10.5						750
10.6						775
10.7	1000	1.0	2.0	2.0	Control test using barrel, same rope as 9.4 - 9.6.	1000
10.8						1000
10.9						1000

TABLE 6

Peak Impact Force in Rope vs. Fall Factor

Fall Factor	Peak Impact Forces Recorded (kgf)	Peak Impact (kgf)
0.5	200 - 370	300
1.0	630 - 850	740
1.78		
2.0	850 - 1340	1100

TABLE 7

Pretension (kgf)	Force at Fall Factor 1.0 (kgf)	Force at Fall Factor 2.0 (kgf)
80	545	
500	545	
800	630	850
1000	700	1175

TABLE 8

SA9 Results

Samples	A	B	C	D
Trigger load 1 (kgf)	225	175	N/A	175
Time Interval (secs)	.035	.035		.05
Trigger load 2	225	200	200	200
Time Interval	.035	.040	.040	.04
Trigger load 3	250	200	200	175
Time Interval	.030	.040	.040	.04
Trigger load 4	200	200	200	200
Time Interval	.030	.035	.040	.07
Trigger load 5	175	200	200	225
Time Interval	.025	.035	.035	
Trigger load 6	175	225	150	N/A
Mean Trigger load	200	200	200	200
Mean Time Interval	.030	.035	.040	.05
Total Time	.155	.185	.155	.020
Peak Secondary Load (kgf)	475	500	475	475

TABLE 9

Effect of 1100 J Shock Absorber on Peak Impact Force

Fall Length (m)	Peak Impact Force at FF 0.5 (kgf)	Peak Impact Force at FF 1.0 (kgf)
1	-	-
2	-	344
3	-	425
4	275	462
5	310	479
6	330	491
7	344	499
8	354	506
9	362	510
10	368	515
12	376	520
14	382	524
16	386	527
18	390	529
20	392	531
oo	415	547

TABLE 10

Control Tests of Industrial Shock Absorbers

Sling Length (m)	Impact Force (kgf) for 3 separate Tests			Mean (kgf)
1.2	1050	1100	1100	1100
2.0	1150	1200	1100	1150

TABLE 11

Results of Static Tests on Bonded Nylon Thread

Thread	Gauge Length (cm)	U.T.S (gf)	Extension (cm)	Elongation (%)	Energy (J)	Energy (J/10 cm)
40s natural	10	4750	1.8	18	.404	.404
40s orange	10	5000	2.1	21	.446	.446
20s natural	10	9000	2.5	25	.936	.936
20s off-white	10	9750	2.5	25	1.040	1.040
20s blue	10	9000	2.2	22	.940	.940
40s natural	20	4600	3.1	15	.700	.350
40s orange	20	5000	3.9	20	.850	.425
20s natural	20	9200	4.0	20	1.480	.740
20s off-white	20	9900	4.6	23	2.000	1.000
20s blue	20	9300	4.3	22	1.680	0.840
40s natural	30	4100	3.8	13	1.702	.567
40s orange	30	5000	6.0	20	1.500	.500
20s natural	30	9400	6.0	20	1.820	.940
20s off-white	30	9300	6.0	20	2.790	.930
20s blue	30	9200	6.0	20	2.760	.920

TABLE 12

Tests to give Value of K, Tape Stiffness

Sample Gauge Length (mm)	Extension (mm)	Strain	Load (N)	Load/Unit Strain (N/unit strain)
100	2	.02	147	7530
	4	.04	441	11025
	6	.06	980	16333
	8	.08	1568	19666
	10	.10	2058	20580
	12	.12	2499	20825
	14	.14	2989	21350
	16	.16	3528	22050
	18	.18	4018	22322
	20	.20	4508	22540
200	10	.05	833	16660
	20	.10	2156	21560
	30	.15	3381	22540
300	10	.033	294	8820
	20	.066	1274	19110
	30	.100	2254	22540
	40	.133	3234	24255
	50	.166	4508	27049

Tape Stiffnesses at Varying Strain Rates

Load (kgf)	Displacement (m)	Gauge Length (m)	Strain Rate (% per min)	K (N/unit strain)
400	0.18	0.1	1000	21777
400	0.18	0.1	100	21777
300	0.15	0.1	10	19600
400	0.18	0.1	10	21777
			$\overline{K}$ =	21232

TABLE 13

Comparison of Theoretical and Experimental Results

Sample	No. of Tacks	Spacing (cm)	Maximum Extension (m)			Energy Absorption (J)		
			Exp.	Theory	% Diff.	Exp.	Theory	% Diff.
SA16	22	1.0	.660	0.494	-25%	980	1079	+10%
SA17	38	0.6	.660	0.520	-21%	1160	1317	+13%
SA18	12	1.7	.640	0.440	-31%	590	722	+22%