

A new method of termination for heavy-duty synthetic fibre ropes

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THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

2004

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ABSTRACT

Termination of heavy-duty synthetic fibre ropes has long been an issue of concern in marine environments. Recent serious rope accidents and new requirements for lighter ropes with better performance in mooring lines have encouraged industry to look for new methods for increasing line performance using existing ropes. One way of increasing rope performance is to use efficient methods for rope termination. This is why the main objective of this study has been to investigate a new method for rope termination.

Rope failure usually happens inside or very close to termination due to high stress concentration areas. The new method, "The Vaseghi Stress Relief Socket", has been proposed to improve the high stress concentration areas inside sockets and move failure points along the rope. The new method has increased the tensile performance of existing ropes up to 13%. It should also be added that the ropes in this study are mainly used in marine environments for mooring oil platforms.

Considering the results of the tensile and cycling tests, The Vaseghi Stress Relief Socket, proved a great potential for replacement of existing methods of termination e.g. the splice. It should also be noted that the reproduction of the socket termination is more consistent than that of other methods of termination.

Tensile properties of ropes using 'The Vaseghi Stress Relief Socket' were initially a matter of concern, for rope termination is the most important feature of ropes. In fact, if there is a termination failure in tensile tests, the rope will not be considered efficient for mooring purpose even though its other performances are excellent. Load cycling was the second property that was considered. Acoustic Emission monitoring was performed to find out the relation between the load-extension behaviour of the rope using The Vaseghi stress Relief socket and the AE signals. Finally, the finite element modelling of sockets helped to investigate the stress concentration areas in the socket to optimise the amount of the reinforcing material and identify the weak point areas in the socket, which could lead to further research studies for new designs.

Acknowledgement

I would like to thank all those who made this study possible. I thank my first supervisor, Dr. Hossain Saidpour, who helped me start this project. I would like to thank JK Yeardley and all other colleagues in Bridon Marine who helped to collect experimental data for this project. My special thanks go to Professor Terry Sheppard who accepted to continue this project to the end with a great deal of support. I would also like to thank Dr. M Hasrati for proofreading the thesis. And finally I would like to thank my wife and my family for their patience and support throughout this time.

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Chapter 1: Introduction

Strength of mooring lines depends on its rope strength. Termination of the rope has a direct effect on load bearing capability of the line. It is always fascinating to end-users to increase the performance of ropes in marine environments. Moreover, interest on different rope terminations has grown because of the high number of serious accidents in recent years. Termination seems to be the crucial part of a marine line which affects the performance of ropes.

Traditionally rope is terminated by splice. Splice is a method that the rope tail is buried in its own body to make a loop as a termination. The splice is known to be the most often used methods of termination in marine environments. The popularity of the splice could be because of lack of information, difficulties and costs of testing ropes through other methods. In addition, it takes a relatively long time to accept a new method because of the high risks of these methods and lack of industrial confidence. This is why there have been very few studies to compare different termination methods.

Hand splicing by itself is difficult to perform, time consuming and very labour dependent. Care in preparation and practice is a key element in producing a good splice termination. Some investigations have suggested that improper splicing methods have caused accelerated rope fatigue (Backer *et al*, 1981). Dunn (1995) suggested that malpractice in use is taken to be yet another problem associated with rope failure.

Socket termination is a method that rope tail is trapped inside a conical shape metal device that stops rope movement. There have been some efforts to use the socket termination instead of the splice over the last three decades. The major problem in the socket termination is a high stress concentration area in ropes near the socket that leads to premature failure of the rope inside the socket. The effects of termination on the breaking point and higher stress concentration areas, followed by premature failure of ropes, have been long known as a problem (Zhang *et al*, 1995). In most of

the previous experiments, sockets failed as a result of the decreasing rope strength in or near the termination (Stange *et al*, 1970 & Flory *et al*, 1995).

In order to overcome the problems associated with the previous methods of rope termination, splice and socket, a new method of termination (Vaseghi, 2000), *The Vaseghi Stress Relief Socket*, for large diameter synthetic ropes, has been innovated, which improves high stress concentration areas in ropes. It is an attempt to prevent premature rope failure inside or near the socket as the termination on a rope is often the site of rope failure except in cases where the rope suffers severe abrasion or bending stresses. The new socket has been designed to accommodate extra material to release stress concentration in the rope.

Based on the Vaseghi Stress Relief Socket, extra material with some arrangement is inserted in the rope tail before it is terminated. Arrangement of the rope tails consists of inserting extra rope material inside sample tail and tapering it right to the end of extra part. The socket is inserted inside the reinforced rope, and heatshrink tubing is covered on the rope. The whole assembly is pulled inside the socket and resin is added on the top to trap any movement of the fibres inside the socket.

As extra material is applied in this method, the effect of labour and care in preparation is eliminated. Also the resin helps to stop any fibre movement and keep the sub-rope together. Heatshrink tubing reduces rope contact area with the socket wall and results in lower abrasion inside the socket. This helps fibres not to break in the socket.

The present thesis is the result of experiments carried out by the author to test the efficiency of the Vaseghi Stress Relief Socket. The thesis consists of four other chapters as follows:

Chapter two covers a review of the various types of fibres & ropes available in marine environments, factors governing rope properties, mechanical performance predictions of rope, different rope testing methods, and rope failure mechanisms.

Chapter three looks specifically at the theory of rope termination and is an insight into existing terminations and their problems. It also looks at the design basis and relative patents for rope termination.

Chapter four specifies the equipment, material specification, and rope structures, which have been used in this study.

Chapter five presents the results and a discussion of the tests carried out to achieve the goals of this study. It discusses the merits of The Vaseghi Stress Relief Socket in achieving a better tensile performance compared with existing terminations. Tensile and fatigue cycling properties of ropes using the new method of rope termination is the first objective of this chapter. Finally, the acoustic emission results and the finite element method for new rope termination are discussed.

Chapter 2: Literature Review

Working on termination without considering the rope behaviour and structure is a difficult task. Perhaps each termination is designed for a special rope. There are some unique features in each rope that must be considered when designing a termination.

This chapter includes a review of various types of fibres & ropes available in marine environments, factors governing rope properties, mechanical performance predictions of rope, different rope testing methods, and rope failure mechanisms.

2.1 Rope

2.1.1 Introduction

A ROPE is a complex material structure consisting of twisted elements such as filaments, yarns and strands in various constructions. Rope is a flexible line made of fibres or wires twisted or braided together for tensile strength. Ropes may be made of natural fibres, such as cotton, hemp, jute, flax, manila, or sisal; of synthetic filaments, such as nylon, polyester, or glass fibres; or of metallic wire (Encarta, 2002). Himmelfarb (1961) states, "*A rope is a long, compact, flexible assembly of fibres serving primarily to transmit tensile force or energy*".

Ropes are in common use in applications ranging from ship mooring, vehicular towing, hoisting, and mountaineering to a wide range of rescue operations.

The requirements for any synthetic fibre rope are:

- The greatest possible tensile strength
- Flexibility, knotability, ease of handling and gripability
- A compact cross section which retains its form during use
- Elastic behaviour, dampening of shock loads, (absorption of mechanical energy)
- Stable load elongation properties in use
- Light weight
- Fatigue resistance

- Abrasion and cutting resistance
- Resistance to chemicals and corrosion, temperature stability
- Ease of splicing or attaching reliable termination
- Low cost
- Torque balanced or torque free construction

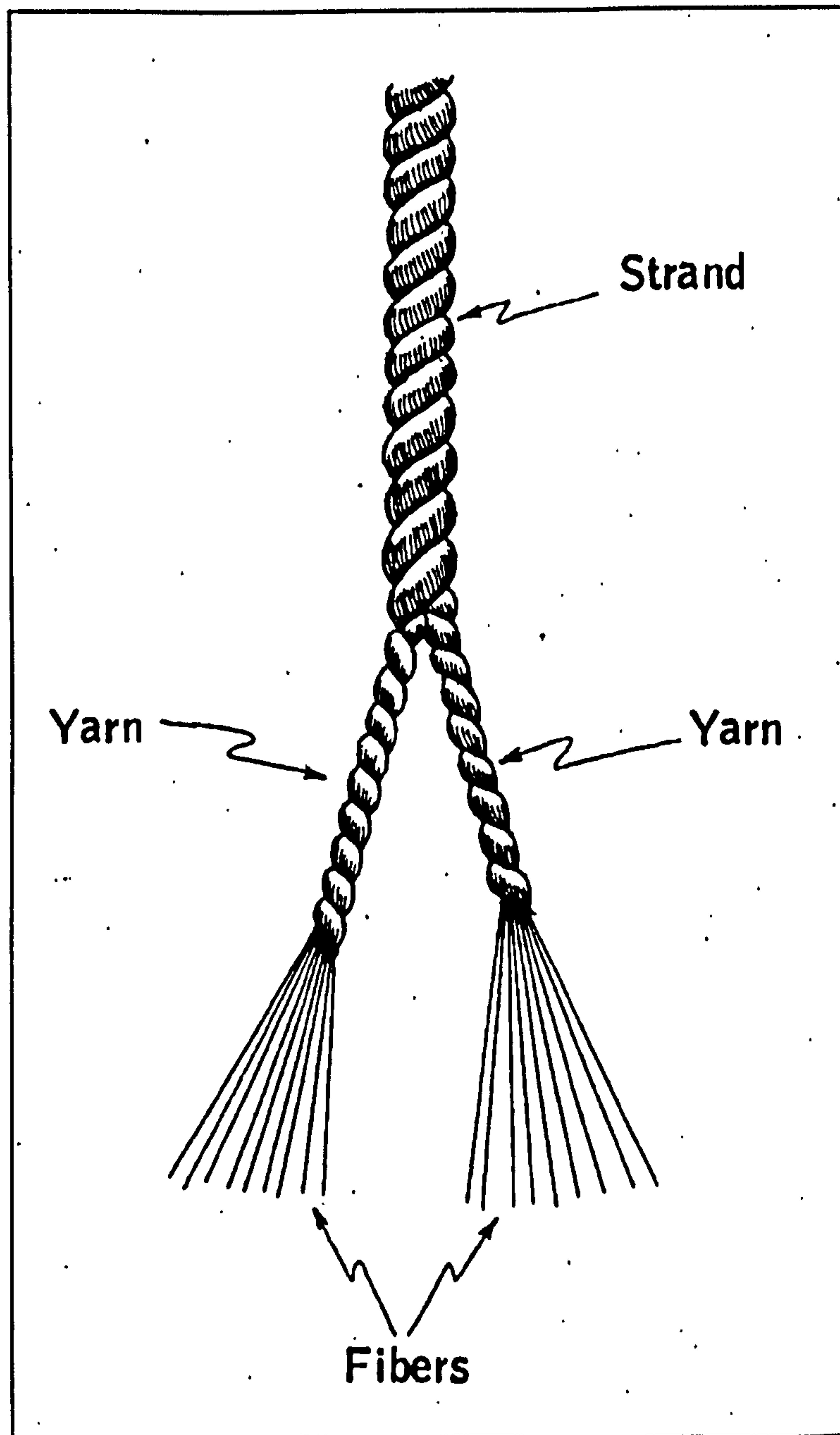


Figure 2-1: The schematic layout of strand made up from yarn and fibre (Flory JF, *et al*, 1977).

2.1.2 Synthetic Fibre Rope

Synthetic fibre ropes are lightweight and easy to handle. They do not corrode. Some fibre ropes have a superior tension and bending fatigue performance than those of wire ropes. Recent advantages in synthetic fibre ropes have dramatically influenced the practice of civil engineering in oceans (Saidpour *et al*, 1995).

Synthetic fibres are usually manufactured in either monofilament or multifilament form. Denier per filament is sometime used to differentiate monofilament fibres from multifilament fibres. The difference between monofilament and multifilament is not universally defined, and it varies among countries and industries.

Most ropes used in marine environments contain one or a combination of nylon, polyester, or polypropylene fibres. However, polyethylene and aramid, have undesirable properties, e.g. low strength of polyethylene and high cost of aramid, which make them undesirable for mooring purposes (Flory *et al*, 1988).

2.1.3 Comparison of different rope materials for marine use

Considering the difficulties of rope comparison in mooring applications, Banfield (1998) compared performance of different ropes for deep-water moorings. Stiffness values determine offset and peak loads Creep gives continuing elongation, which must be removed, and fatigue relates to long-term life. The ratio of strength to modulus determines the minimum depth possible for a given mooring geometry in a given environment. Subject to this restriction, the highest modulus gives the lowest rope weight.

There are stronger fibres than polyester, nylon, and polypropylene but certain physical properties make these fibres undesirable for use in marine applications. Of these three fibres, nylon is the strongest, polyester ranks second and polypropylene is the weakest. The strength difference between nylon and polyester is small.

It seems polyester and polypropylene ropes have superior resistance in cyclic loading compared with nylon. Crawford (1983) and Flory (1988) in separate studied found

that Nylon loses approximately 15% of its strength in wet conditions while polyester and polypropylene do not lose their strength.

Nylon is more elastic than either polyethylene or polyester. The high elasticity of nylon gives it high-energy absorption capabilities. Polypropylene fibre is slightly more elastic than polyester fibre. However, polyester fibres, which have been exposed to heat, set as part of the rope-making process, may be slightly more elastic than polypropylene fibres, which are normally not heat set. This effect causes apparent discrepancies in comparison with elasticities for ropes of different materials (Flory *et al*, 1988).

In wet cyclic loadings, nylon ropes lose their strength faster and fail much sooner than polyester ropes. Thus polyester is preferred for wet cyclic load applications. The physical properties of nylon and polyester vary with fibre manufacturer, and some manufacturers produce several grades of nylon and polyester. The main differences between different grades of polypropylene are resistance to sunlight. This property is not important in large synthetic ropes used in mooring lines. The relative performance of different fibre ropes compared with wire is recorded in Table 2-1.

Property	Steel Wire	Polyester	Nylon	Aramid	HMPE
Strength	1.0	0.5 x wire	0.5 x wire	Equal to wire	1-1.2 x Wire
Dry Weight equal strength %	100	35	30	20-25	20
Submerged weight per equal strength %	100	11	9	7-8	Neutrally buoyant
Cost/equal strength	1.0	1.5-2 x wire	1.5-2 x wire	3 x wire	4-5 x wire
Modulus (stiffness)	1.0	0.25 x wire	0.1 x wire	0.9-1.1 x wire	0.9-1.0 x wire
Creep	Extremely low	Very low	Moderate to high	Extremely low	Moderate to high/load dependent
Corrosion	High without extra protection	Nil	Nil	Nil	Nil
Internal abrasion resistance	Fretting corrosion	Excellent	Moderate to high	Poor especially wet	Excellent
External abrasion resistance	Very good	Fair	Poor	Poor	Good
Compression fatigue resistance	Nil	Excellent	Excellent	Poor	Fair
Cyclic load fatigue	Moderate	Excellent	Poor (wet)	Excellent to fair	Excellent
Max. load (short term)	50% strength	>50% strength	<40% strength	>60 strength	<35% strength
Temperature degradation	Nil	Possible	Possible	Nil	Very good

Table 2-1: Comparative rope performance relative to steel wire rope (Bridon, 1995).

2.1.4 Rope Structures

The following rope constructions cover most ropes existing in the market (Dunn BJ 1985):

- ◆ **3-Strands hawser laid:** Three-strands are twisted or laid together to form the rope. This structure is still the most commonly used (Figure 2-2). Perhaps one of the earliest ropes made so far, is this type of rope because of its simple construction. Figure 2-3, which is an ancient rope, presents the same construction. The rope is still highly used because of its availability in market, standardisation and the price.

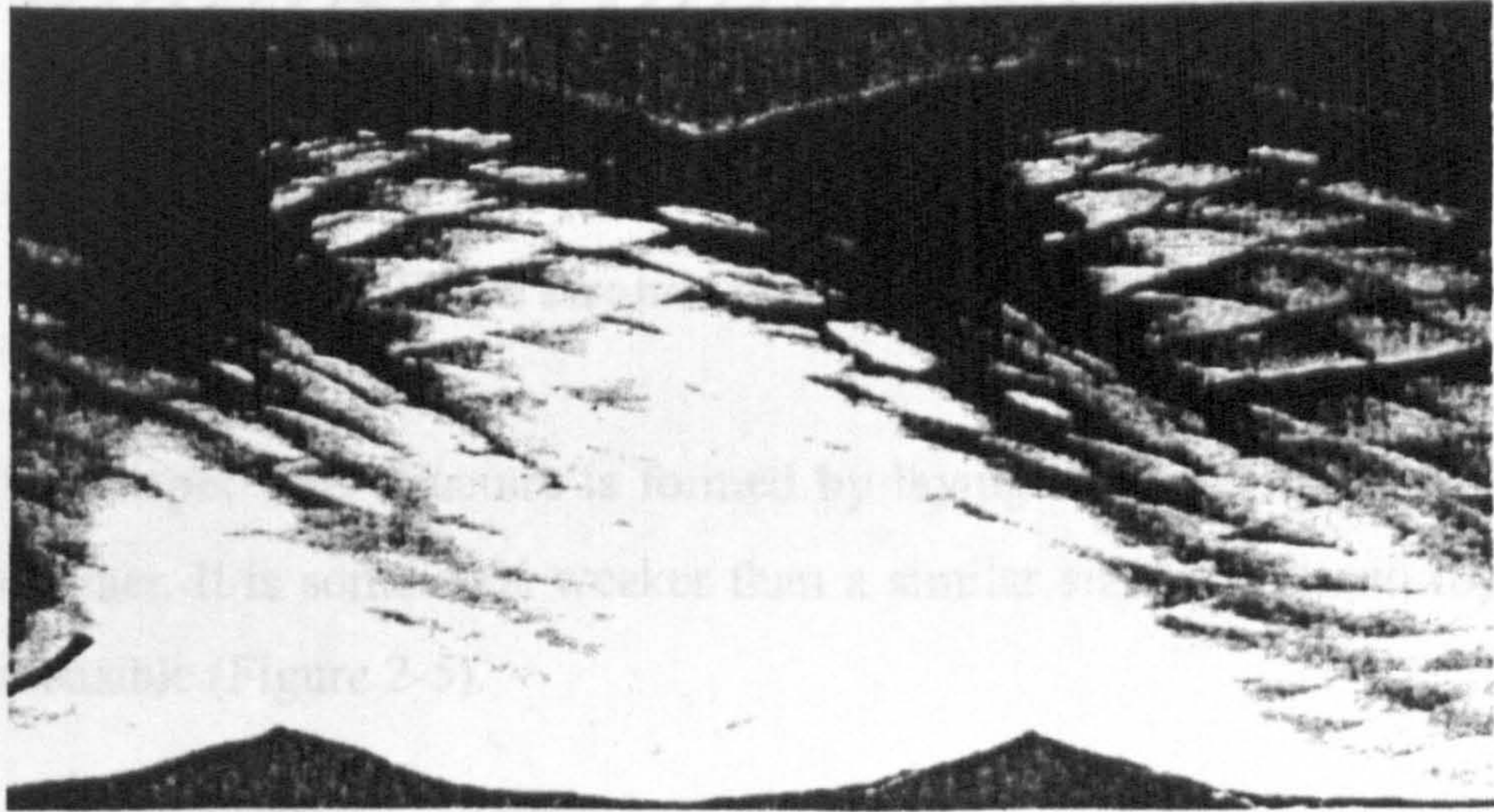


Figure 2-2: The nylon rope from 1950s (Tyson, 1966).

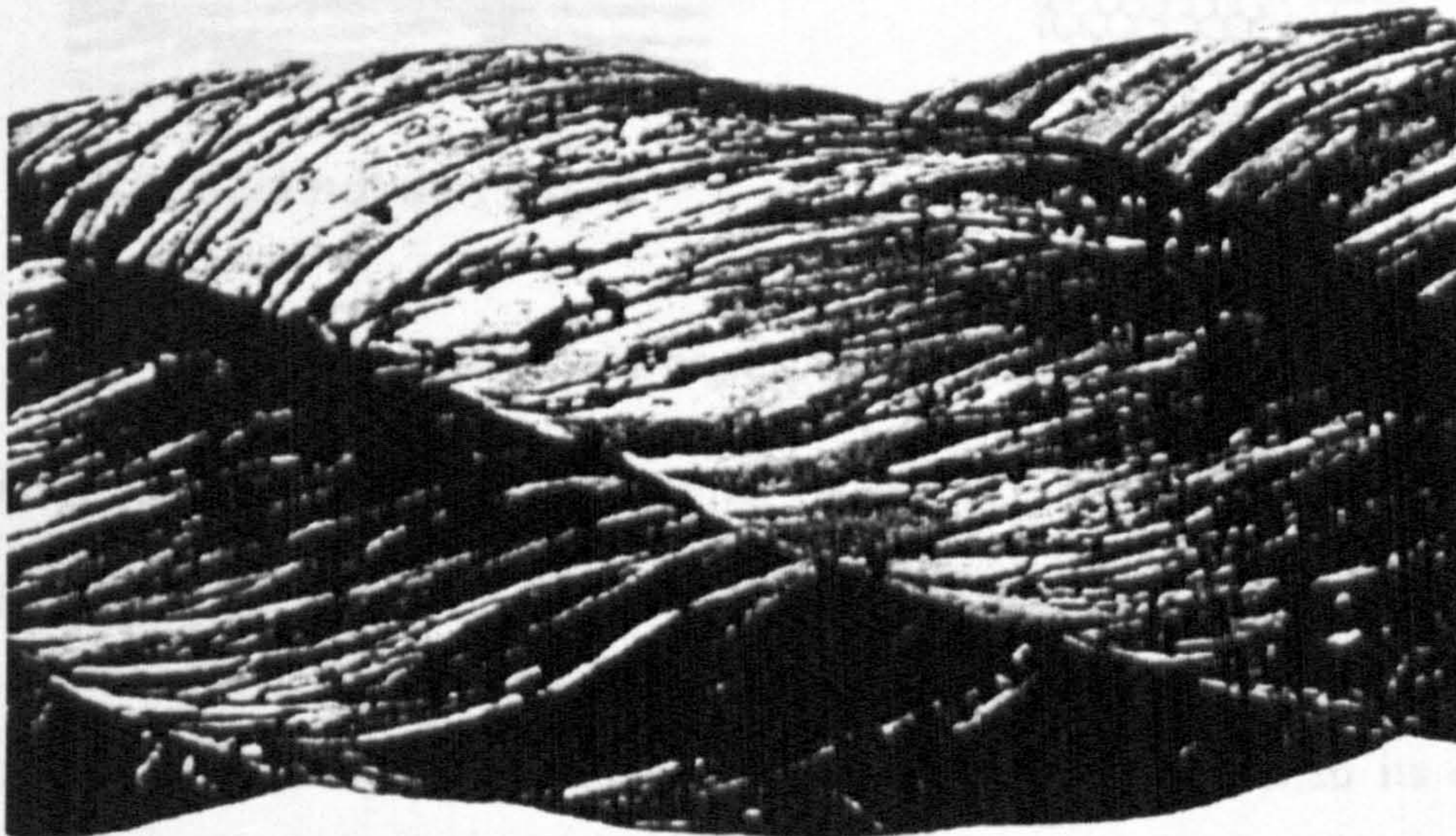


Figure 2-3: Ancient three-strand papyrus rope from 500BC (Tyson, 1966).

- ◆ **4- Strand shroud laid:** Four strands are laid normally over a central core. The core may be omitted for ladder ropes where two strands pass on either side of the rungs. The structure was formerly used for running rigging on sailing vessels, but nowadays it is rarely used to make ropes. The rope is 11% weaker than an equivalent size of 3-strand rope (Figure 2-4).

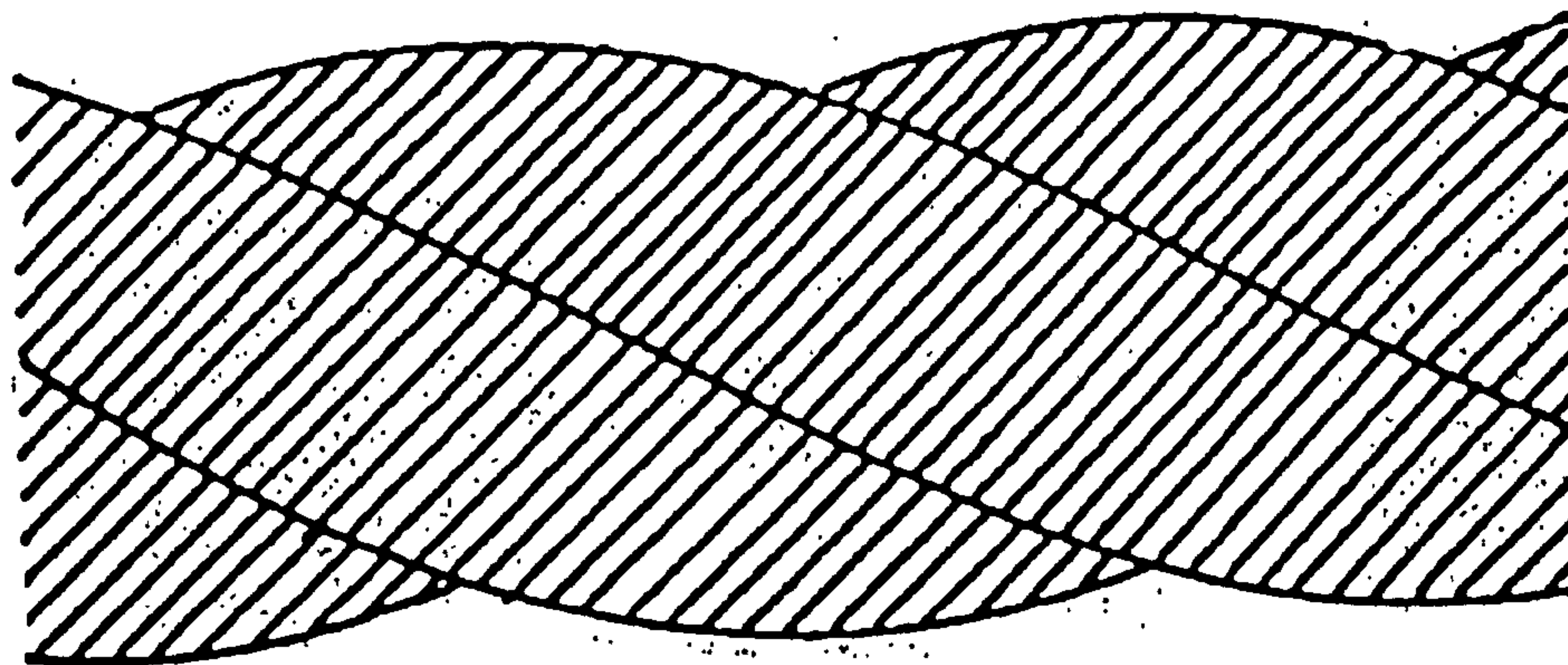


Figure 2-4: Three strands laid rope (OCIMF, 1992).

- ◆ **Cable laid rope:** This structure is formed by laying three (or more) hawser laid ropes together. It is some 40% weaker than a similar size of 3-strand rope but is more extensible (Figure 2-5).



(jacket not shown)

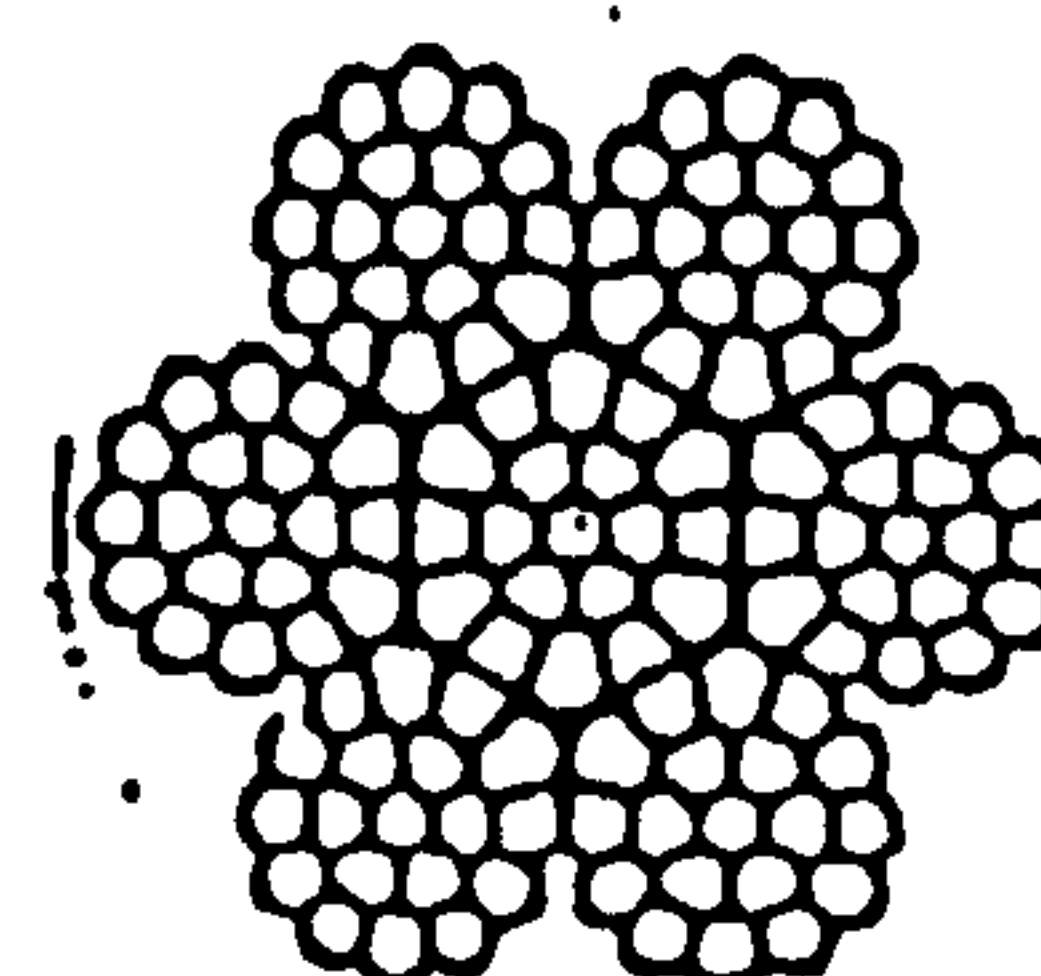


Figure 2-5: Cable laid rope (Aker Omega, 1995).

- ◆ **8-strand plaited structure:** "Squareline" 8-strand plaited ropes are made by plaiting together eight strands in four pairs of strands in the form of a double four strand round sennit. The rope has the same number of yarns as an equivalent size of 3-strand rope, but is referred to by its size number, rather than its diameter (Figure 2-6).

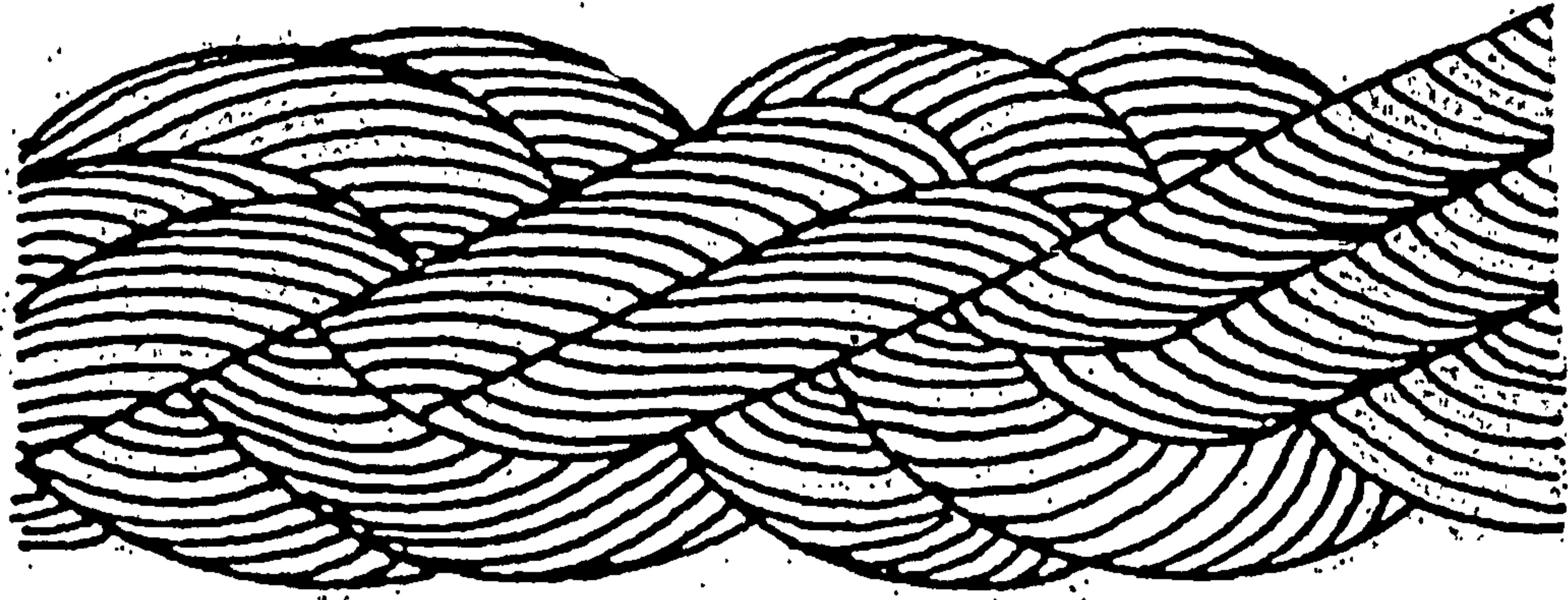


Figure 2-6: Eight-strand plaited rope (OCIMF, 1992).

- ◆ **Braidline rope:** A Braidline rope consists of a plaited hollow core, over which is plaited an overlaying sheath. The rope structure is similar to two hose placed coaxially within one another. This structure utilises more efficiently the aggregate strength of the component yarns, and the guaranteed rope strength is some 15% stronger (size by size) than a 3-strand or an 8-strand nylon rope (Figure 2-7).

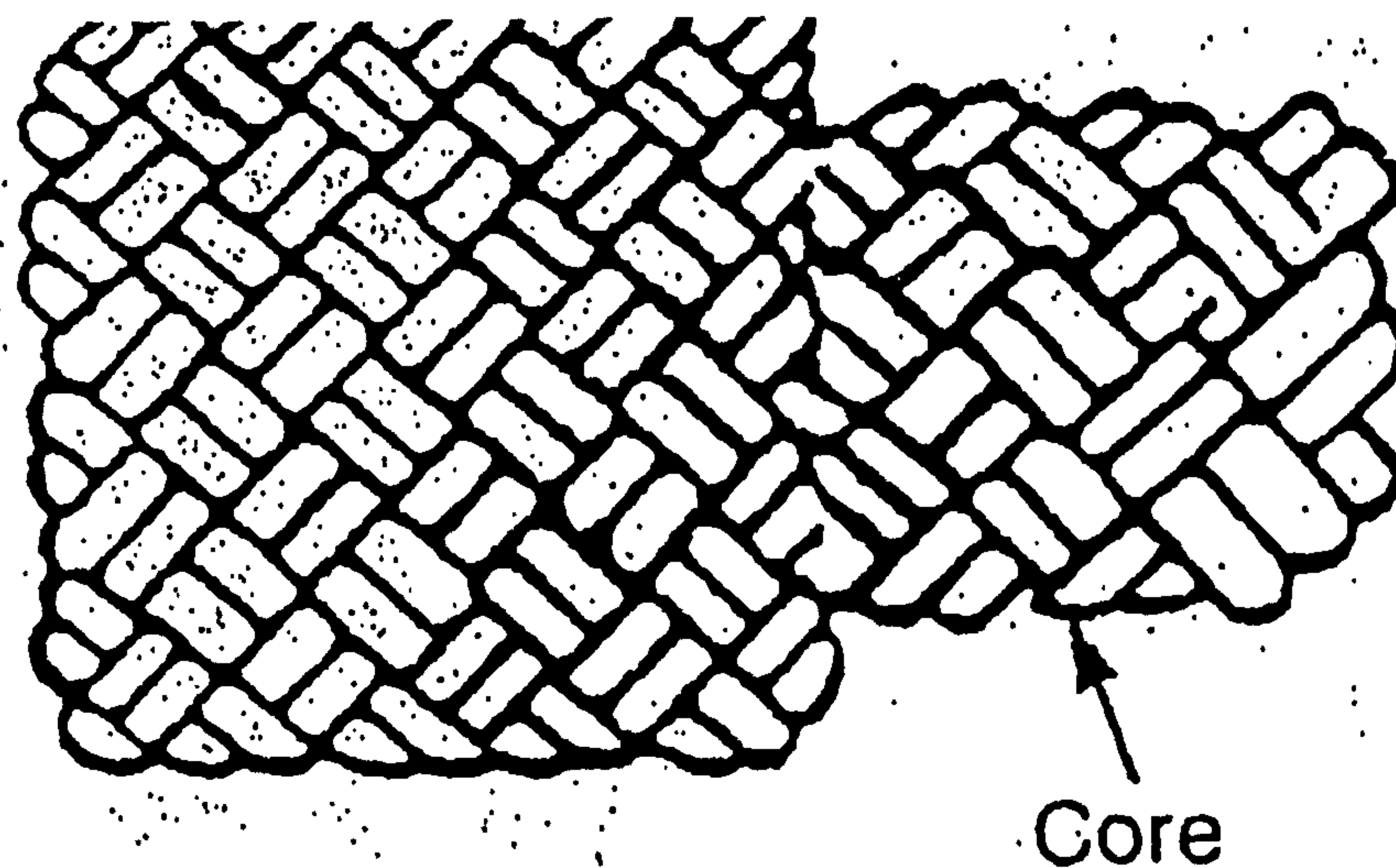


Figure 2-7: Braid over braid rope (OCIMF, 1992).

- ◆ **"Thor" Nylon ropes:** This rope is made of six strands that are laid over a core. Each strand is composed of large nylon monofilaments, interspersed with multifilament yarns of conventional structure. The monofilaments vary in size from 1.6 to 6mm diameters depending upon the size of the finished rope. The stability of the rope is achieved by a well-balanced ratio of mono & multifilament with the load-bearing function of the rope being taken by both.

- ◆ **"Viking7" Polyester rope:** Yeardley (1996) introduced the "Viking7" rope, which consists of a parallel array of seven long braided sub-ropes, secured within a unifying protective overbraid. This structure overcomes length limitation problems by utilising seven small sub-ropes rather than a single large strength member. The long braid angle gives a very high strength transfer relative to the input material while retaining the facility for load sharing between the fibre bundles. The protective overbraid gives a high degree of abrasion protection to the load-bearing member. The structure also offers a unique opportunity for termination due to the parallel arrangement of sub-ropes (Figure 2-8).

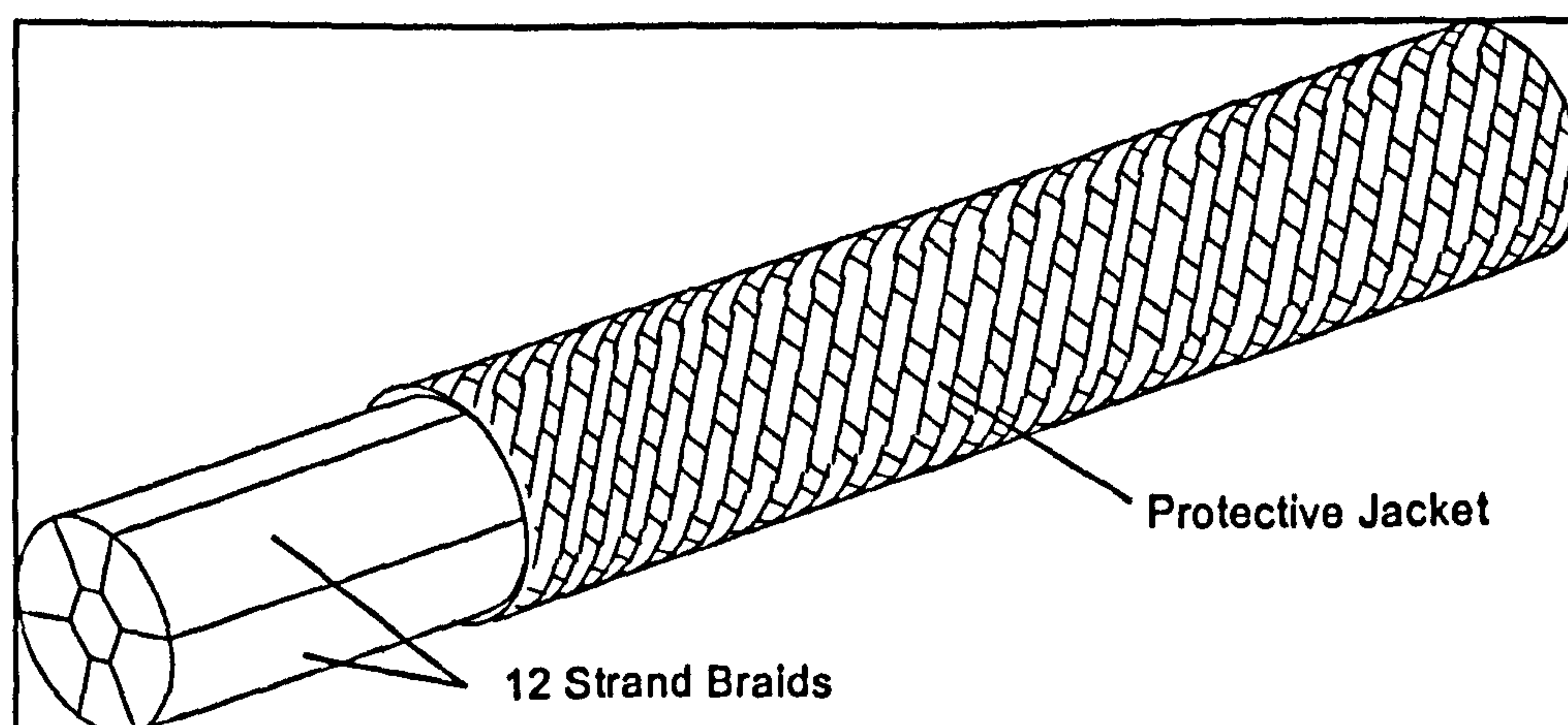


Figure 2-8: Parallel sub-rope Viking 7 rope (Yeardley 1996).

- ◆ **Superlines:** Superlines (Figure 2-9) have the same structure as Viking 7, but its number of sub-ropes is more than 7. The core consists of a number of parallel laid ropes, half "S" and half "Z" twist, to provide a torque balance. The torque balance property is a very important issue in rope manufacturing. If the rope is not torque balanced, it might unlay during the service. In new constructions, braided sub-ropes have been used to make Superlines. The rope has a braided synthetic fibre cover and may be supplied with an extruded jacket (Street *et al*, 1993).

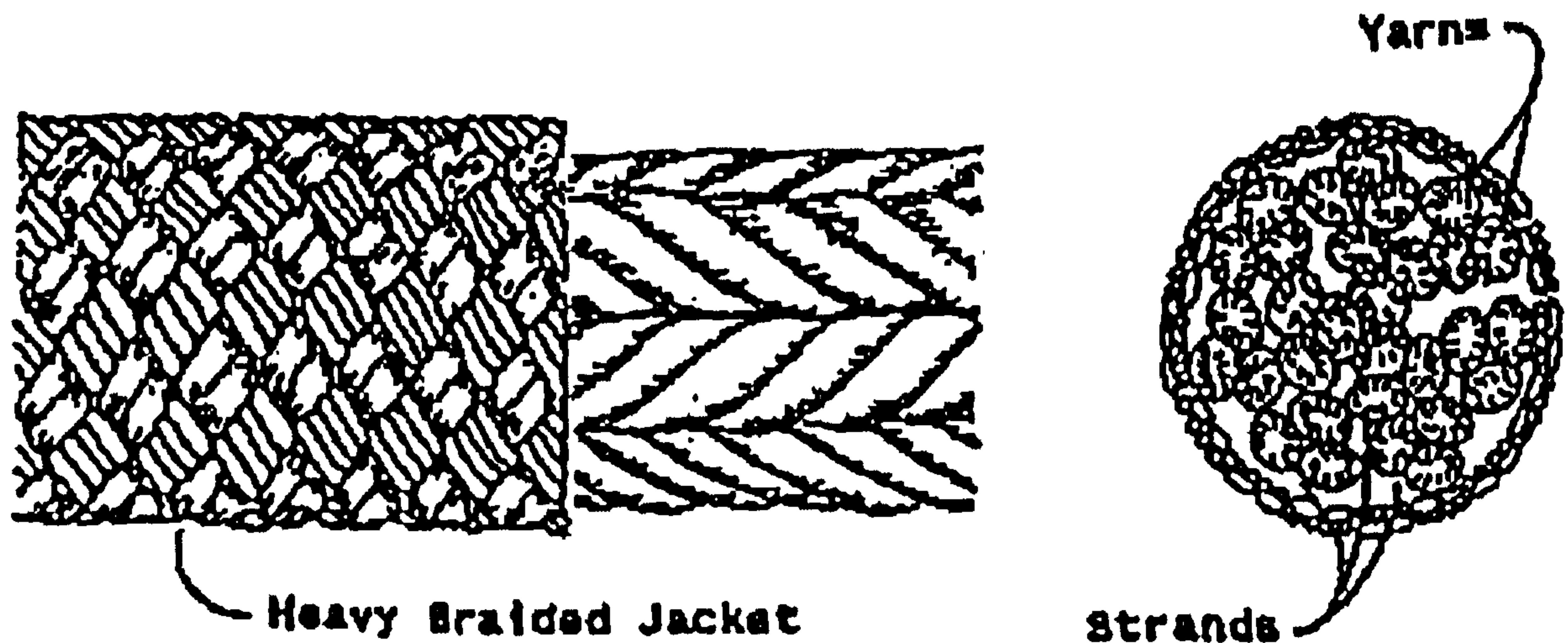


Figure 2-9: Schematic layout of Superlines (Aker Omega, 1995).

2.2 Rope Requirements in the Marine Environment

Marine ropes have different requirements from normal ropes. They should be highly efficient in utilising the strength of continuous fibres, robust and yet flexible for offshore handling, durable for long term (over 20 years) exposure in underwater, have an efficient method of termination, and capable of being made in large diameters and long length (Yeardley, 1996).

The important parameters indicating properties for a rope applied in marine environments are as follow:

- 2.2.1 **Handleability:** The feature which describes the ability of the rope to be man-handled, in the case of wire rope this parameter is closely allied to stiffness.
- 2.2.2 **Corrosion resistance:** Resistance to attack from seawater and other additives is known as “corrosion resistance”. Fibre ropes of all sorts, are known to be very resistant to corrosion and seawater effects, which are usually neglected. However in the case of wire ropes in marine environments, corrosion has been a matter of concern from early stages of usage. Different types of coatings have been used, such as polymeric coating, galvanising and so on. Galvanising of individual wires of a rope provides one method of restricting corrosive attacks on the stress carrying elements, and this approach is usually applied for all long life applications. Lubrication, of the correct type, at rope manufacture

and subsequently in service is the secondary source of protection against corrosion (Petrina *et al*, 1997).

2.2.3 Abrasion resistance: Abrasion resistance may simply be defined as a function of the outer wire size used in the rope. For synthetic fibre ropes, abrasion resistance is a function of the fibre type and the rope construction employed. In the case of fibre rope covered with a jacket, it is proved that the jackets on strands significantly increase the strand lifetime, but the effects of different polymer lubricants coating the cords in a strand are not as significant as might be expected (Petrina *et al*, 1995).

2.2.4 Strength: The proportion of the breaking load to input material is known as “strength” in the rope industry. The characteristics of the feed material for rope manufacturers are modified by the construction of the rope. The helical formulation of the rope, which is essential to achieve the handleability and fatigue resistance associated with usage, causes losses from the theoretically available strength. The latter is a function of the tensile strength of the feed material, its mass and the rope construction. In the case of wire ropes, the strength size characteristic is designed by a value in Newton per square millimetre (N/mm²).

2.2.5 Fatigue resistance: The ability to sustain cyclic loading by bending, rotation or pulsation is called “fatigue resistance”. Wear and fatigue in synthetic fibre lines depend on a multitude of mechanisms, including cumulative creep to rupture, heating due to cyclic loading of filaments or to relative displacement of structural rope elements, internal wear caused by relative movement between yarns or strands, and external abrasion against deck hardware or rough surfaces (Seo *et al*, 1997).

2.2.6 Elasticity: “Elasticity” shows the strain history of the rope, and has a bearing on energy absorption. Fibre rope structures are designed to obtain the maximum utilisation of the fibre strength from a compact rope cross sectional areas in order to produce certain rope breaking strengths and elasticity while

using a minimum amount of fibres. They are composed of a large number of single fibres. The fibre bundle has to be arranged to form torque free or torque balanced structures. At the same time, the structure has to produce a maximum utilisation of the fibre strength and sufficient flexibility and elasticity (Niedzwechi, 1978).

2.2.7 Extension under load: “Extension” has been defined as a measurement of the strain at a given applied load. In some cases, it is required to have extension in mooring systems. Therefore, nylon material is considered in such cases. However, it appears that extension is an unwanted feature in most mooring systems and it should be decreased if possible.

2.2.8 Energy absorption: A measurement of the strain energy absorbed by the rope during the operational cycle is called “Energy absorption”. Energy absorption i.e., the capacity to accept shock loads, (as in towing) is a function of the area of the load-extension curves. These features and a value of the apparent modulus of elasticity (E) for man-made fibre ropes, stress and strain are not proportional and no value of 'E' can be determined. It is quite clear that for the synthetic fibre ropes, the elastic elongation characteristics are non-linear and vary significantly for each type of rope. It should be noted that wire rope and, to a lesser degree, chain also elongate under loading, but it is negligible when compared with most natural fibre and synthetic fibre ropes (Niedzwechi, 1978).

2.2.9 Rotational Characteristic: This is the feature which characterises the inherent load: torque and load, and turn properties of the rope. As a result of the helical form of the wire or fibres, most laid ropes have a rotational characteristic which allows the end to turn if not fixed, or alternatively to create a torque on fixed terminations. The characteristic varies from construction to construction, and in particular designs it is possible to create a torque-balanced condition.

2.2.10 Fishbite Protection: Fibre ropes may be damaged by fishbite when submerged in particular marine environments. A protective cover could save the rope from fishbite effectively. Only a limited amount of information is available on fishbite as it is not easily assessable.

2.2.11 Bending Around Small Radii: This feature which is particularly important in many marine applications, should not be confused with fatigue resistance. Ropes which bend around small radii, whether rotating or fixed components (i.e. shave or bollard respectively) sustain a loss in their effective strength compared with the breaking load achieved at an in-line pull. This loss is a function of the rope construction and the bending radii.

2.2.12 Temperature Effect: Wire ropes will operate with no severe deterioration in performance through a temperature range of -40 °C to 300 °C. However, at the extremities of the range, normal lubrication is ineffective so that fatigue resistance will be impaired unless special in-service lubricants are applied. Synthetic fibre ropes have a more limited temperature range. The softening point at which thermal creep becomes pronounced is an important temperature. The coefficient of thermal expansion and contraction for wire rope is 0.0000125 per centigrade, and therefore, the change in length (L) of rope produced by a temperature change of t°C will be: Change in length = L x 0.0000125 x t (Qiu *et al*, 1998)

2.3 Rope Applications in Marine Environments

There are several applications for synthetic fibre ropes e.g. mooring large off-shore structures, towing, post tensional concrete, bridge cables, ground anchors, and roof structures (Kingston, 1990). The only application, which is of concern in the present study, is mooring in marine applications.

2.3.1 Mooring

Mooring ropes account for the highest percentage of weight of cordage used in marine applications. The techniques used in handling mooring ropes and the degree of mechanical assistance, which the crew may receive, will vary depending broadly on the dead-weight of the vessel. It follows that the preferred choice of mooring rope materials will also vary to take these conditions into account.

2.3.2 Towing

Towing is another major area of rope application in marine environments, for which nylon ropes are mostly used. This is because high extension is required in lines used in towing. Also its low density helps the line to float on the water. The splice is known to be the best method of termination for a towing line. Socket weight is known a disadvantage.

2.4 Mechanical Performance Predictions of Rope

2.4.1 Determination of Breaking Strength by Realisation Factors

The rated breaking strength given by manufacturers of large synthetic ropes is in general extrapolated from smaller-rope breaking strengths, or breaking strengths of the rope components. Extrapolation has been necessary because the size and the breaking strength of large diameter ropes have increased at a faster rate than the capabilities of rope break testing apparatus. This method is potentially inaccurate and should be used with caution because it is based on the strength of individual elements while the actual rope may behave differently. The rope breaking strength is affected by a number of factors, which may vary with rope size and construction. Such factors are the twist of the yarns and strands, the helix angle of the strands, and the tensions of the braiding machines used in rope manufacture (Walter *et al*, 1980).

It is proposed that the total strength of large ropes could be related to the strength of their components. The relationship between the strength of the component and the strength of the complete rope, known as the realisation factor (RF), is determined by tests on small ropes. The total breaking strength is determined by the following formula:

$$TS = CS \times NC \times RF \quad \text{Equation 2-1 (Walter, 1979)}$$

Where

- TS = Total rope breaking strength
- CS = Component breaking strength
- NC = Number of component
- RF = Realisation factor

The tests are repeated for a series of rope sizes, and realisation factors are determined for each rope size. From these RFs for smaller ropes, RFs for larger untested rope sizes are extrapolated. To determine the breaking strength of large ropes, their sample components are break tested and the component breaking strength is determined. The total rope strength is then determined using the appropriate realisation factor in equation 2-1.

Table 2-2 shows Realisation factors for different materials and constructions. Like the extrapolation of rope strength, the use of realisation factors to determine the total rope strength is potentially inaccurate and should be used with caution. Industry-standardised realisation factors which relate composite rope strengths to the strength of the rope component may not be accurate for all rope manufactures because of variation in rope construction (Walter, 1979). The accuracy of the realisation factors depends on the nature of the rope components (yarn or strand) selected, their numbers and positions, and the accuracy in determining their individual breaking strengths. The number of factors involved are so varied that a reliable RF is difficult, if not impossible, to obtain.

Material	Type	Construction	Realisation Factor (RF)
Aramid	K225	16 Carrier	1.18
Nylon	Suspension rope	3 Strand	1.26
Nylon	ATLAS	6 Strand	0.98
Nylon		Braidline	1.31
Nylon		8 strand	1.15
Polyester	Viking 7		0.85
Polyester	Pre-stretched	3 Strand	1.19
Polyester		Braidline	0.78
Polyester	Viking 7	Braid	0.87
Polypropylene	Blue Film	3 Strand	1.22
Twaron	K222	16 Carrier	0.97

Table 2-2: Realisation factors for different materials and constructions (Walter, 1979).

It is not very clear how realisation factor could be more than one although improving effects due to some construction make up has been reported in some literatures. However this effect can only be found in small ropes to some extent while it is very difficult to understand these results in larger ropes.

2.4.2 Prediction of the tensile strength & dynamic properties by computer simulation

Leech *et al* (1993) developed a model to predict the tensile behaviour of twisted ropes based on geometry and fibre content. The data showed a high correlation with experimental results. The model has also been applied for braided ropes. They concluded that there are inevitable assumptions and approximations, due to mathematical simplifications and uncertainties in rope construction. Tension and torque can be computed for their dependence on elongation and twist, and the breakage of both the rope and the splice predicted.

Kumaniecka (1994) simulated the dynamic stability of a rope in axial direction. The dynamic state of the investigated system is described by a set of non-linear coupled partial differential equations with boundary conditions varying in time. The damping properties of the non-linear rope material as well as dry friction between particular strands are taken into account. The unstable regions for the main, secondary and combination resonances have been found by applying the harmonic balance method. General results are illustrated by a numerical example in which the effect of the starting and braking of the winding machine is included. The influence of the material non-linearity and the character of kinematics excitation are also considered. The results, with slow variability of the parameter, show a high correlation with experimental results.

In developing very large ropes made of high-modulus materials such as aramid or polyester, the use of computer models is considered to reduce final cost. Through computer modelling, parameters such as fibre properties and component arrangements can be studied to determine a near-optimum design before making and testing a prototype rope. Test results can be used to calibrate the computer model, and

additional modelling can then be conducted to improve rope properties or predict rope performance under other conditions. Some conclusions are as follow:

A: Modelling of the Stress/Strain Relationship

With appropriate modelling of the rope structure, described above, it is then necessary to relate the tensions, extensions, torques and twists applied to the entire rope structure to those imposed on the individual rope elements. This is done through the Principal of Virtual Work. This means that work performed by tension P changing the rope length L plus work performed by torque T changing the rope twist 2 is equal to the overall work U performed on all elements of that rope. Prescribed changes in length and twist are applied to the most major structural element, which is the rope. From the rope structural model, the resulting changes in the length and twist of the next lower structural level are calculated. And from those changes, the succeeding lower level changes are calculated, until the resulting change in the length (stress) of the lowest structural level or basic element is known. (Torque/twist properties of the basic element can be input if known.) The tension in the basic element which corresponds to this imposed change in length is also calculated. Tensions and torques on each of the succeeding hierarchial elements are then calculated to determine the corresponding tension and torque on the rope itself (Banfield *et al*, 1995).

B: Accounting for Deformation Modes

Of fundamental importance in modelling fibre ropes are the many possible deformation modes. The various structural levels can compress and change in shape. The resulting changes in diameter then alter the helical paths of succeeding levels and thus change other important properties. Various elements can slip relative to each other. The degree of inter-element movement depends on the tension on an element, the pressure between elements, and the coefficient of friction. As a result of slippage, the balance of tensions between elements is changed, abrasion damage may be produced, and heat may be released (Banfield *et al*, 1995).

2.5 Rope Characterisation

2.5.1 Introduction

Testing ropes is carried out to understand ropes and their performance and behaviour. There are several destructive testing methods to characterise rope. In the past few years, some non-destructive methods have been introduced. The important factor is to design a test that would give the desired and reliable data. As big diameter ropes have been mostly used in marine applications, most of the available data seems to be in this area compared with other small diameter ropes.

Banfield *et al* (1998) did a series of tests to evaluate the synthetic fibre ropes used in marine environments, combining with some environmental data. The fibre rope mechanical properties measured in laboratory tests on materials, constructions and terminations intended for deepwater mooring applications were examined. The tests included static tensile, fatigue cycling in wet conditions and creep. The results, combined with field experience, provided a better understanding of rope behaviour and enhanced the knowledge required to engineer fibre ropes for these demanding applications. This has also led to improved laboratory test techniques for measuring mechanical properties relevant to mooring system response analyses required to meet regulatory requirements.

2.5.2 Destructive Testing of Ropes

The commonest and oldest testing technique is destructive testing, where the results are obtained at the expense of the destruction of the test sample. Tensile, fatigue cycling and creep are the most important tests for marine applications. A list of most common tests is as follow:

I. Fatigue

Marine ropes experience a complex history of static and cyclic loading and environmental exposure. Some aspects of this history apparently combine to sufficiently weaken some ropes so that unexpected failures occur (Starsmore *et al*, 1980).

The fatigue loading of polymers has received considerable attention in some areas such as fatigue crack growth, but experience with polymers is much less extensive than that with metals (Hertzberg *et al*, 1980). In inert environments, ductile polymers commonly fail by two distinct modes depending upon loading conditions. In a cyclic creep mode, failure is dominated by time under load, and in some cases occurs more rapidly with a constant load than a cyclic load which allows some relaxation during the unloading parts of the cycle (McKenna *et al*, 1980). The other failure mode is associated with fatigue crack initiation and propagation, and occurs much more rapidly with cyclic loads (Mandell *et al*, 1981), although very slow crack growth can also occur at low static loads, sometimes termed creep cracking (Kausch, 1987).

The fatigue data for nylon and polyester marine ropes from several testing programmes in Europe and the US have been compared. A model based on the creep-rupture behaviour of individual fibres and yarns could predict failures at loads above 30-40% of the new breaking strength for nylon or 60-70% for polyester. Failures at lower loads and higher cycles usually occur by external or internal abrasion. Polyester outperforms nylon under wet conditions in both regimes. Rope failures in tests tend to occur in or at the end of the splice; at the tangent of the eye and the bollard, or at the back of the eye. The failure position appears to depend on the ratio of the rope to bollard diameter, the type of eye protection (if any), and the rope construction. Important factors in rope fatigue tests are the environment and the test period. Tests on dry ropes at high loads, unless run at very low frequencies (long periods), fail due to hysteretic heating (Mandell, 1987). If the specimen is immersed in water or sprayed with water during testing, heat build-up does not appear to be a problem. The additional effects that complicate the rope behaviour include:

1. Fibre shrinkage with long term water exposure
2. Transverse loading

3. Abrasion (internal or external)
4. Recovery periods between loading
5. Hysteretic heating
6. Photochemical degradation.

II. Tensile

Fibre strength is represented by tenacity. Tenacity is defined as the breaking strength of the filament per unit weight. In SI unit tenacity is expressed in Newton per tex. Traditionally it is expressed in gram per denier. Tex is defined as weight of identical rope lengths, and expressed as gr/m or Kg/Km.

The stress-strain measurement of fibre material comprises several difficulties. It includes designing a proper gripping method and choosing appropriate specimen lengths. But in almost every case, stress concentration occurs at the clamped jaw, which causes the specimen to break at the jaw resulting in lower values than the true strength of the filament material. Therefore, the measured strength values often show lower values than the true strength value. To reduce this stress concentration, gradual reinforcements or embedding methods were applied to the fibre material at the jaw and its exit boundary region. The gradual reinforcing materials allow for stress redistribution between the fibre materials and their relatively rigid embedding. For gradual reinforcing, adhesive tapes and silicon rubbers and epoxy glues are used for fibre and yarn tests. Capstan grips are used for large yarns and small ropes. Since the use of each of these methods is accomplished by slippage during the loading, the values of elongation based on the jaws' displacement of the tensile tester do not represent the true elongation of the material.

To obtain valid stress-strain curves for a single fibre to fibre bundles, the following four methods are applied (Seo, 1988):

- 1- The first method allows for measuring the strain between the gauge marks on the specimen using a cathetometer or a video recorder, together with the Instron tensile tester. This method shows pretty good results on tensile properties of large size yarns and ropes. In case of the cathetometer use, readings are not continuous and as a result,

strain values include relaxation effects. Using video camera reduces the effect of relaxation to a minimum level.

2- The second method is the extrapolation of the data obtained in the same testing method and reinforcement but in various gauge lengths. If at any given load, the measured elongation includes the same amount of slipping at the grip, then the extrapolation of the data to zero gauge length designates the actual jaw slippage at the load. If this value of slippage is then subtracted from the measured elongation data at each given load, we can get the true stress-strain curves for such specimens. This method has been used for measuring the stress-strain curve of a strand of double braided rope or that of its yarn. This method has several uncertainties. One of them is the assumption of the magnitude of slippage that occurs for all gauge lengths. This is difficult to prove.

It takes considerable time to obtain a single stress strain curve for the above two methods. When the magnitude of the surface shear force available from the grip is larger than the required tensile force to break the specimen, the significance of the stress concentration effect near the grip is significantly reduced. This occurs when the relative magnitude of the surface area with respect to its cross section is large, such as a single filament or a single yarn, or when the boundary shear force between the gripping material and the fibre material is as high as that for the embedding materials.

3- The third method constitutes a reinforcing grip employing adhesives or epoxy glues. This method precedes a good break in most cases, however, a possibility of slippage involvement at this grip as seen when the effect of specimen length is measured (Kenny et al., 1985). Since the magnitude of the slippage is relatively small, the effect of the slippage becomes smaller when the length of the specimen becomes longer. This third method can be applied successfully on reasonably long single filaments and on yarn specimens of 25 cm or longer.

4- The fourth method is measuring the elongation of the specimen with the Linear Variable Differential Transformer (LVDT). The data are collected using a digital recorder. Since this method gives the most accurate results, load elongation curves of the bundle and ropes were measured in this way (Seo, 1988).

III. Abrasion

Synthetic fibre ropes are attractive alternatives to wire ropes in many marine applications because they are much lighter in weight, do not corrode, and are more elastic. However, resistance to external abrasion is a concern.

Abrasive wear is said to occur when there is a progressive loss of material from the softer surface when two surfaces are rubbed back and forth. In a 'clean' environment this is most often caused by hard protuberances of one surface gouging grooves in the softer surface as they are reciprocated under normal loading. The swarf is initially pushed to one side but after many cycles it is removed altogether. If grit is present, this process is speeded up, but the terminations are usually sealed to prevent water penetration, so that no grit will be able to get in. In polymers, strong adhesion occurs at the points of contact of the asperities; when sliding occurs, fragments are torn from the softer surface and are left deposited on the harder one (Meredith, 1959).

Flory (1997) tried abrasion test trials on 8-strands and double braid ropes made of nylon, polyester, and polypropylene. The polyester ropes suffered slightly less strength loss than the nylon and polypropylene ropes. The 8-strand ropes exhibited a significantly better abrasion performance.

A yarn-on-yarn abrasion test for use on continuous-filament rope yarns was developed by Goksoy (1988). It involved the application of a reciprocating motion to two yarn sections wrapped helically together under tension. Different modes of behaviour were found under more severe and less severe conditions yielding reproducible results with acceptably low variability. Tests were made on two nylon and two polyester-fibre yarns. Results were presented for the influence of tensioning weight, number of wraps, wrap angle, cyclic stroke, and cyclic speed on the cycles to failure of two nylon and two polyester-fibre yarns, both wet and dry. The measurements made were dry as received, in tap water, in distilled water, in synthetic sea water, and in Sodium Chloride (NaCl) solution, and also after drying from these environments. The effects of pre-soaking were studied. The different wet environments did not yield large differences in abrasion life, but nylon had a lower life wet than dry. Severe reductions of life occurred in yarns dried from the salt solutions.

IV. Creep

The creep behaviour is mostly presented by elongation under constant load in constant time interval. The experimental data generated in creep test could give some idea about the long term behaviour of the rope. Practically it is not possible to monitor the creep behaviour of the rope in the long time exposure in water because most often it is a very low fraction of the whole line and it is not possible to differentiate how much extension is due to creep. The extension in the line could be as a result of other effects like damage in sub-ropes and so on. That is why the short term data in the laboratory could be useful. High loads are applied to monitor the creep although it may not be applied in the actual loading condition (Backer, 1982).

The creep is very important for mooring systems in which the line length is a matter of concern e.g. single point mooring. Designers need to know if the tension elements will be carrying a specified force after the initial creep losses have occurred, and this is very sensitive to subsequent small length changes caused by the creep. Contractors need to know how to cut a length of rope off a reel so that, after they have terminated the rope, possibly preloaded it, transported it around the country, installed it in place and then loaded it, it will have the correct length and the correct tension. This factor may seem mundane, but the alternative is to build into the structure adjustable anchorages, which are usually very bulky and hugely expensive; such considerations are known to have deterred using these materials.

It is well known that the creep of fibres is significantly reduced when they are preloaded, but it is not known why, nor is it known whether there is a consequential loss of lifetime. Tests are underway which will fill the gaps in the knowledge with a view of producing a single comprehensive model which relates all these properties (Walter, 1979).

Since the creep failure time shows a high correlation with the tensile fatigue life of the fibre, it might be expected that normalised stress versus the creep failure time relation of the filament can also be used for predicting of its tensile fatigue life at very low loads.

Type G parafil parallel-lay Kevlar 49 rope has been creep tested over a period of up to 580 days. The applied stress varied from 24.5%-81.6% ultimate tensile strength. The results of the experimental investigation conducted on ropes of 1.5 and 3.0 tonne nominal breaking load show:

- Creep and recovery in parallel-lay ropes could be adequately described using a logarithmic time law.
- The creep rate at any time increases with stress
- The creep coefficient for parallel-lay aramid ropes can be considered as stress independent.
- The comparison between the creep rate values for parallel-lay ropes and Kevlar 49 fibres indicated that the application of pre-tensioning load has the effect of reducing the creep strain in subsequent loading (Watson *et al*, 1988).

V. Stiffness

The dynamic stiffness increases significantly, approximately 100%, for nylon double braid rope and 30% for polyester 8 strand plaited rope, after 4-5 years in the ocean. This can result in the nylon rope being stiffer than the polyester after exposure to the marine environment. As the rope ages, the variability of the dynamic stiffness also increases. This indicates that it is more difficult to predict how a mooring would perform after a period of time. The dynamic stiffness of nylon rope is more dependent on the magnitude of the load amplitude than the rate of load variation. The mean load has a much greater effect on the dynamic stiffness than on both the frequency and load amplitude (Bitting, 1980). It is thought the figure of 20-40% is an acceptable value for stiffness improvement but it is not very clear how stiffness could increase up to 100%.

VI. Bending

Bending is a phenomenon, which occurs when the cover is extended. It also occurs when the rope sub-elements interact, making the axial compression fatigue an

important criterion. The axial compressive fatigue of twisted ropes has been modelled (Koohgilani, 1998).

When the rope bends around a sheave, the rope's strands and sub-ropes must move towards one another. This movement allows the sub-rope to compensate for the difference in the travelling distance between the underside and the topside of the rope, the distance being greater along the topside. The rope action is adversely affected if the sub-ropes cannot move properly. Any changes, which take place in the rope, due to the conditions under which it operates, will materially change the bending stress. These conditions include any instance or circumstance that restricts the movement of the sub-ropes (Anon, 1999).

VII. Torsion

Synthetic fibre ropes are often used under circumstances that result in a rotational displacement (twist) of the rope due to either inherent torque imbalance or the application of an external torque to the end of the rope. The ability of a rope to tolerate this twist without experiencing a significant reduction in strength or service life depends on both the rope construction and the material of which the rope is manufactured. The development of several new high strength, high modulus synthetic fibres, such as Dyneema, Kevlar, Technora, Vectran, Twaron, Spectra and Zylon has led to the evolution of new rope designs which take advantage of the special properties of these materials. For instance, they, using intelligent design, can replace traditional wire ropes for mooring of offshore installations as the water depths increase. However, these new ropes are much less twist tolerant than the conventional ropes made from common low modulus synthetic fibres such as polypropylene, nylon, and polyester (Gibson, 1990).

VIII. Residual Strength

Tensile fatigue and residual strength test on braid-on-braid small size aramid rope has showed that the strength reduction of aramid ropes by cyclic loading in dry condition starts early and proceeds gradually (Tsurta, 1986). At 20% load level, the values of the average residual strength for 20% at each test number of cycles was larger than the

value of the average breaking strength, and it indicated no strength reduction even after 200,000 cycles. Before the beginning of the gradual decrease of residual strength, the data showed that the strength of the aramid rope increased at first, which was similar to that of nylon.

A method for predicting the residual strength of a maritime synthetic fibre rope subjected to tension cyclic loading was developed by Flory *et al*, (1989). The method was demonstrated by limited laboratory testing. A residual strength curve showed retained strength vs. the number of cycles. It could indicate when a rope should be removed from service. In constant load cycling, failure would occur when the residual strength fell to the cyclic load level, a point of the CTF (cycles to failure) curve. Residual strength curves together with the CTF curve could be used to relate the equivalency between the number of cycles applied at one load level and those at another. This then allowed the effects of various numbers of cycles at different load levels to be summed in accounting for random loading. Residual strength curves could be plotted from laboratory cyclic load testing and from carefully instrumented field trials. It was emphasised that computer simulation would be a more economical means of predicting residual strength and cycles to failure .

IX. Energy Absorption

Energy absorption in rope is a matter of concern because it may cause premature failure. It could be measured by calculating the rope extension.

Kevlar ropes, due to their lower stretch, store less potential energy than the equivalent nylon or polyester ropes. In addition, Kevlar is less efficient at transferring its stored potential energy to kinetic energy as the broken ends propel at rope failure. Thus Kevlar ropes are inherently less lethal and therefore, are more amenable to snap-back reduction or control. Three-strand Kevlar ropes show evidence of snap-back reduction by cascading, that is, breaking one strand at a time, allowing elongation and load relaxation (Swenson, 1983).

2.5.3 Non-destructive Testing

Non-destructive evaluation (NDE) is a branch of applied science that is concerned with all aspects of the uniformity, quality and serviceability of materials and structures. By definition, non-destructive techniques involve those processes by which the materials and structures could be examined without damage or disruption of their use. At present, there are no standards relating to the implementation of NDE techniques or the interpretation of NDE results for either new or used ropes.

Over the past 20 years there has been a huge growth of interest in what are generally called non-destructive testing (NDT) and non-destructive evaluation (NDE) techniques. These are methods for probing into the materials that are used to construct structures, manufacturing plants, etc. The aim is to characterise the material and defects present, but without damaging, or disturbing the material or structure. The main motivation for NDT has been increased safety standards, but economic considerations are equally important, especially when quality control of a material product is at stake (Koohgilani, 1998).

Non-destructive evaluation of ropes is done to monitor the rope performance in service. This could be used to control the ageing of the rope during usage. One of the main concerns about a line, in a mooring system, is the life of different parts making the line. To monitor the rope ageing, different sensors are installed along the line and all data are collected and verified during the service. In most cases, the data from the sensors could prevent accidents that may end in disaster.

- Acoustic Emission

Acoustic Emission refers to the generation of transient elastic waves during the rapid release of energy from localized sources within a material. The source of these emissions in metals is closely associated with the dislocation movement accompanying plastic deformation and the initiation and extension of cracks in a structure under stress. Other sources of Acoustic Emission are: melting, phase transformation, thermal stresses, cool down cracking and stress build up.

The Acoustic Emission NDT technique is based on the detection and conversion of these high frequency elastic waves to electrical signals. This is accomplished by directly coupling piezoelectric transducers on the surface of the structure under test and loading the structure. Sensors are coupled to the structure by means of a fluid couplant and are secured with tape, adhesive bonds or magnetic hold downs. The output of each piezoelectric sensor (during structure loading) is amplified through a low-noise preamplifier, filtered to remove any extraneous noise and furthered processed by suitable electronic equipment.

The instrumentation of Acoustic Emission must provide some measure of the total quantity of detected emission for correlation with time and/or load (Figure 2-10).

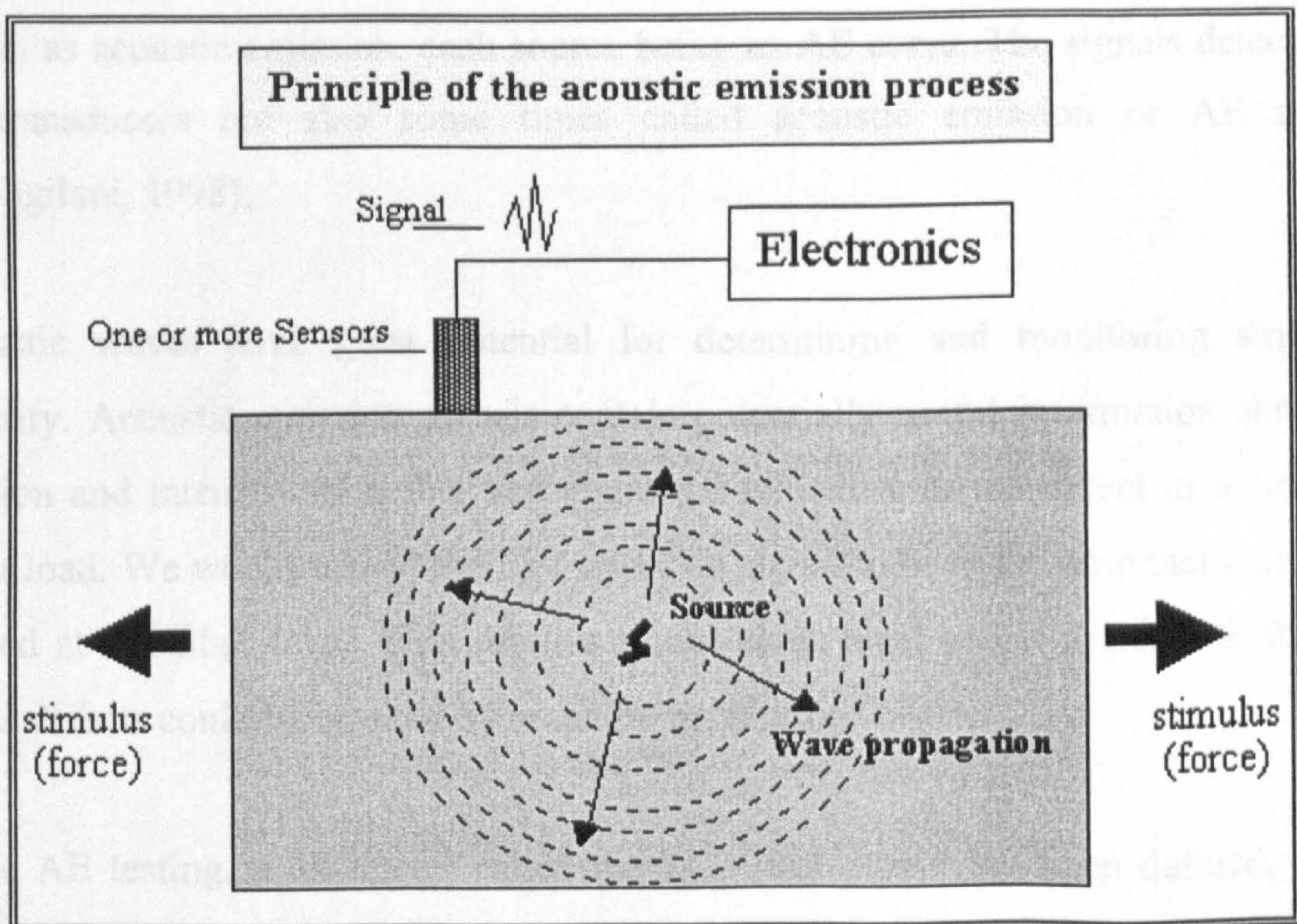


Figure 2-10: Acoustic emission is transient elastic waves generated by rapid release of energy from localised source within a material.

- Acoustic emission in fibre rope

The term acoustic emission is used to describe both a technique and the phenomenon upon which the technique is based. Acoustic Emission (AE) or stress wave emission is the phenomenon of transient elastic wave generation due to a rapid release of strain energy caused by a structural alteration in a solid material. It should be emphasised that, unlike ultrasonic, acoustic emission is a passive monitoring system. Signals are not injected into the structure except for calibration purposes. Generally speaking, the proportion of the energy that is released as elastic wave rather than heat, depends on the nature of the source, how localised it is and how rapidly the releases takes place. Localised rapid energy releases give rise to elastic waves in the ultrasonic frequency regime that can be detected by microphones or transducers attached to the surface of the specimen provided the waves are of sufficient amplitude. This whole process is known as acoustic emission, each source being an AE event. The signals detected by the transducers are also some times called acoustic emission or AE signals (Koohgilani, 1998).

Acoustic waves have great potential for determining and monitoring structural integrity. Acoustic emission signals contain potentially useful information about the location and intensity of defect and about the criticality of the defect in a structure under load. We would expect the first emission signal to be at the time that a defect is located at the fibre level. This implies a molecular level and it is possible that the initial defects could be masked by machine noise, etc.

In the AE testing, a parameter called the "AE load delay" has been defined, as the tensile load required producing a specified low baseline level of the AE activity. It has been observed that the AE load delay can be correlated with the ultimate rupture load of the ropes having various numbers of cut core yarn and a variety of stress concentrating knots.

When a specimen is loaded gradually from a zero load, the AE begins to be detected at a specific time, which corresponds to a specific load. The corresponding load level is defined as the "AE load delay". Because of the potential noise problems and the intrinsic threshold limitations of the AE test system, a convenient and practical level

of the AE activity is defined to be the load delay. Specifically, the load delay is defined, as the load required producing a specific load level of cumulative AE event and ring-down counts. Thus, the AE load delay based on the cumulative AE events or ring-down counts from the same specimen may be different, depending on the specified levels set for the cumulative AE event and ring-down count, respectively (William *et al*, 1982).

- Discussion of the Kaiser and Felicity Effects

Historically, the term “Kaiser Effect” honours J. Kaiser (1950) and his original observations of reloading phenomena in several metals. The important points here is that these are physical observation not immutable laws. Fowler (1979) originally conceived the term felicity ratio, for the observed behaviour of many composite materials, defined to be:

$$\text{Felicity Ratio} = \frac{\text{load at which AE is observed on reloading}}{\text{previously applied Maximum load}} \quad \text{Equation 2-2}$$

Over the past several years, several inaccurate notions have arisen regarding these phenomena including:

- All metals exhibit the Kaiser effect (e.g. materials which exhibit twinning do not exhibit this effect.
- All composites exhibit the felicity effect
- If a material exhibit the Kaiser effect for a particular test condition, it will exhibit the Kaiser effect for all conditions and geometries.

The Kaiser effect has been shown to be valid only for unflawed polycrystalline metals tested under uniaxial loading conditions where reloading was immediate. However, if not, (the time is dependent on the material and the temperature) some AE activity can be observed. This is principally attributable to the migration of dislocations, the readhesion of cracked particulates, or the reformation of oxide coatings in the in the

intervening time period. It should be also mentioned that most tests are conducted under uniaxial test conditions while most structural materials are actually subjected to biaxial or triaxial loading conditions. In these conditions it is plausible to expect that the results would be path dependent, i.e. if one were to change the manner in which the load was applied on reloading, even though the final stress state was the same (e.g. tension followed by torsion initially vs. torsion followed by tension) the Kaiser effect would probably not be seen. For these materials, local material failure (either via matrix cracking, fibre matrix debonding, fibre friction, etc.) is the principal AE source not dislocation motions. Upon reloading AE can still be generated at these microfunction sites, principally by rubbing of mating crack surfaces. In this regard, composites are similar to flawed metals where the Kaiser effect is not nearly as evident (Kline, *et al*, 1987 & Scott, 1991). Both the above effects refer to the presence or the absence of AE activity upon reloading of a sample. If no acoustic emission is observed, the Kaiser effect is said to hold. Any deviation from this behaviour is known as the Felicity ratio.

Obviously, a felicity ratio of one would correspond to the Kaiser effect. Ratios greater than one, while possible, would also indicate that the Kaiser effect was present. It should be noted that Japanese researchers use the term Kaiser ratio in place of Felicity ratio.

- Generation of AE by Source Events

The source of the elastic waves is an event inside the body. In many cases it is no trivial matter understanding what the source events are in practical materials or what the generation mechanism is. In the case of a growing crack, still arguably the most important AE source and the formation of new crack faces must be accompanied by sudden changes in stress and displacement of material in the vicinity of the crack. Varying stresses and strains must by definition act as sources of stress (elastic waves).

2.6 Rope Failure

Synthetic fibre ropes have many unique features that make them attractive for use in marine environments. The cost of failure in the mooring line is very high and failure in the line could cause a major disaster in platform or ship apart from the line itself. The probability of the failure at any given load increases with the total line length and the number of terminations. It also depends on the mean strength and the strength variability of the terminations and other components (Seo *et al*, 1990).

Some investigations on single point mooring (SPM) hawser system accidents recommended using a more durable fibre rope material, which alleviated a pattern of breakouts at fleet moorings. In another case, an improper splicing method was determined to accelerate the rope fatigue. In an SPM accident case, computer analyses and model tests demonstrated that mooring loads probably exceeded the strength of the failed component (Backer *et al*, 1985).

The factors, which adversely affect the life of synthetic fibre ropes in marine services, are as follows (Flory *et al*, 1990):

1. Environmental factors: Moisture, oxygen, chemicals, biochemical attack, ultraviolet light, and heat.
2. Physical factors: Molecular structure, lay effects, specific gravity, and physical structure.
3. Mechanical factors: overload, creep, hysteresis, stress rupture, internal & external abrasion, bending, fibre fatigue, structural realignment, fishbites, failure by rotational cycling, and human interaction.
4. Termination: Different termination methods affect rope failure and breaking patterns differently.

The most relevant properties mentioned above are mechanical factors and termination effects.

2.6.1 Mechanical Factors

Mechanical factors are parameters like overload, tensile, creep, hysteresis, fibre fatigue, and internal abrasion. These are generally associated with straight tension or tension cyclic loadings. They also occur in torsion and bend cyclic loadings. The salient mechanical factors that may affect rope performance are discussed below:

I. Overload: Like any other structure, synthetic fibre ropes fail when the components are overloaded. The strength of the rope depends not only on the strength of the fibre material but also on the efficiency of the rope structure, including the terminations. In an inefficient structure or termination, stresses are not uniformly shared, and some fibres reach the breaking strength long before the full potential strength (Flory, 1990). It is also possible that failures caused by energy differences between moored objects, which exceed the mooring systems' energy absorption capability, typically found when too short mooring lines are used to moor or tow a vessel subjected to wave motions (Flory *et al*, 1998).

II. Creep: Creep, is the permanent increase in length as a result of loading and takes place in all synthetic fibres at low loads and its rate decreases with time until it becomes virtually indiscernible. However, in some materials at high load, significant creep continues and eventually causes failure. Creep failure in ropes only occurs in high loads. All the synthetic yarns used in the marine environments exhibit some creep effects. Below a critical load residual extensibility stabilises as loading continues. Above the critical load, creep continues until failure. Before this most ropes will show an increase in strength due to the progressive alignment of the load bearing fibres (Parsey, 1982). All synthetic materials exhibit a certain amount of creep. However, it is only significant in ordinary and high modulus polyethylene. Shin (1994) has found that the creep-time behaviour of nylon rope test specimen follows a logarithmic law.

III. Hysteresis: Hysteresis is the loss of energy during cyclic loading. Friction due to relative slippage of adjacent elements causes loss of energy and heat build-up. When a synthetic fibre rope is used at sea to tow a load, the rope is subjected to a dynamic, cyclic tensioning due to ship displacement induced by wave action. This cyclic

tensioning is superimposed on a mean tension which is determined by the wind velocity, vessel speed and heating. Under such a cyclic loading, the rope, as a viscoelastic structure, absorbs energy. Part of this energy is dissipated in the form of heat, which results from the plastic deformation and the inter-filament friction between rope fibres. This energy is absorbed by the rope, or the hysteresis, causes temperature rise inside the rope. Increasing the temperature melts or fuses fibres, and accelerates rope failure (Shipeng *et al*, 1990; Cerqueira *et al*, 1998).

IV. Stress rupture: When some materials are subjected to permanently applied loads, they eventually creep to failure. This phenomenon is generally referred to as stress rupture. In some studies it is named as creep rupture. Mandell *et al*, (1987) studied fatigue resistance of individual synthetic fibers e.g. polyester and nylon 6,6 fibers and yarns and proved that fibre failure over a range of loading conditions and frequencies occur at a critical cumulative strain, governed by a creep rupture process.

V. Internal abrasion: Relative motion between various rope components, fibres, yarns, and strands results in abrasion damage. Examinations by Flory (1989) on nylon rope showed strong evidence that internal abrasion was the principle cause of strength reduction. Yarn-on-yarn abrasion tests at low load levels on nylon ropes showed that the dry yarn withstood about one hundred times as much abrasion cycles as did the wet yarn. However, the same yarn with an improved finish performed much better, both dry and wet. Mandell (1987) stated that the abrasion failure depends on the number of cycles rather than loading in a time dominated fashion. Failure occurs when enough material is removed so that the maximum cyclic load applied to the remaining material reaches the new breaking strength of the rope that has lost part of its material.

Crawford (1983 & 1985) reported that most of the abrasion damage takes place between strands on the inner and outer braids, either in the eye, the splice, or along the free part of the rope; this is classified as internal abrasion. Leeuwen (1981) believed that the internal abrasion is not a pre-dominating factor in fatigue cycling test. This was concluded by measuring the residual breaking strength of ropes after some hundred thousands of cycles.

VI. External abrasion: The rope can be abraded against any proximate object, such as termination fittings, sheaves and fairleads, and also on the ship's deck and the sea floor. Goksoy *et al*, (1988) conducted a series of yarn-on-yarn abrasion tests on nylon and polyester in different environments (tap-water, in distilled water, in synthetic sea-water, and in NaCl solution). The effects of pre-soaking were studied as well. The different wet environments did not give large differences in abrasion life, but nylon exhibited a lower life wet than dry. Severe reduction of life occurs in yarns dried from the salt solutions.

VII. Bending: While in service, a rope may be bent around a pulley or sheaves, and this bending has been shown to increase expected tensile loads, radial forces, and torsional moment (Heirigs *et al*, 1992).

When a rope bends around a sheave, the rope's strands and sub-ropes must move relative to one another. This movement allows the sub-rope to compensate for the difference in travelling distance between the underside and the topside of the rope, the distance being greater along the topside. Rope action is adversely affected if the sub-ropes cannot move properly. Any changes, which take place in the rope, due to the conditions under which it operates, will materially change the bending stress. These conditions include any instance or circumstance that restricts the movement of the sub-ropes (Anon, 1999).

VIII. Rope fatigue: Marine ropes may be subjected to a complex variability of static and cyclic load under varying environmental conditions. Nylon and other synthetic fibres are known to be degraded by cyclic loading.

Polyester and polypropylene ropes have superior resistance in cyclic loading compared with nylon. Nylon ropes lose approximately 15% of their strength in wet conditions while this is approximately nil for polyester and polypropylene. Nylon fibres and yarns are found to lose a significant fraction of their strength when subjected to cyclic fatigue loads (Crawford *et al*, 1983; Flory, 1977).

IX. Structural realignment: Mechanical distortions, such as hackles and birdcaging, cause undesirable redistribution of stress and strain in the rope. Structural realignment also leads to a progressive failure of sub-elements.

X. Fishbites: Deep-sea mooring lines are subjected to fishbite attacks, which can and often do cause total failure of the mooring. Practically it is not possible to stop fishbite, but there has been extensive research on deploying different covers to reduce its effect on the line. Three types of fishbite resistant materials have been tested; tubular plastics, Zytel extrusion, and Kevlar and Spectra braids. The two new braided jackets seem to offer excellent protection to synthetic fibre ropes of smaller size (Berteaux, 1991).

XI. Failure by rotational cycling: The rope unwinds under low tension (less than 3% of break strength), that makes the strands bulge or birdcage. The tight jacket prevents gross rope bulging so the strands go into compression and kink. Cycling the compressive load through the kink causes accumulated damage and loss of strength, which basically depends on the rate of cycling, and the load applied. A reduction of up to 30% for high loads is reported while in low loads the reduction could be ignored (Hervey, 1988).

XII. Human Interaction: Rope failure can be caused by human interaction, natural occurrences or by the rope system and its components. Typical human interaction is through ships or fishing equipment overrunning moorings either accidentally or with the intention to “salvage” (McKenna, 1996).

XIII. Failure due to snap Loading: Bitting (1980) proved that nylon line can fail at relatively low loads (about 70% of its new breaking strength) due to snap loading. Also cyclic test results suggest that the tensile strength of nylon line is not reduced if the minimum load does not reach zero and maximum load does not exceed approximately 60% RBS (Rope Breaking Strength). A preliminary design guideline states that if the line is under tension, the maximum applied dynamic load may be as high as 60% RBS. If there is no tension, then the maximum dynamic load should not exceed 30% RBS.

2.6.2 Termination effect

One of the most important considerations in rope failure is termination. It has been reported that most rope failures, in service, occur in or near the termination area [Chaplin (1999), Smith *et al*, (1981)]. In order to obtain valid data from laboratory tests, the failure position must be outside the termination area. Otherwise the termination has a limiting effect on the rope performance.

2.7 Rope failure mechanisms

Interest in failure mechanisms in synthetic fibre ropes has increased in proportion to the number of serious accidents which have occurred during marine usage (Seo *et al*, 1990). Most accidents are caused by malpractice in use rather than faulty material (Dunn, 1995). Investigations are being carried out to assess the causes of failure in rope and the more sensitive elements in a mooring line. Tension Technology International (TTI) has participated in almost a thousand break tests of fibre ropes and have analysed many rope failures. TTI has investigated three major towing accidents. One involved the use of two tugs towing a platform. Computer analyses examined on the failed mooring lines. In most cases it has been proved that mooring loads exceeded the strength of the failed component (TTI Report, 1999).

Backer *et al*, (1981) conducted an extensive work to investigate the deterioration of synthetic fibre ropes in marine environments. Each of the worn ropes selected was analysed to its structural composition. Different mechanisms of failure are discussed below.

2.7.1 Tensile failure mechanism

Ropes and chains are bodies, whose symmetrical, mostly circular cross sections, are small compared with their lengths. They are able to transfer loads only along their axes. They can not transfer bending moments or transverse forces of any magnitude and are unstable under compressive loads, they will bend out.

Many successful structural models have been developed (Backer *et al*, 1985) to predict the static tensile behaviour of ropes and its failure mechanism. These models often assume that spatial locations along individual strands can be described by a helix with a sinusoidal undulation in their radius direction. Thus the local strand strain can be calculated on the basis of the differential geometry of strand segments before and after the rope is stretched. Strand load is readily determined through the load strain relationship. By converting the individual strand load into the rope axial load

and summing up the contributions from different strands, a load/strain curve is generated.

2.7.2 Fatigue failure mechanism

Most of the existing literature on rope fatigue includes wire ropes (Niedzwechi, 1978; Hear, 1982; Muskalski, 1998; Golis, 1998; Anon, 1999; Chaplin, 1999). However some work has been carried out on synthetic fibre ropes in the past two decades (Casey *et al*, 1993; Wu, 1992; Heirigs *et al*, 1992; Mandell *et al*, 1987; Kenney *et al* 1985). Experiments have shown that the strength of synthetic ropes may degrade due to cyclic loading (Flory *et al*, 1972). The mechanism of fatigue is not fully understood yet and cannot be accurately predicted. One factor, which may affect the fatigue rate at which the fibres are tensioned, is their position in the mooring line. Another factor is the load range over which the rope is cycled.

The fatigue deterioration of a rope is a complex process. Often, as in the case of marine usage, a rope will be subjected to repetitive tensioning accompanied by free transverse motion. Although the average loading level may be less than 10% of the nominal breaking strength, the transverse motion may cause local bending, inter-strand movement, and high lateral pressure (Heirigs *et al*, 1992).

2.7.3 Creep failure mechanism

When some materials are subjected to permanently applied loads they eventually creep to failure. This phenomenon is generally referred to as creep-rupture.

Shin *et al* (1994) carried out a series of tests on nylon fibre ropes under the constant loads 30% and 14.7% of the breaking strength. The creep curves of synthetic fibre rope test specimen showing extension versus log(time) seemed to be almost straight lines. It means that the creep-time behaviour followed a logarithmic law.

Chiao *et al* (1977), Glaser *et al* (1984) and Howard *et al* (1985) are amongst many researchers who have paid considerable attention to the creep-rupture behaviour of the

Kevlar ropes. In all cases it was found that Kevlar yarns would support a large proportion of their nominal short-term ultimate loadings, for long periods of time, but that there was considerable variability in the creep-rupture lifetimes for any given load level.

The creep of Kevlar 49 and Kevlar 29 is generally considered to be a logarithmic function with time. The creep rates for Kevlar are low when compared with other synthetics such as nylon or polyester, and it actually approaches that of steel. Lafitte *et al*, (1980) reported that the creep rates for yarns of Kevlar 29 and Kevlar 49 are insensitive to the loads between 20% and 50% of the ultimate load but that they decrease at lower loads. Creep rates of 0.02% and 0.052% per decade were observed at room temperature for Kevlar 49 and Kevlar 29 respectively (one decade is equivalent to one unit on a log time scale to base 10).

2.7.4 Failure due to line elasticity

Flory *et al*, 1987 suggested that under a given load, an elastic line will stretch more than a stiff line. Elasticity plays an important role in the mooring system for several reasons:

1. High elasticity can absorb higher dynamic loads. For this reason, high elasticity is desirable for ship-to-ship transfer operations, or at terminals subject to wave or swell.
2. On the other hand, high elasticity means that the ship will move further in her berth and this could cause problems with loading arms or hoses. Such movement also creates additional kinetic energy in the mooring system that could lead to line failure.
3. A third and the most important aspect is the effect of elasticity on the distribution of force among several mooring lines. The simple four-line mooring pattern is insensitive to the elasticity of lines, but it is suitable only for boats or very small ships. Due to size limitation of individual lines, many more lines must be used for larger ships. The optimum restraint is generally accomplished if all lines, except spring lines, are stressed to the same percentage of their breaking strengths.

2.7.5 Failure due to energy absorption

Walter (1980) reviewed energy absorption in the rope. The high total weight of a chain and/or wire rope mooring systems provides some advantages in terms of energy absorption. As a moored platform experiences an excursion, the individual mooring lines must respond by either rising from or lowering to the ocean floor a portion of their total length. Thus, a simple movement of the individual mooring lines dissipates energy. To improve the energy absorption of non-metallic ropes, chain segments at the ocean floor or clump weights could be introduced. Alternatively, one could add more line until this situation improves, but it is conceivable that the length of line required could be impractical. As the water depth increases significantly, the advantages of a conventional mooring decrease. For example, as the water depth increases, chain is required to use an ever-increasing portion of its strength just to lift the chain off the ocean floor. This means that the vertical component increases while the station keeping component (the horizontal component) decreases. Thus the weight of the chain required as the water depth increases exceeds the safe working loads and eventually exceed the chain's breaking strength. The same holds true for wire ropes, but because it is lighter than chain, the water depth before this happens is much deeper. In comparison, non-metallic ropes have little difficulty in this regard.

2.8 Prediction of rope failure

Given the costs of failure, the importance of rope failure prediction is apparent. A lot of effort is being made to predict mechanisms and time of the failure to reduce these costs.

Non-destructive tests is a field which has been widely studied in recent years [Casey *et al*, (1985), Ludden *et al* (1996), Casey *et al*, (1997)]. It is considered that any crack in the rope, produces a signal, which could be interpreted as a sign of damage or failure. The different accumulated signals could lead to different interpretations regarding the final failure. Therefore, by recording and analysing the different signals, it is potentially possible to predict the rope failure.

2.8.1 Acoustic Emission Applied to Synthetic Fibre Rope

The applicability of the stress wave emission phenomena from synthetic ropes can give an indication of the imminent failure by an increase of at least an order of magnitude in the slope of the curve. Comparison of the number of stress wave emissions with the applied load is a good indicator of impending catastrophic failure. However, no significant differences in the stress wave emission characteristics, were observed for the three types of materials considered (Ludden *et al*, 1996).

2.8.2 Computer modelling

In an ideal rope structure, all elements share load equally such that they all reach rupture strain at the same time. In an actual rope, load sharing varies among elements due to many factors, including: unequal tensions applied during the rope making process, differences among lengths along various helical paths, non-linear stress-strain characteristics of synthetic material fibres, statistical variations of stress-strain and strain-to-rupture characteristics, compaction of elements, and slippage among elements.

“OpTTI Rope”, a computer model developed by Tension Technology International (TTI), has successfully been deployed to calculate and monitor the strains in all

elements throughout the rope. It accounts for all the important aspects mentioned above. Thus the program has been found to be able to predict which element will reach breaking strain and fail first and at what imposed rope strain or torque that element failure will occur (Banfield *et al*, 1995).

The program then models the cessation of load-carrying ability of that element and transfers that load to adjacent elements. The program establishes the changes in strain in those adjacent elements and the resulting change in the overall rope length. In some cases, the failure of one or several elements will cause the adjacent elements to fail immediately, possibly leading to a catastrophic failure of the entire rope. In other cases, the rope does not fail but suffers a loss in its strength (TTI Report, 1999).

2.8.3 Mathematical modelling of tensile fatigue life

Coleman (1958) derived general expressions of the fatigue life of the fibre bundle with uniform load sharing. He concluded that given a semi-log S-N relationship for the fibre fatigue behaviour, the Minor's rule would provide a similar linear S-N relationship for the fibre bundles. Since both these treatments assume large numbers of elements with uniform load sharing, the results can not be directly applied to a small sample size, such as for a double braided rope made of two layers, sheath and core, and with ideal yarn helices lying in several distinct layers. The fatigue behaviour of fibre bundles structured in different layers will now be derived using the Minor's rule as the cumulative damage rule.

2.9 Conclusion

In this chapter, parameters related to rope termination were discussed. Ropes and their structure, requirements and applications in marine environments, mechanical performance, failure and its mechanism and some proposed methods for rope failure prediction were also reviewed in this chapter. This was done to make the reader familiar with the current situation of this field, and to pave the ground for more specific concepts in the following chapters. In the next chapter, parameters related specifically to terminations are discussed.

Chapter 3: Background and Theory of Rope Termination

3.1 Introduction

One of the most important considerations in developing an effective fibre mooring system is the design and performance of termination. This will decide the efficiency of load transfer in the system, since failure usually occurs in high stress concentration areas around the rope-termination interface (Vaseghi *et al*, 1996).

Horn *et al*, (1977) studied the choice of termination for three important types of rope constructions including impregnated rope construction, braided and parallel lay ropes. He believed that termination should be chosen based on the type of rope construction and the type of loading and service conditions to which it would be subjected.

Despite some new efforts to utilise socket termination, e.g. “Deep Star” project in Gulf of Mexico, termination of synthetic fibre ropes, as it is known up to now in marine environments, is by means of splicing. This is a typical method of termination for small ropes. The popularity of the splice usage could be due to the lack of information on other terminations and the difficulties in testing methods. Testing procedures on large diameter ropes are not as easy as those for filaments and yarns. In most cases manufacturers do not undertake the risk of new methods in practice because of high development costs unless the traditional method(s) are unable to fulfil the expected requirements for a new project.

Recently there have been some efforts on improving socket termination for synthetic fibre ropes (Vaseghi, 2000; Bardoliwalla, 1997; Brown, 1997; Flory, 1995). These show that the socket could be a potential replacement for the splice and in some cases performs even better. The most recent case (Vaseghi, 2000), suggests an improvement of 10-13% in tensile strength compared with the best spliced ropes tested.

3.2 A new method of termination, The Vaseghi Stress Relief Socket

The present invention is related to a method of terminating a fibre rope utilising a socket and a spike. This method is based on trapping the fibres between the socket and the spike. The relevant patent specification UK 2 313 853 B and US 5,904,438 are presented in appendixes 1 & 2 respectively. The detailed designed resulting from these patents is given in appendix 3.

Using this method of terminating a rope, it has been found that there is a tendency for the fibre of the rope end portion to abrade. Abrasion of the fibre occurs mainly in the region where the fibre contacts an apex part of the spike. The abrasion of the rope fibres substantially reduces the breaking strain of the rope.

To overcome this problem, it has been suggested (British Patent, GB 2 236 546) to use resin on the rope end portion. The resin composition is applied to provide a lubricating effect on the fibre to reduce abrasion thereof around the apex part of the spike. Despite this, stress concentration around the apex part of the spike results in the tensile failure of the rope.

The aim of the present invention is to obviate or mitigate the aforesaid problems associated with the previous methods of terminating a fibre rope. It is a further object of the present invention to provide a method of terminating a fibre rope having a diameter in the order of 1 inch (2.5cm) or larger fibre ropes of this and much larger diameters are employed in marine applications when light weight but high tensile strength is required. Based on the first aspect of the present invention, a method for terminating a fibre rope is developed. This method includes the following steps:

- introducing into or incorporating in an end portion of the rope means for reinforcing rope end portion;
- locating the spike inside the reinforced rope end portion; and securing the rope end portion in the socket.

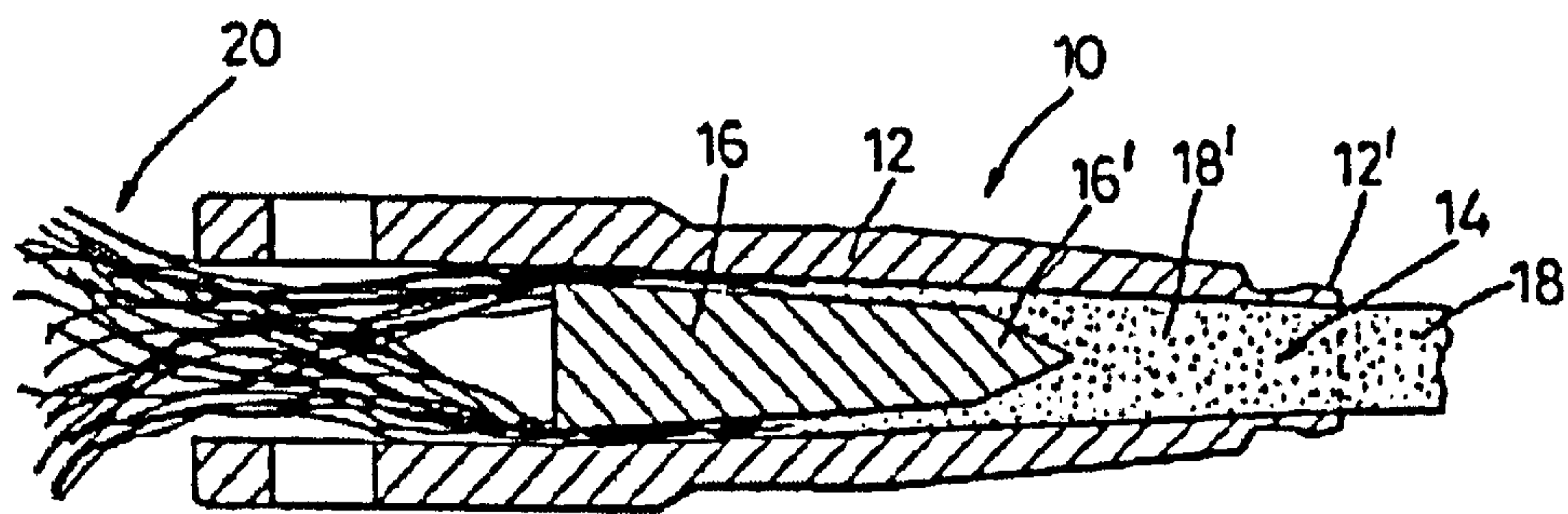


Figure 3-1: Cross-sectional side view of a rope and a socket

Figure 3.1 shows the traditional method of rope termination in which the Parafil socket (10) is used to terminate a rope. The spike (16) is used to trap the rope (18) inside the socket. The tensile load applied to rope end portion 18 will cause rope end portion 18' to become more securely retained within socket (12). However wedge member of spike (16) applies a greater crushing force on trapped fibres 20 and causes fibre damage. Another problem with this method is that the rope becomes abraded between the socket and the spike; thus substantially reducing the breaking strain of the rope. Also the fibres may also become abraded in a region surrounding a mouth part 12' of the socket. Experience has shown that this is the most likely point of tensile failure of the rope.

Figure 3.2a illustrates a method of terminating a rope end portion in accordance with the first method of the present invention. The socket and the spike have similar structures to that utilised in the previous method.

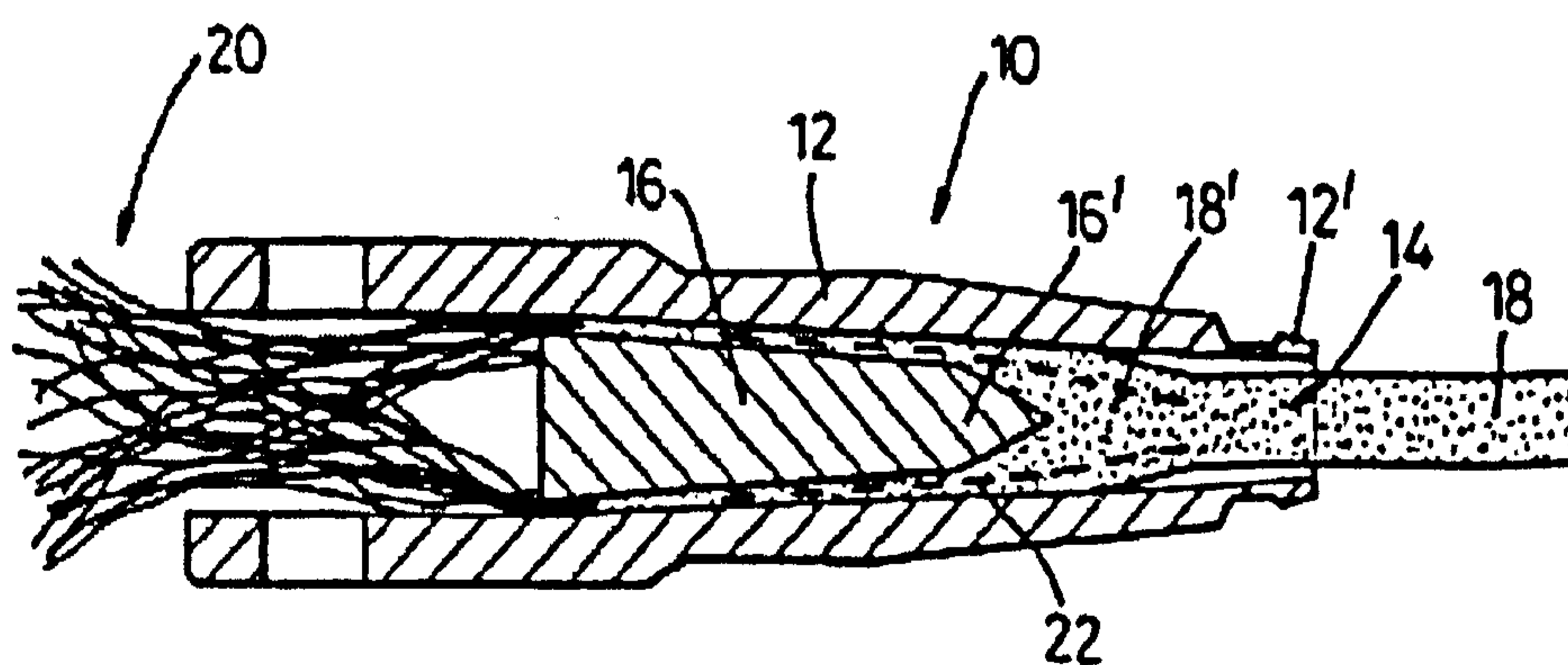


Figure 3-2a: Cross-sectional side view of a rope and a rope end termination device illustrating a first method of terminating a rope in accordance with the present invention

The first part of this invention comprises inserting reinforcing material inside rope end portion 18' in the region surrounding the apex part of the spike. The reinforcing material is preferably the same as the rope to be terminated. A tensile load on rope 18 transfers through friction to the fibres of the reinforcing rope portion 22 thus transferring part of the tensile load away from apex part 16' of wedge member 16. The reinforcing material is inserted inside the hollow part of the rope.

Figure 3.2b shows an enlarged view of a braided layer of a fibre rope which is reinforced over its length by splicing strands 19 of a reinforcing section of rope of the same structure with strands 18a of the fibre rope 18. For convenience, only one strand 19 of the reinforcing rope is shown in the figure. It will be appreciated that splicing the strand as mentioned above is impracticable with fibre ropes of relatively small diameters. However, for ropes having a diameter of greater than 1 inch (2.5cm), the size of strands comprising the rope is of a size which allows splicing to be relatively easily achieved.

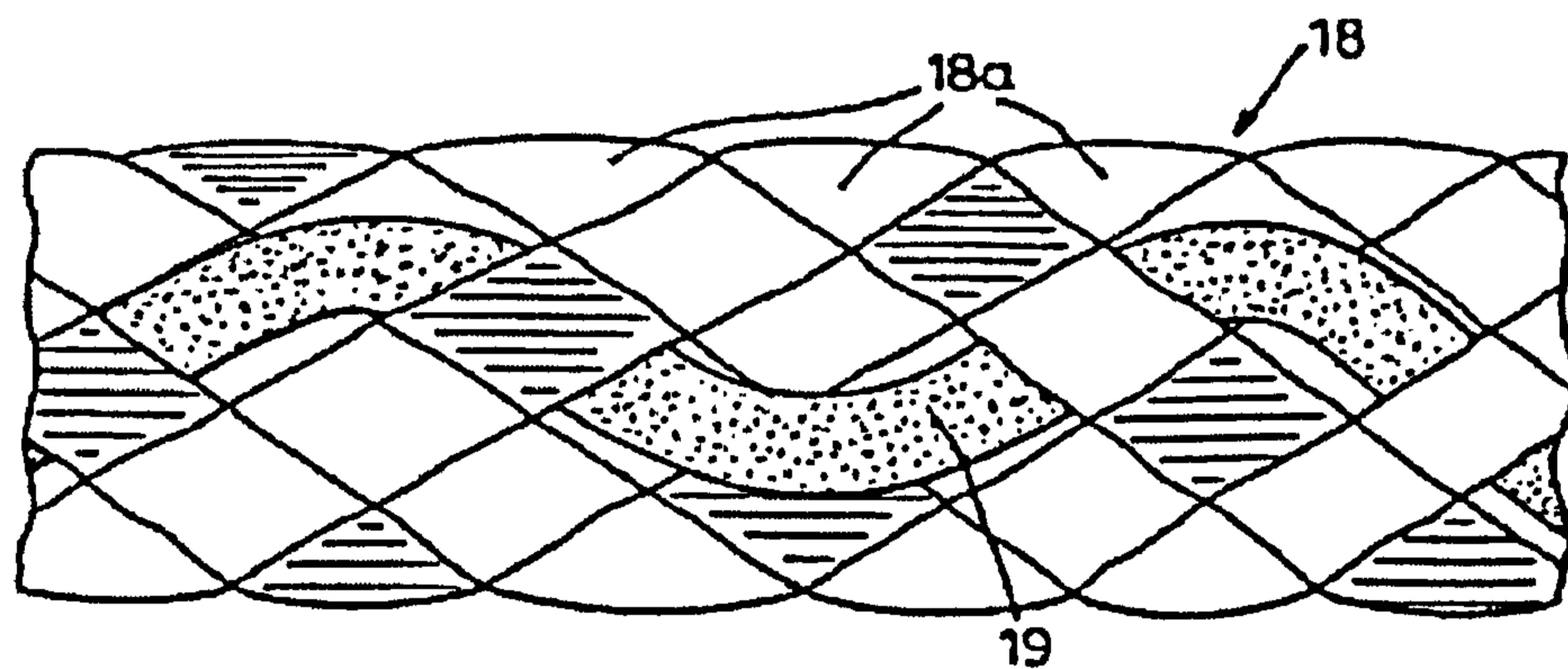


Figure 3.2b: An enlarged view of a braided layer of a fibre rope is reinforced over its length by splicing strands

The splicing of the reinforcing strands 19 with the strands 18a of the rope 18 greatly increases tensile load transference within the structure of the reinforced rope end when compared with a reinforcing rope section being inserted within the core of a braided fibre rope.

Figure 3.3 illustrate a second method in accordance with the invention. This method is similar to that of the first method. However, the reinforcing material length is longer than the previous method to move the stress far from the socket.

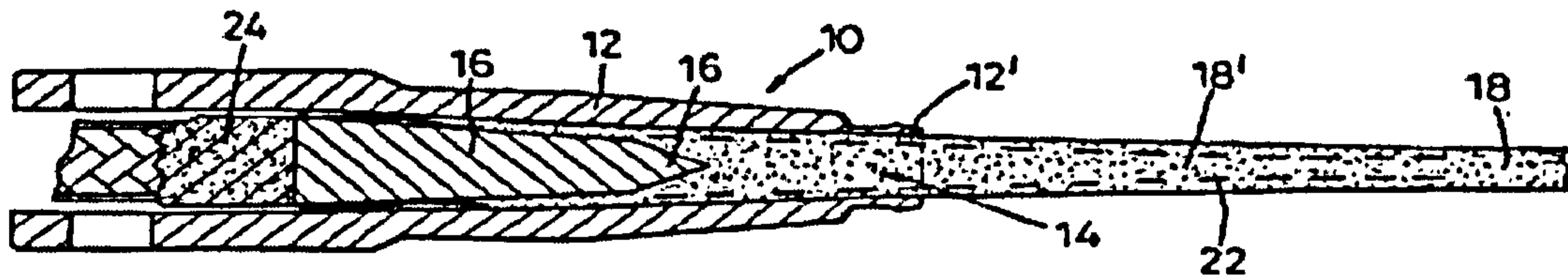


Figure 3-3: Cross-section side view of a rope and a rope end termination device illustrating a second method of terminating a rope in accordance with the present invention

It has been found that it is possible to transfer up to half of the load away from the socket by applying the reinforcing material.

The reinforcing material is tapered to transfer the load gradually to its tail and avoid stress concentration along the rope.

The method may include placing a further resin composition 24 in the end of the rope behind the socket to bind loose fibres 24 of rope at the rear end of the socket.

Figure 3.4 illustrates a third method of terminating a rope in accordance with the present invention. This method involves reinforcing rope end portion 18' in a manner similar to either of the methods described respectively with reference to Figure 3.1 and 3.2, but a spike is not required to secure rope in the socket. In this method, the reinforced rope end portion is secured by locating it in bore of the socket and by pouring a resin composition into the bore. The resin application makes a conical shape inside the socket and traps the reinforced rope, thus preventing it from being pulled out.

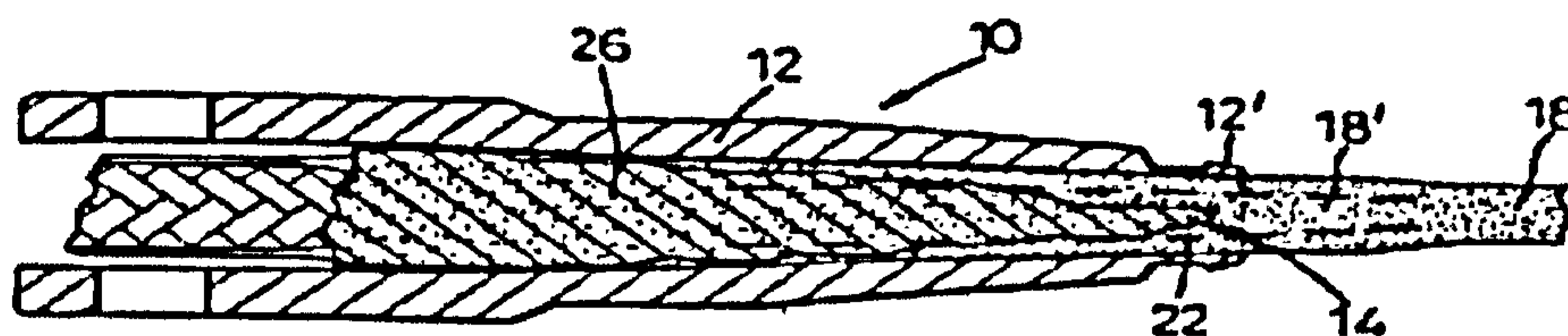


Figure 3-4: Cross-section side view of a rope and a rope end termination device illustrating a second method of terminating a rope in accordance with the present invention

Figure 3.5 illustrates a fourth method in accordance with the present invention. This method is similar to that described with respect to figure 3.4, but differs in that the reinforcing fibre rope portion 22 is preformed with a resin cone 28 at an end and the combined rope portion 22 and resin cone 28 is inserted into the rope end portion 18'. Rope end portion 18' is then drawn into bore 14 of the housing member 12 where the resin cone 28 wedgedly retains rope end portion 18' in the housing member 12 and rope portion 22 reinforces rope end portion 18'. This method has the advantage of reducing the number of components to be combined when terminating the rope 18.

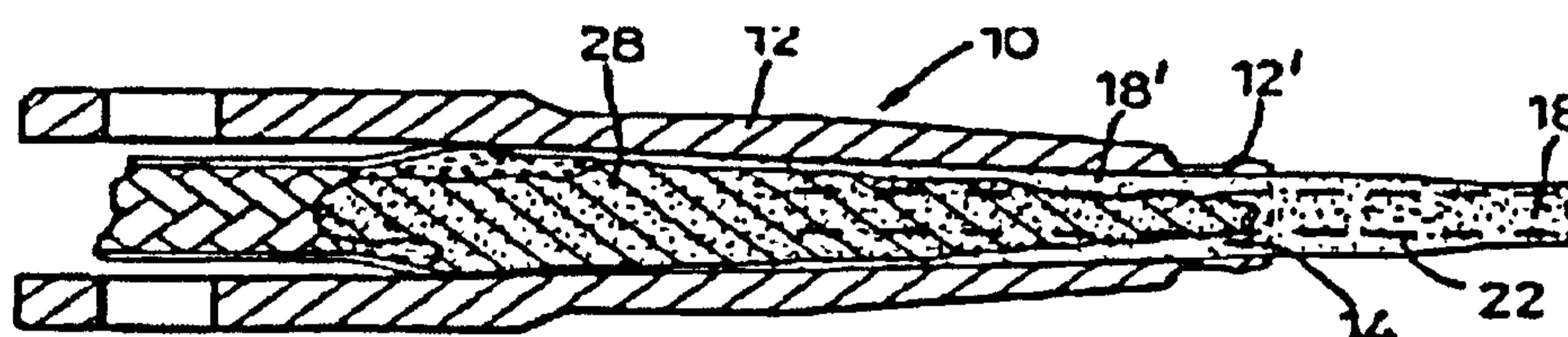


Figure 3-5: Cross-sectional side view of a rope and a rope end termination device illustrating fourth method of terminating a rope in accordance with the present invention.

Figure 3.6 illustrates a fifth method of reinforcing a fibre rope in accordance with a fifth method of the present invention. This method is particularly applicable to terminating fibre ropes of relatively large diameter, i.e. having a diameter in the order of 4 inches (10cm) or greater.

This method of the invention can also be used to terminate a bundle of fibre ropes comprising a plurality of parallel lengths of fibre rope of similar construction for use in heavy duty marine application. The methods of the present invention make use of load transference by means of introducing into or incorporating in an end portion of a

rope to be terminated a material or means which increases the load bearing characteristics of the rope end portion such that a portion of the tensile load exerted on the rope transfers down the rope away from the reinforced end portion.

Whist various methods of the present invention have been described generally with reference to terminating a fibre rope having a braided construction using a reinforcing fibre rope portion also of a braided construction, it is understood that the method can be applied to any fibre rope which is capable of exerting a transverse compressive load when subjected to an axial force (tensile load).

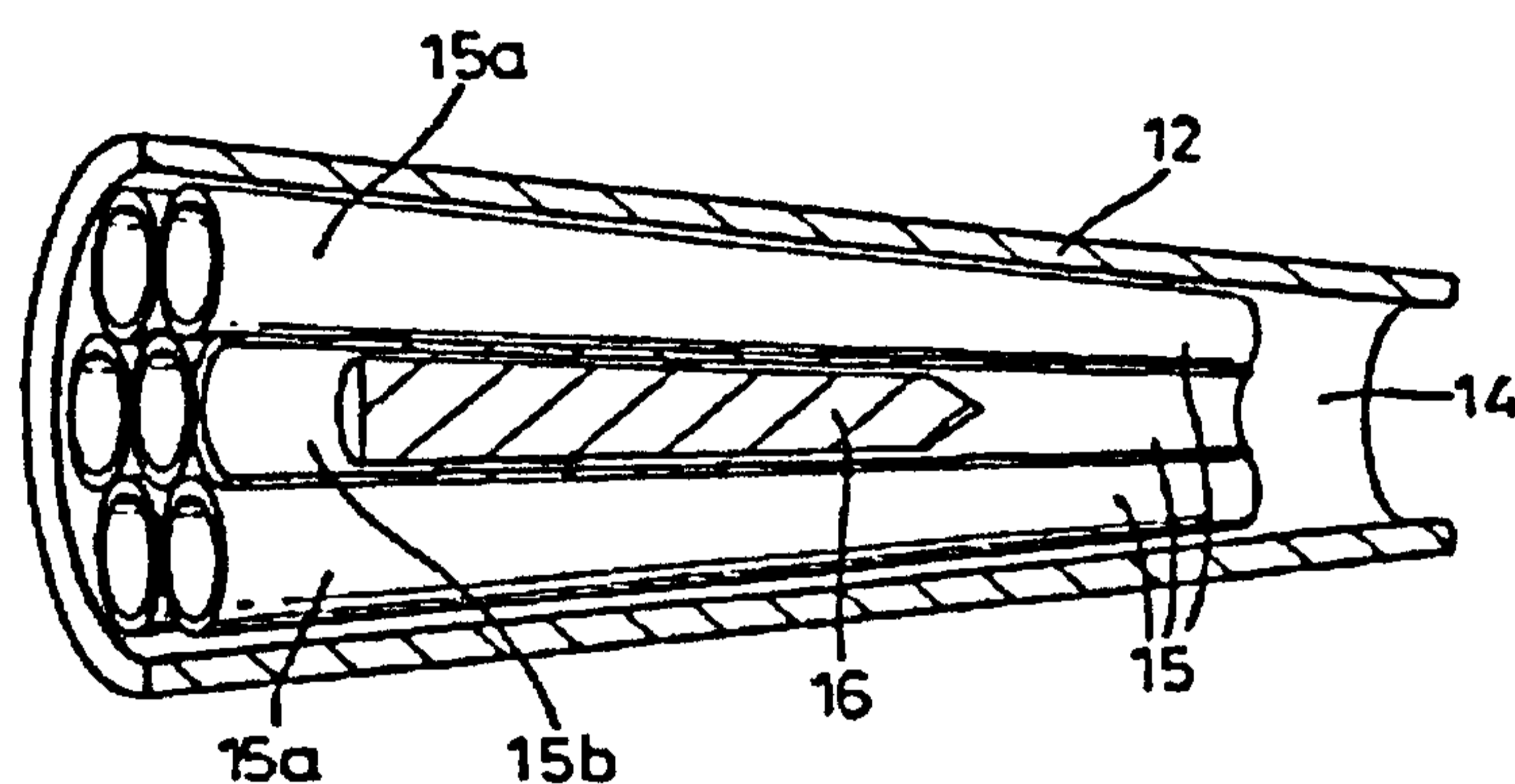


Figure 3-6: Cross-sectional side view of a rope end termination device illustrating a fifth method of terminating a rope in accordance with the present invention.

3.3 Background to existing terminations

3.3.1 Self-accommodating Termination methods

Self-accommodating termination methods use the rope itself to construct the termination and no other additional component is required.

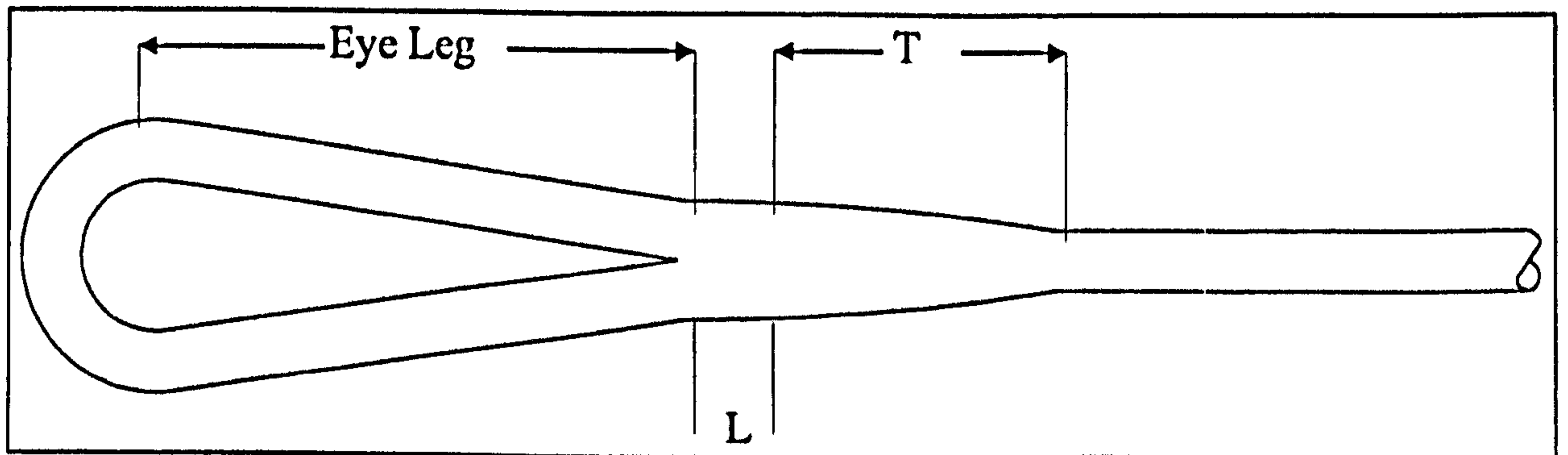
I. Splice termination

Splice is a traditional type of termination, which is widely used in industry. In this method, the rope tail is turned back and buried inside its own body. To deliver stress uniformly, the tail is tapered inside the buried area. The outer part of the buried area

plays a role of cover for the rope tail, which is inside the body. When the load is applied on the rope, compression in the buried area, keeps the whole assembly together. As the rope is pulled, the increasing load causes more lateral compression, which in turn leads to more adhesion between the rope and the tail in the buried area. Figure 3.7 shows a typical eye splice termination. The eye part is used to connect the rope to the seabed or platform. To reduce the abrading effects, a thimble (eye-shaped metal part) is used inside the eye splice. Although the strength of the rope around the radius of the thimble is reduced due to curvature, the rope is under less tension around the thimble, and does not tend to break in this area (Flory *et al*, 1977).

Some believe that splice termination can only be used on braided ropes because only braided ropes can provide an internal hollow-shape required to accommodate the tail. This can be considered as a restriction (Kenny, 1992). However it has been shown that laid ropes can also be spliced.

Splice terminations are generally the weakest points of a mooring system. Increased stresses in the hawser at a splice cause a reduction in the hawser strength. Results of a Flory (1988) survey for SPMs showed that most of the broken hawsers reported in the study failed in the area of a splice. The strength of both double-braid ropes and eight-strand braided ropes were reduced by approximately 10% when spliced, although the methods of splicing differed. The rope failures in the tests tended to occur in or at the end of the splice tail, at the tangent of the eye and the bollard, or at the back the eye. Peterline (1975) stated that the failure position appears to depend on the ratio of the rope to the thimble diameter, the type of eye protection (if any), and the rope construction. The most severe stress comes at the end of the splice, where the whole rope tension is born by the strands in a disturbed geometry, since the tuck ends can carry no load. Back along the splice, there is a progressive transfer of load from strands of two ropes until it is equally shared (Leech, 1991).



L = Length of Splice Standing part
 T = Length of Splice Tapered part



Figure 3-7: Schematic layouts of Splice termination (Woehleke, 1978).

If the platform is anchored by several legs, it is important that one splice be made in each leg to insure equal loading, and the splices should be adjacent but preferably staggered so that they do not chafe against each other. Splices affect hawser elasticity. In an eye-spliced hawser the area of rope around the thimble is equal to the area of the rope in the midsection. Under tension T , the total tension is present in the midsection, but the tension in each leg of the splice around the thimble is $T/2$ (neglecting the effect of the angle of the crotch) (Flory *et al*, 1977).

Several fatigue tests have been carried out to investigate the mode of failure in splice terminations. Fatigue failures tend to occur at or near the end of the splice tail or in the middle of the rope. Failures at the back or tangent of the eye at relatively high cycles are expected to be dominated by external abrasion, consistent with expressed opinions in several references. It appears that the effects of termination are more important in fatigue testing than the effects of rope construction (Crawford, 1983 & 1985, Leeuwen, 1981, Flory 1981 & Werth 1980).

Hand splicing by itself, whilst generating high breaking loads, is difficult to perform, time consuming and requires extra length of rope to provide for the loop and the splice tail.

II. Strop termination

A strop termination, shown in Figure 3.8, is constructed by inserting two ends of one rope into one another to form a double loop. It is important that the loads are equally shared by both legs in the strop. The two sides of the loop, referred to as legs, are usually lashed together with a small line to hold them together to prevent them from tangling.

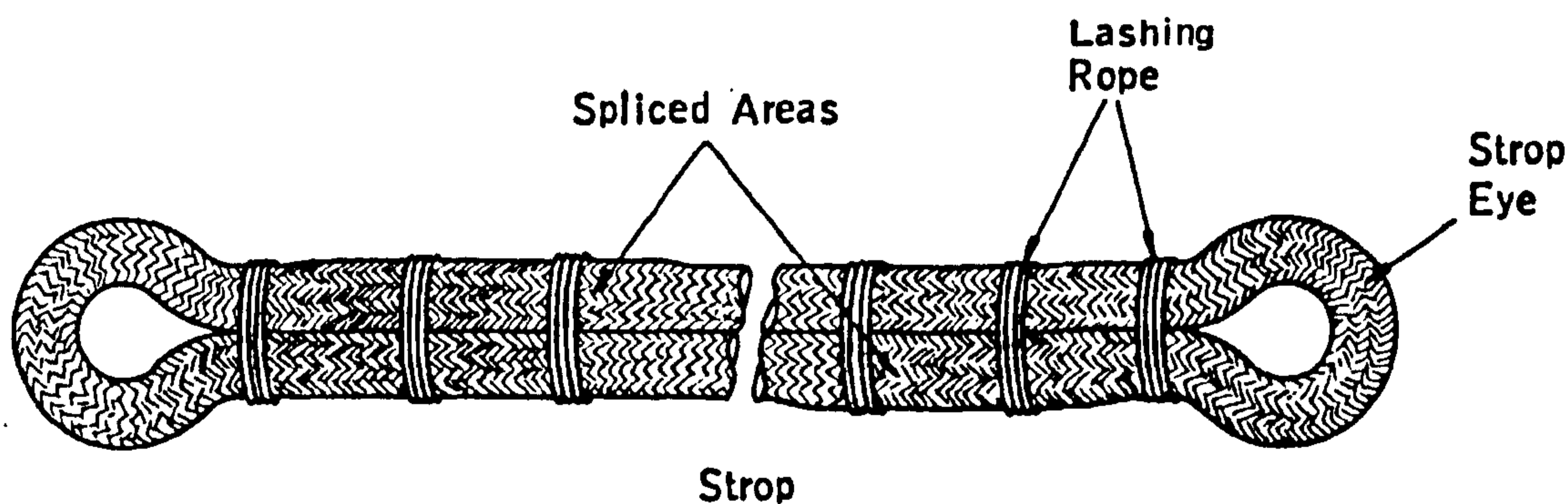


Figure 3-8: Schematic layout of Strop termination (Flory, 1977).

There seems to be disagreement on the strength in the eyes of strops. Samson (1974) believes that the strength of the strop may be 1.7 times the minimum breaking strength of rope in each leg but Hocker (1996) believes the reduction in strength in the eye of a strop is negligible.

III. Compression Sleeves

Compression sleeves are used with a rope thimble to form an eye splice in cables. The schematic diagram of a compression sleeve termination is shown in Figure 3.9. This type of termination provides a simple and inexpensive termination technique yielding good static strength efficiency. However, it has been observed that they tend to slip under high rate of loading, and abrade ropes, which are cycled at loads above 25% of static strength (Horn *et al*, 1977).

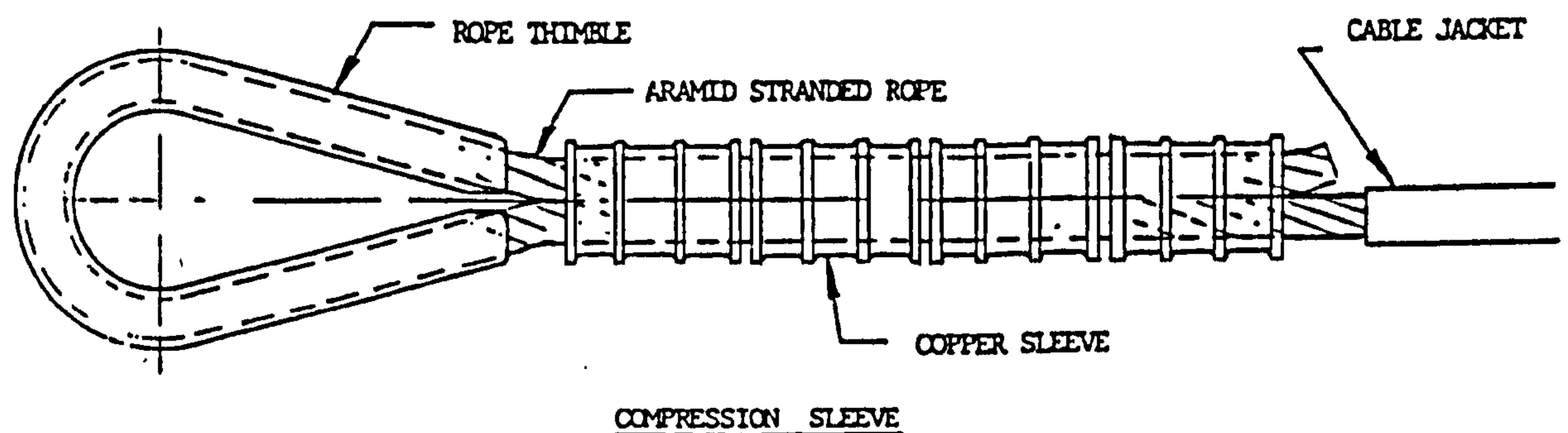


Figure 3-9: Schematic layout of Compression Sleeves termination (OCIMF, 1992).

Compression sleeves have been used in column members, as connections, using high strength reinforcements and concrete, a redundant compressive range occurs at the ends and this range is considered to contribute to improving the ultimate flexure capacity.

Recently, a Venezuelan oil company used compression sleeves for joints in the pipeline of gas exploration. Dual fusion-bonded epoxy was selected as the main coating, combined with high-temperature compression sleeves for the joints. This type of pipeline was unique in that no one had previously applied and evaluated external coatings for this combination of heavy wall thickness, pressure, and temperature (Rodriguez *et al*, 1998).

3.3.2 Socket termination methods

It is believed that termination has a major effect on the efficiency of the rope. In this method, termination is achieved by an additional item such as a socket. Recently

different socket terminations for braided fibre ropes have been developed for high tensile strength applications.

Socket terminations were first used on wire ropes. This is perhaps because the splice in wire rope is not as easy as fibre rope due to the rigidity of wire material. The metal socket termination (and spike) is more compatible with wire ropes than with synthetic fibre ropes because of the similarity of the materials and the ease of element arrangement inside the socket. Similarity of material will affect the load transfer between the elements and hence improve the breaking strength of the wire rope.

Synthetic fibre materials, due to their abrasion properties, are more sensitive to metal contact points, which may result in fibre rope failure within the termination.

I. Parafil Socket

Parafil socket (Figure 3.10) termination was specifically designed for parallel-elements ropes. It is based on a conical wedge principal, developed and patented by ICI (ICI Technical Report, 1988). They are usually made from anodised aluminium alloy or galvanised mild steel. However, stainless steel or other materials may be used to suit particular requirements.

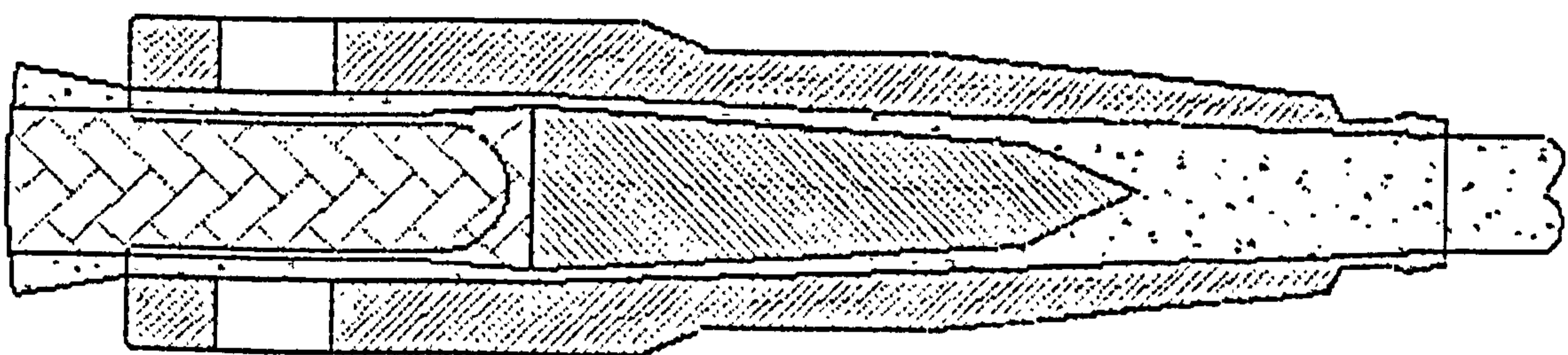


Figure 3-10: Schematic layout of Parafil termination (ICI, 1988).

It is believed that the barrel and the spike termination developed for Parafil ropes is capable of developing the full strength of the rope, since tests on long ropes almost invariably fail in the middle of the rope, rather than at the ends.

II. Epoxy potting

Epoxy potting comprises of a socket with conical internal surface (Figure 3.11). The rope is pulled in a metal tube which is attached to the nose of the socket. Then the rope enters from the metal tube to the socket and the additional volume of socket is filled with epoxy resin. Metal tube has been used to overcome the problem associated with failure points near the socket. The rigid epoxy resin traps any movement of the rope on the tension direction. Static and fatigue tests have demonstrated 100% rope efficiency, relative to the splice (Horn et al, 1977).

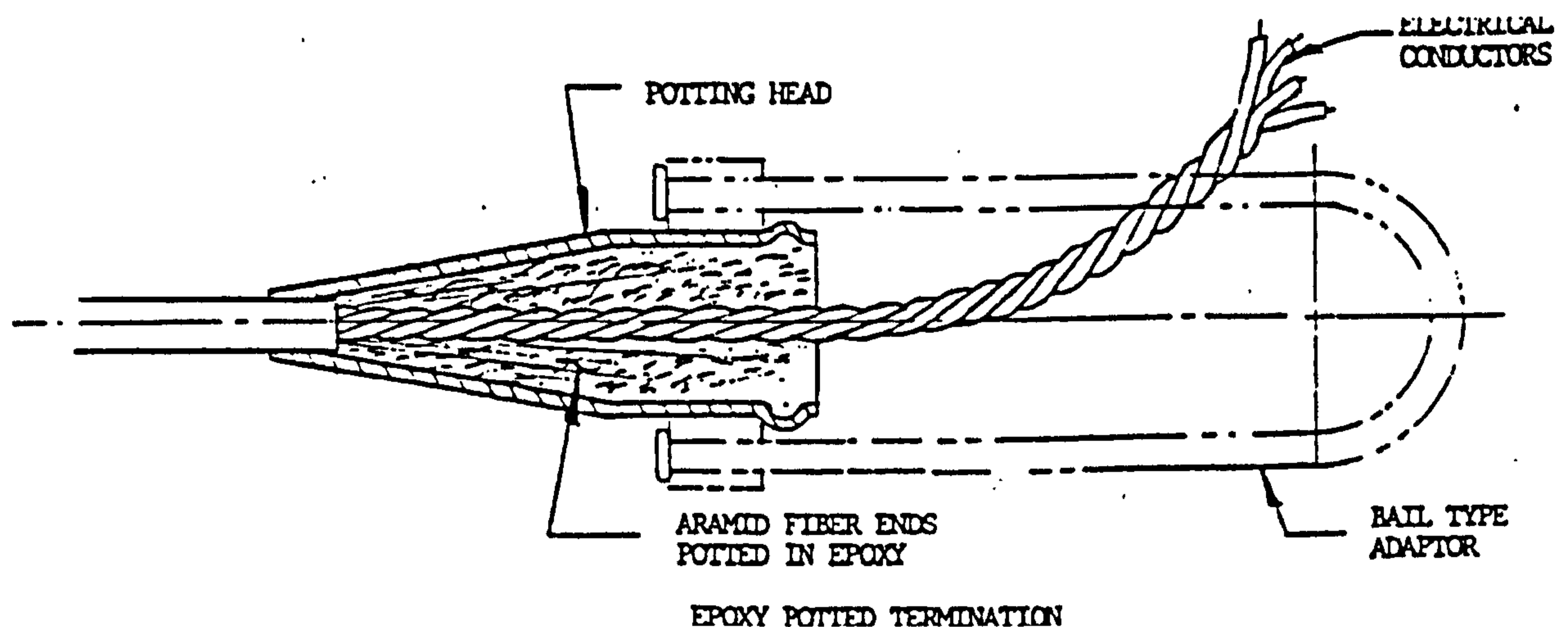


Figure 3-11: Schematic layout of Epoxy potting termination (OCIMF, 1992).

The epoxy potting due to its fast-cure and low exotherm, offers good mechanical versatility in properties. Epoxy is an obvious choice for plotting and encapsulating applications designed to protect sensitive rope elements. The epoxy potting is also being used in electrical applications and advanced semiconductor packaging which require fast cure setting (Bardoliwalla, 1997).

Although epoxy potting is reported as a highly effective termination method, but it is only possible for small diameter ropes. As the diameter of rope increases, stress concentration areas in the rope inside the socket grow rapidly and results in premature rope failure.

III. Potted Socket

The conical-shaped potted socket (Figure 3.12) comprises several cavities and each cavity holds one sub-rope. The sub-rope is held in a cavity by filling the cavity with a thermosetting resin. The resin and fibres interaction and conical shape of cavities would prevent any sub-ropes movement. This termination type is proposed for small diameter ropes (Flory *et al*, 1995).

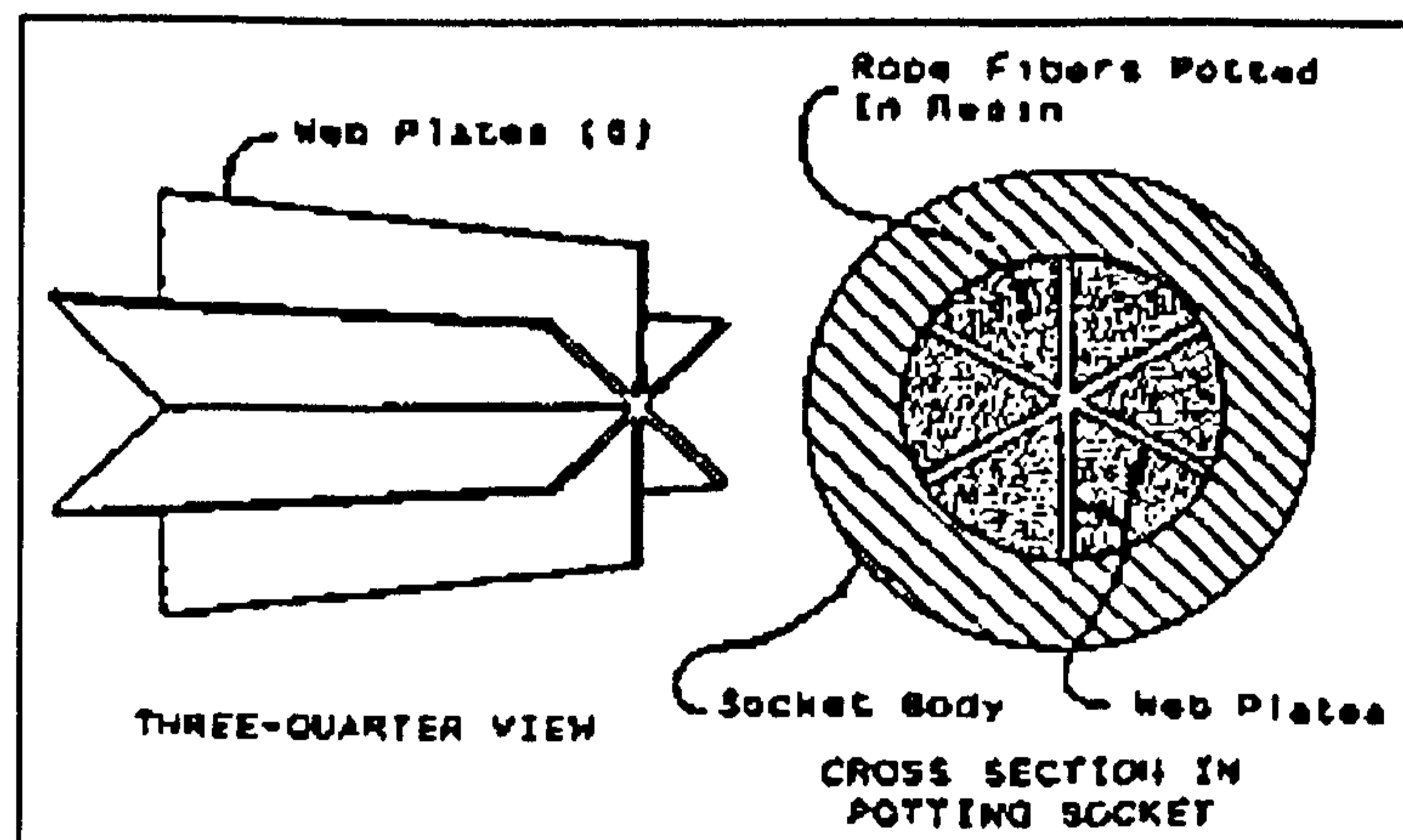


Figure 3-12: Schematic layout of potted socket termination (Flory JF et al, 1995).

Tests were conducted to examine the effects of using cavities in the potted terminations on the performance of 38mm diameter, six strands Aramid fibre rope showed that the use of six cavities resulted in an increase of 50% in the new-rope breaking strength. In cyclic tension tests, after 200,000 cycles at 45% of that improved breaking strength, there was no strength reduction (Flory et al, 1995). This indicates that the use of cavities in the potted design can have a major contribution in the loading performance of the structure.

However, the termination suffers from an inherent problem associated with the load transfer at the point where the rope exits the resin compound, which will lead to a high stress concentration in the termination-rope structure. This is a major unresolved problem and this study aims to investigate and improve the loading performance of a specific potted socket.

IV. Plug-on-sleeves

This type of termination has been made from a combination of Parafil socket and Sleeves. In this way, rope is terminated by metallic sleeves after it is inserted inside the Parafil socket (Figure 3.13).

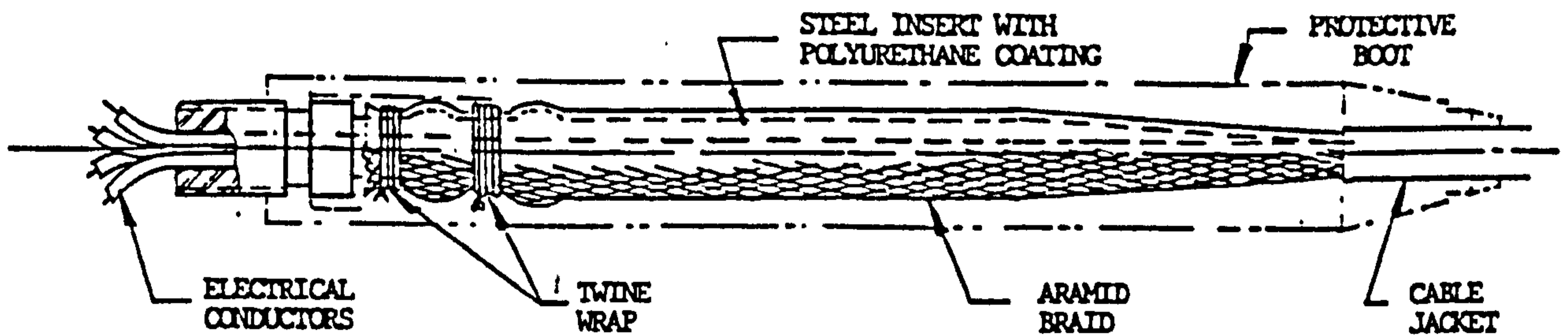


Figure 3-13: Schematic layout of Plug-on-sleeves termination (OCIMF, 1992).

Limited evaluation has been performed with this type of termination on Parafil ropes. Static strength has been shown to be greater than the guaranteed minimum value, but large amplitude fatigue loading causes abrasion within the socket which results in premature failure (Horn *et al*, 1977).

The stress concentration as a result of the gripping pressure by sleeves inside the socket can increase the risk of rope failure inside the socket. Also due to the limitation in sleeve size, it is not possible to use large-diameter ropes.

V. Helical wire wrap-on terminations

This method applies a split wedge socket termination, which is placed around the rope (Figure 3.14). A galvanised steel helical rod, which is connected to the split wedge, is used to hold the rope elements together. These components, now a single unit, are installed into a tapered housing. To complete the assembly, an adapter is screwed into the housing. The wrap-on rod will therefore prevent any slippage of rope, which also improves the load carrying capability of the structure by delaying the rope failure near the socket. This method has provided excellent loading results for a single layer braided aramid strength members (Stange *et al*, 1977).

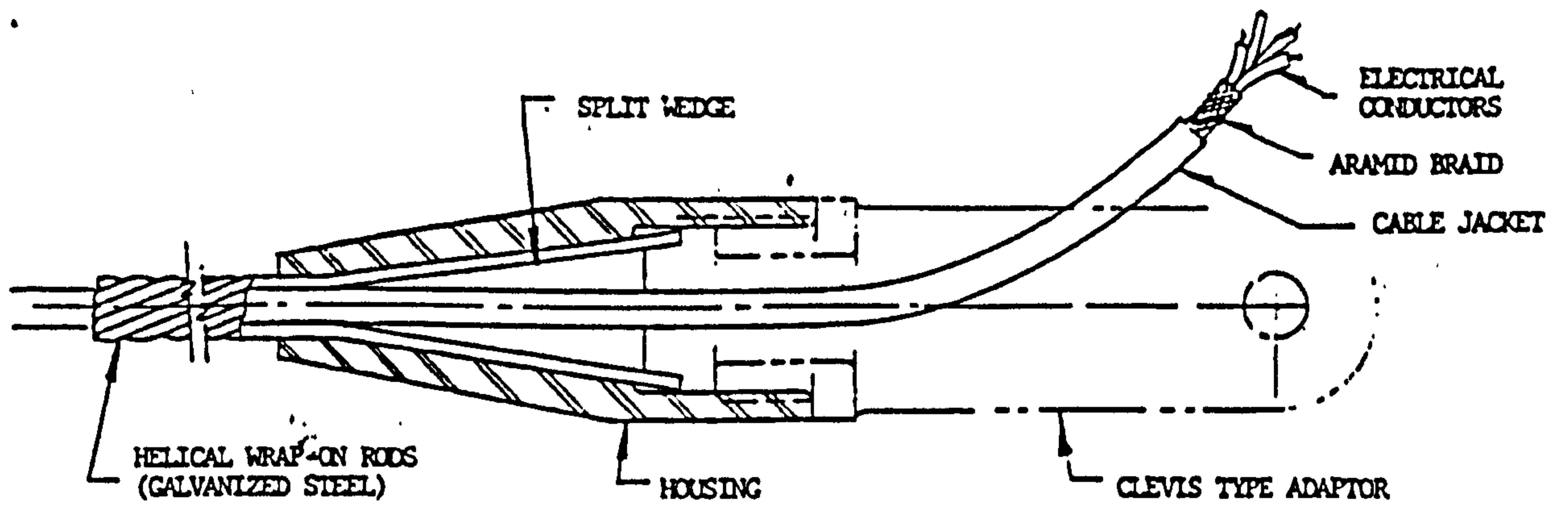


Figure 3-14: Schematic layout of helical wrap-on termination (OCIMF, 1992).

VI. Bridon fitting for wire ropes

The termination comprises a conically-shaped socket, which uses zinc or filled synthetic resin, designed for specific rope dimensions (Figure 3.15). The rope is brushed and unlaidd before resin casting. To stop resin leaking, the rope is taped in the necking area of the socket. Zinc or epoxy resin is applied on top of the rope (A and B areas) when it is pulled into the socket. The adhesion between the strands and the resin traps any movements of the rope in the socket (Dunn, 1995).

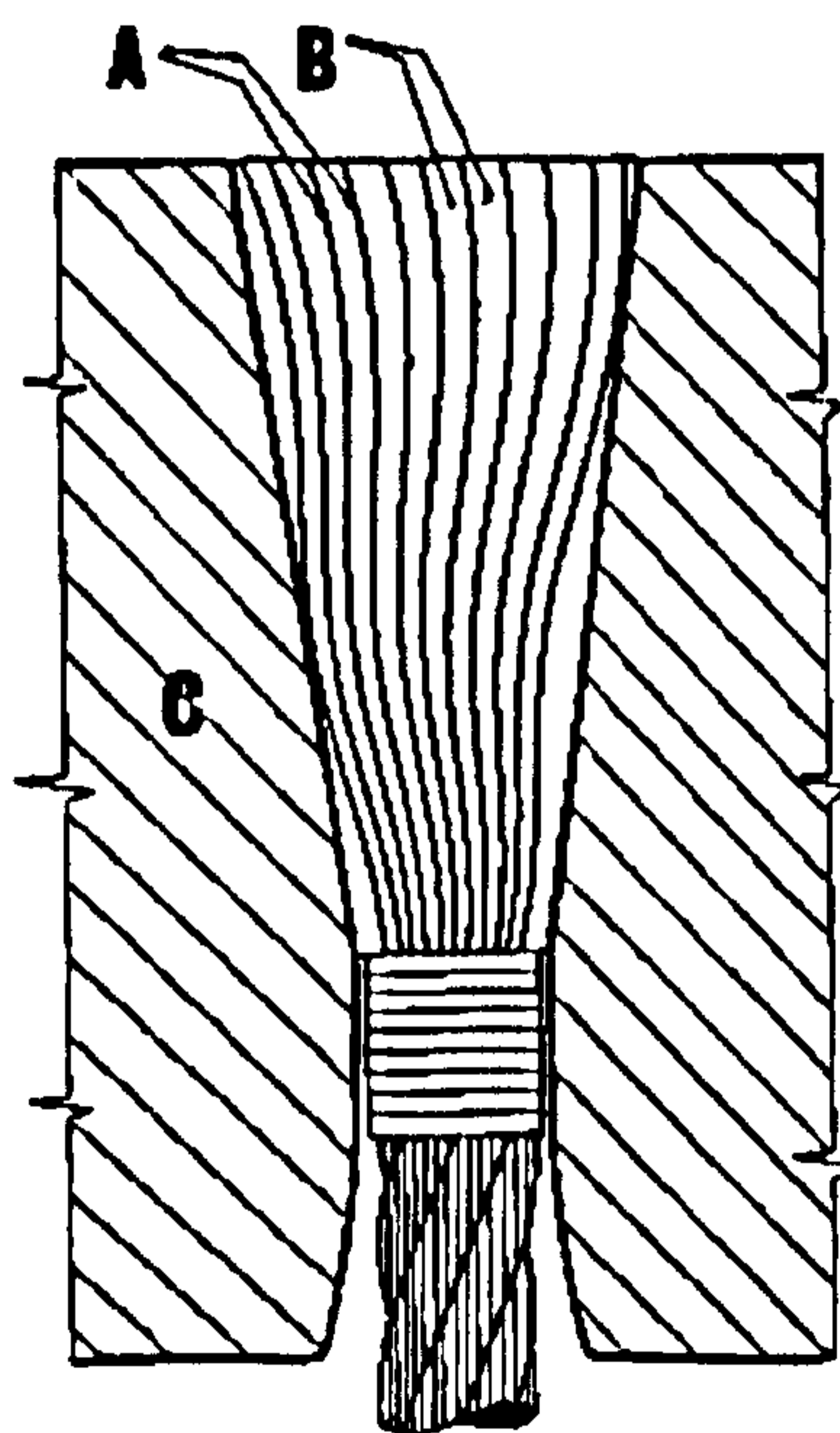


Figure 3-15: Schematic layout of Bridon fitting (British Ropes, 1997).

VII. SEFAC Fittings

The fittings have been designed, manufactured and commercialised by a French company SEFAC (Figure 3.16). The fitting consists of two parts, which apply pressure on the rope as they are screwed together. They are used when a very firm hold between the cable and the fitting is needed for mostly non-load bearing applications such as:

- Synthetic fibres, strands, ropes, and parallel braids
- Electromechanical cables: Either with steel sheathing, or with synthetic fibre sheathing

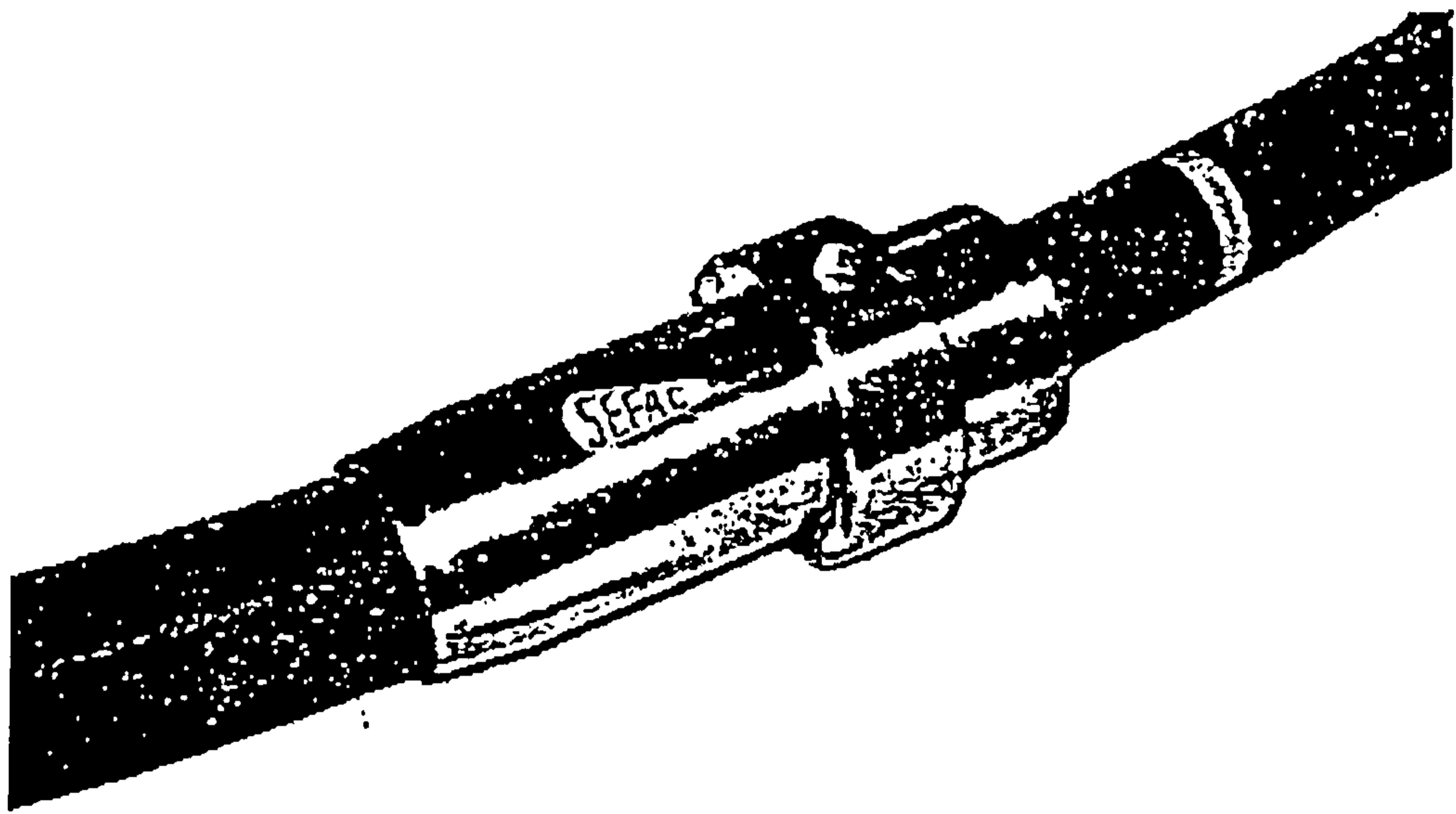


Figure 3-16: Schematic layout of SEFAC fitting (SEFAC, 1992).

Two main types of SEFAC fittings are used:

- (i) Fitting with simple mechanical nipping action, designed for easy assembly at the factory or on site by the customer.
- (ii) Fittings with mechanical nipping action using a compound.

The rope and termination are mainly marketed by the manufacturer (SEFAC, 1992).

3.4 Conclusion

In this chapter the theory of a new rope termination the “Vaseghi Stress Relief Socket” has been discussed. Also current termination methods for rope have been revised. Although some of the methods in this chapter are not applicable for the heavy duty ropes, they are mentioned to give the reader some idea for number of terminations in the market.

In the next chapter, devices, machines and materials, used in this study, are discussed.

Chapter 4: Experimental details

4.1 Background

The testing equipments, materials' specification, and ropes' constructions, which have been used in this project, are presented in this chapter. The aim of the experimental work in this study is to investigate the loading performance of different rope-termination systems for large diameter synthetic fiber ropes. Also other test methods have been used to support the new terminating method. To fulfill the aim, the tensile test was performed at an early stage of this study. The tests have been carried out on different types of ropes from filaments to 120mm ropes.

The following studies were carried out in different stages to examine the performance of 5 different termination methods:

- I. Static tensile test
- II. Residual strength measurement after cyclic loading regime
- III. Acoustic emission monitoring of ropes in tensile test
- IV. Finite element modeling of socket termination

Ropes samples with different diameters, constructions, terminations, and materials were used. The filaments were provided from Akzo and Hoechst manufacturers. The first termination was obtained from ICI, which was previously used for Parafil ropes. This type of termination was used for the 18mm sub-rope in this study. The new terminations were designed on the basis of some improvement and ideas of previous sockets. Based upon the ropes' diameter, four types of tensile machines were used to monitor correct strength capacities. Fatigue cycling was carried out using 500 kN horizontal Dension tensile. The MR1004 AE analyser was used for acoustic emission test. The finite element modeling of the socket was carried out using Ansys5.3 software.

4.2 Rope materials

The glossary of different terminologies, used in this study, is as follow:

Filament: Collection of fibres of indefinite length provided by original suppliers.

Yarn: Twist entity composed of filaments held together by twist.

Strand: A twisted collection of yarns

Sub-rope: Braided strands which was formed by using 12-carrier twill strands

Rope: Parallel collection of 7 sub-rope.

Detailed construction is given in 4.3.

Akzo material was supplied by Akzo Noble Industrial Fibres and Hoechst 785 material was supplied by Hoechst Corp. US. The physical properties of the two materials used are presented in Tables 4.1-4.4. The polyester material supplied by Hoechst contained a surface coating to improve the water resistance property. The difference between Hoechst and Akzo polyester grades was a shiny appearance of the Hoechst material. Although the strength properties of both fibre materials are similar, as indicated by the manufacturers catalogue (Tables 4.1-4.4), when the materials were used in rope construction, Hoechst performed much better than Akzo.

		Filament Type	
		Akzo	Hoechst
Failure Load (N)	Mean	174.64	175.24
	STD	0.22	0.47
Elongation at break (%)	Mean	26.77	17.50
	STD	0.50	1.36
Tenacity (kN/Tex)	Mean	699.36	701.46
	STD	8.44	18.53

Table 4-1: As-received Akzo & Hoechst filament properties (Akzo, 1997 & Dunn BJ, 1985).

Denier	Linear Density (d'tex)	Filament Count	Tenacity (dN/tex)	Breaking Load (N)	Elongation at Break (%)	Hot air Shrinkage (%)
1079	1100	210	8.36	92	15.00	15.1
1413	1440	210	8.26	119	14.50	7.0
1638	1670	210	8.19	137	14.40	6.8
2158	2200	210	8.19	184	14.30	6.3
3237	3300	420	8.09	267	14.10	6.0
4316	4400	420	8.14	358	14.00	5.7

Table 4-2: Typical physical properties of Akzo type 877TN polyester (Akzo, 1997).

Denier	Linear Density (d'tex)	Filament Count	Tenacity (dN/tex)	Breaking Load (N)	Elongation at Break (%)	Hot air Shrinkage (%)
206	210		7.7	16.17	15.00	15.1
922	940	105	7.75	74	14.5	7.0
1373	1400	210	7.55	108	14.4	6.8
1843	1880	210	7.68	147	14.3	6.3

Table 4-3: Typical physical properties of Akzo type 855TN polyester (Akzo, 1997).

Denier	Linear Density (d'tex)	Filament Count	Tenacity (dN/tex)	Breaking Load (N)	Elongation at Break (%)	Hot air Shrinkage (%)
250	278	75	4.20	22.30	15.00	11.40
500	550	118	6.80	41.60	14.00	11.00
840	930	170	7.70	71.60	13.20	11.30
1000	1100	192	8.0	89.20	12.30	13.20
1100	1220	192	8.10	98.70	12.60	13.20
1500	1670	218	7.70	128.00	12.60	11.30
2600	2890	384	7.90	233.60	12.80	13.20

Table 4-4: Typical physical properties of Hoechst type 785 polyester (Hoechst, 1995).

The construction of all the polyester grades supplied was semi-crystalline. This means that the fibre consisted of more oriented regions (crystalline regions) and less oriented regions (amorphous regions). Both the orientation of polymer chains in the fibre and the size of the crystalline regions were important for the fibre properties. The differences between the performances of different polyester grades originated from the processes involved in fibre production, including the adjustability of the properties to a specific end use by heat treatment.

For comparison purposes, at the trial stage of this study, two different grades of Akzo were used, namely Diolen 877TN and Diolen 855TN high-grade multi-filament polyester yarns suitable for high performance marine environment. The mechanical properties of these two grades are listed in Tables 4.2-4.3.

The use of Diolen 855TN fibre materials provides a rope with better abrasion resistance and higher tenacity than 877 TN grade. Also due to the specially designed finish, the knot strength level is comparable with that of polyamide yarn. This means that the same strength can be reached in ropes and nets, using the same amount of material.

Hoechst 785 is a compacted, high-tenacity, regular-shrinkage filament yarn used in different rope applications, seat belts, vinyl laminate scrims, hose, conveyor belts, and general industrial applications. The higher denier per filament yarn grades has been designed for seat belts and other applications in which abrasion resistance is important. Type 785 yarn is also suitable for weaving, when used for in-rubber applications. The use of Hoechst 785 yarns leads to good adhesion with rubber using either a double-dip or modified RFL single-dip system. Typical physical properties are recorded in Table 4.2.

4.3 Rope constructions

In this study, different constructions were tested namely filament, yarn, strand, sub-rope, 44mm (Viking 7) and 120mm rope.

The filaments consisted of

- 1880 d'tex Akzo polyester fibres and
- 1220 d'tex Hoechst polyester fibres.

The yarn constructions used in the experiments were

- 10 x 1880 d'tex for Akzo and
- 16 x 1220 d'tex Hoechst polyester fibres

The strand constructions used in the experiments were

- 10 x 8 x 1880 d'tex + 1 x 4 x 1880 for Akzo and
- 16 x 8 x 1220 d'tex + 2 x 1 x 1220 Hoechst polyester fibres

The Sub-rope construction consisted of a braided construction, which was formed by using 12-carrier twill strands (one over 2 under 2). The sub-rope assembly was 18mm in diameter.

The 44 mm rope (known as Viking 7) construction was made up of 7 parallel sub-ropes assembled together using a braided polyester protective jacket (Table 4-3). To maintain the same weight for both Akzo and Hoechst ropes less Hoechst fibres were used to meet the same construction as Akzo since the basic Hoechst yarn material was heavier than Akzo.

The basic construction of 120mm rope was the same as 44mm rope. However, the rope diameter was increased approximately by 3 times as compared with that in 44mm rope. The detailed construction of 120 mm rope is listed in Table 4-4.

4.4 Termination types and parts

In this study, four different types of termination were used to terminate all the above-mentioned rope types. The termination methods include;

- Splice for the sub-rope and rope,
- Parafil socket for 18 mm sub-rope,
- Viking 7 socket for 44 mm rope and
- Stress relief socket for 44 mm Viking 7 rope

4.4.1 Splice

The splice is the most common type of termination for rope in industry. In this method the rope-end is turned into an eye-shaped loop with the end inserted into the middle of the rope.

The splice termination (Figure 4.1) was used as a benchmark for further work. This method of termination has been used traditionally in fibre and wire ropes. It seems that all standards, indicating rope strength, have been reported on the basis of this termination method.

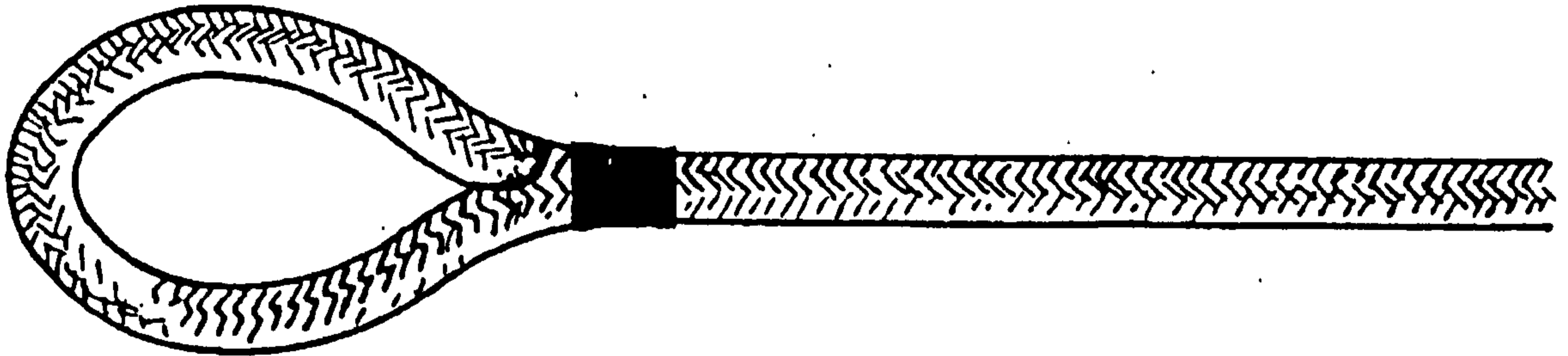


Figure 4.1: Typical Splice termination.

4.4.2 Parafil socket

In this study, Parafil sockets with a loading capability of 100 kN was provided by Linear Composite Ltd., UK. The socket was made of a conically shaped galvanised steel tube. In order to ensure firm gripping of the rope inside the tube, a combination of steel spike and setting compound was applied. During the trial stages of this study, different termination settings were used to achieve a better loading performance of the rope. The different termination settings included full and half spike with polyethylene heatshrink tubing and Paralock epoxy resin, supplied by ICI.

100 kN Parafil socket (Figure 4.2) was used to terminate the 18 mm braided sub-ropes. Traditionally, these types of fitting were used for parallel filament Parafil rope except in marine constructions. However it was decided to use this type of termination to assess its performance in relation to the splice.

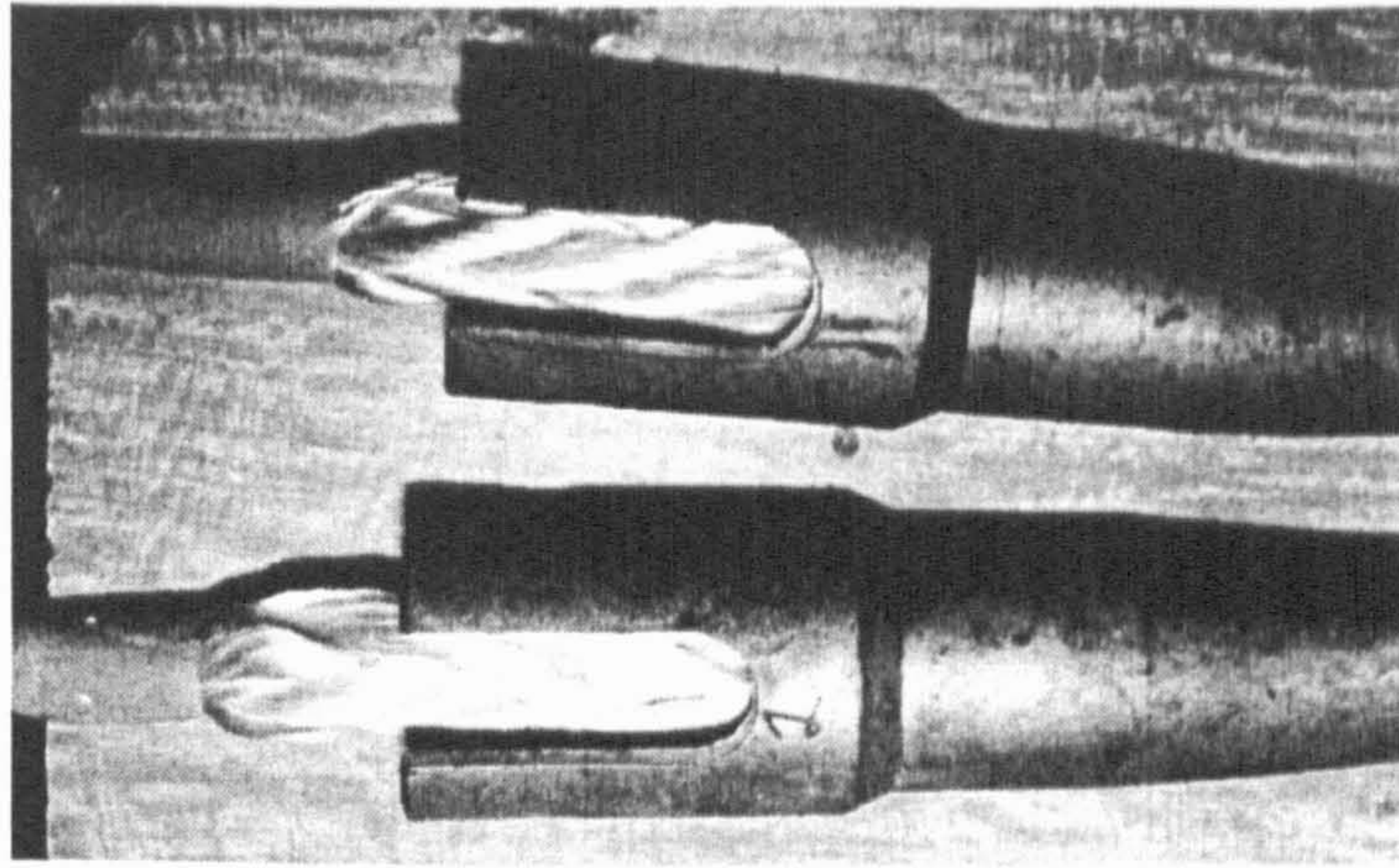


Figure 4.2: 100 kN Parafil Socket termination.

4.4.3 “Viking 7” socket

Viking 7 socket, designed and developed by Bridon Marine (the sponsoring company of this study), was used to terminate 44mm “Viking7” ropes. The termination construction is similar to the Parafil socket in which a conical steel tube accommodates seven individual sub-ropes and the spike assembly. Each sub-rope was covered by the heatshrink tubing followed by the epoxy resin compound to fix the rope construction (Figure 4.3).

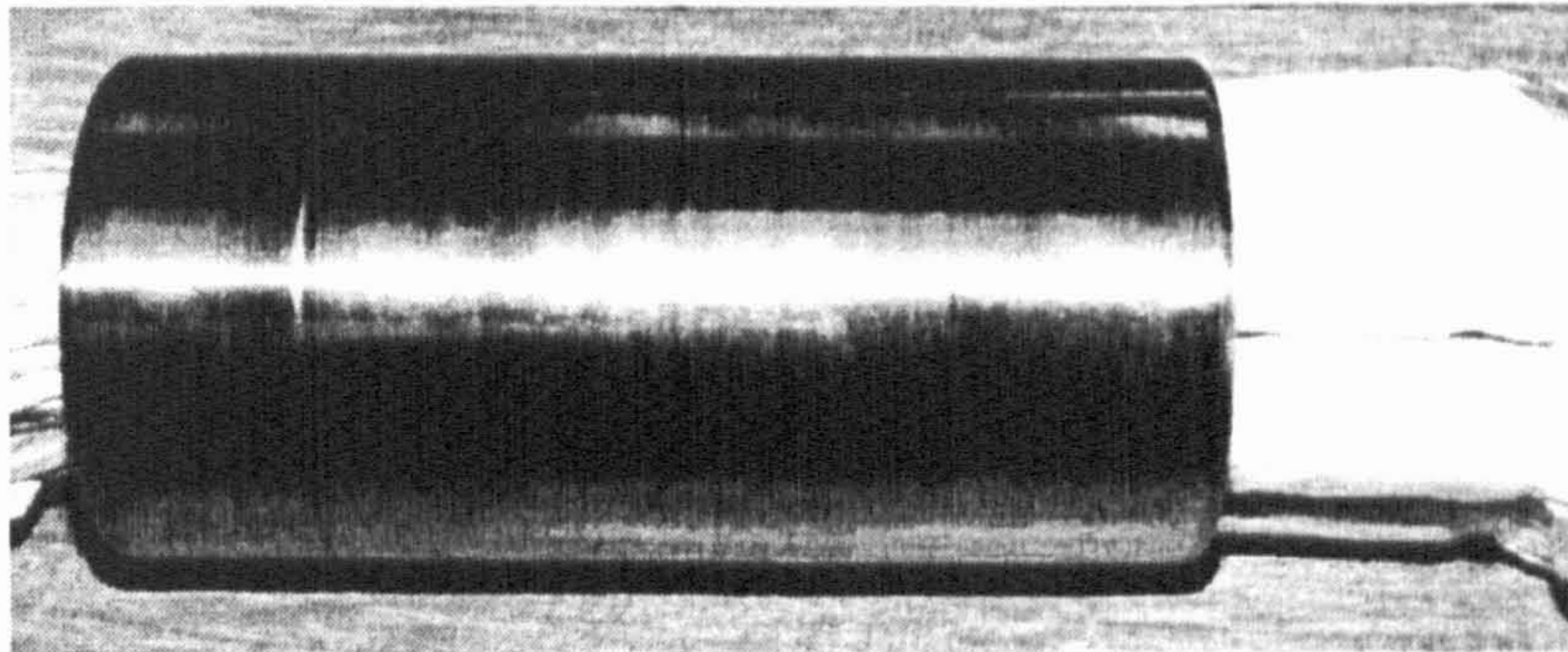


Figure 4.3: “Viking 7” Socket.

4.4.4 Vaseghi Stress Relief Socket

For termination purposes the seven component ropes of Viking7 were treated as individual entities each to be terminated in its own mini socket, seven of which were subsequently housed within the main socket body (Figure 4.4).

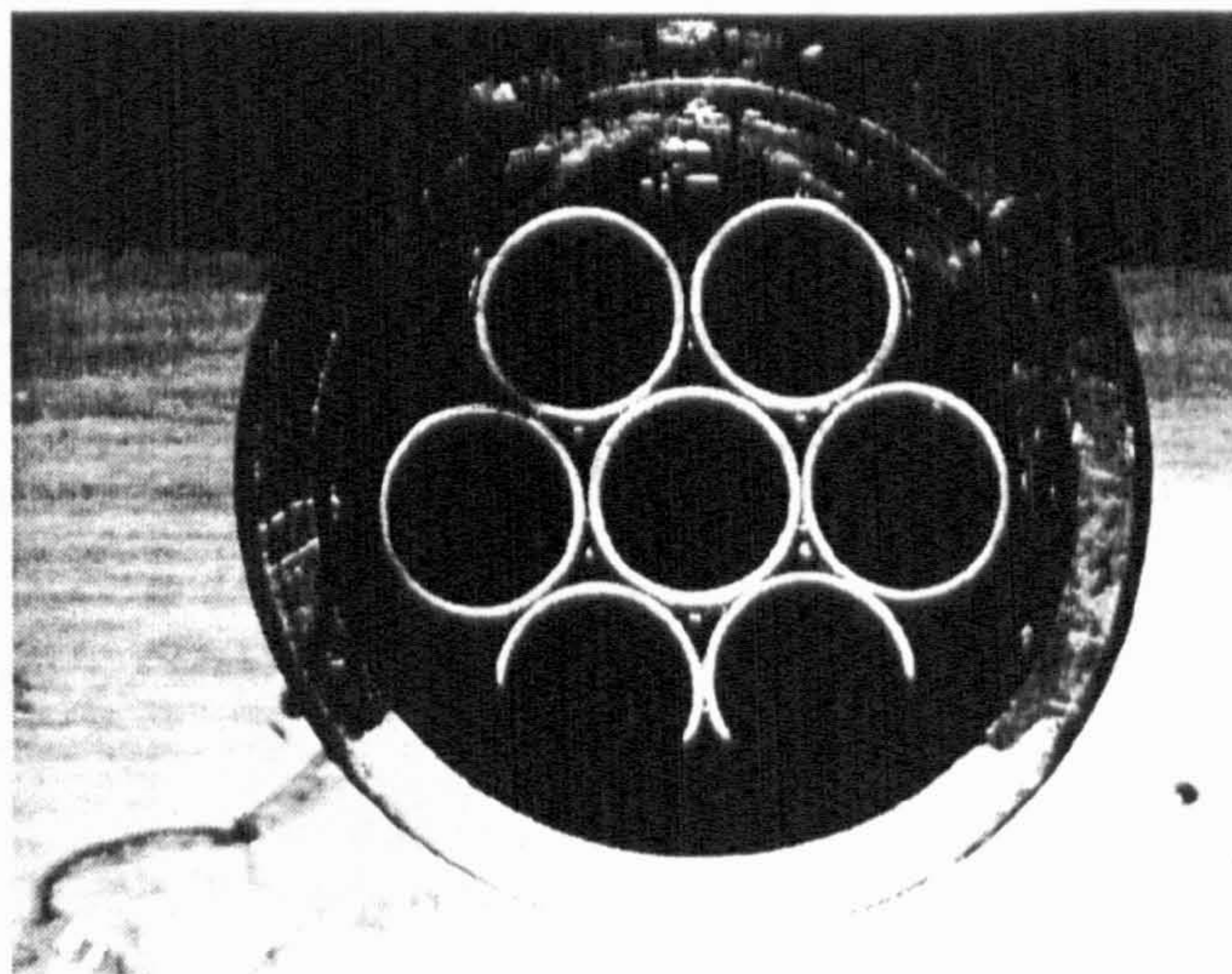


Figure 4.4: Seven individual mini-socket to make the big socket.

A patent in conjunction with Bridon International, on a new improved termination based on the “stress relief socket” has been applied for. The socket comprises seven individual sockets, one for each of the component sub-ropes in the “VIKING 7” assembly, nested together within a single housing (Vaseghi, 2000). The difference between this socket and “Viking 7” socket was the reinforcement of material in the socket. This idea was founded as a result of breaking points, which were near or inside the socket. The new design avoided the effects of socket on the breaking point of the socket. The unique design enables the fitting to be much shorter, lighter in weight and more efficient than one large single socket.

4.5 Sample preparation

4.5.1 Filaments

Samples were taken randomly from the original spools to test filaments. Initial filament was used as the first step of the work. 1 ply filament was the original untwisted construction, which was provided by suppliers. Different numbers of filament, up to yarn-size, were tested with 100 kN Lloyds tensile machine (Figure 4.5), with identical bollards.

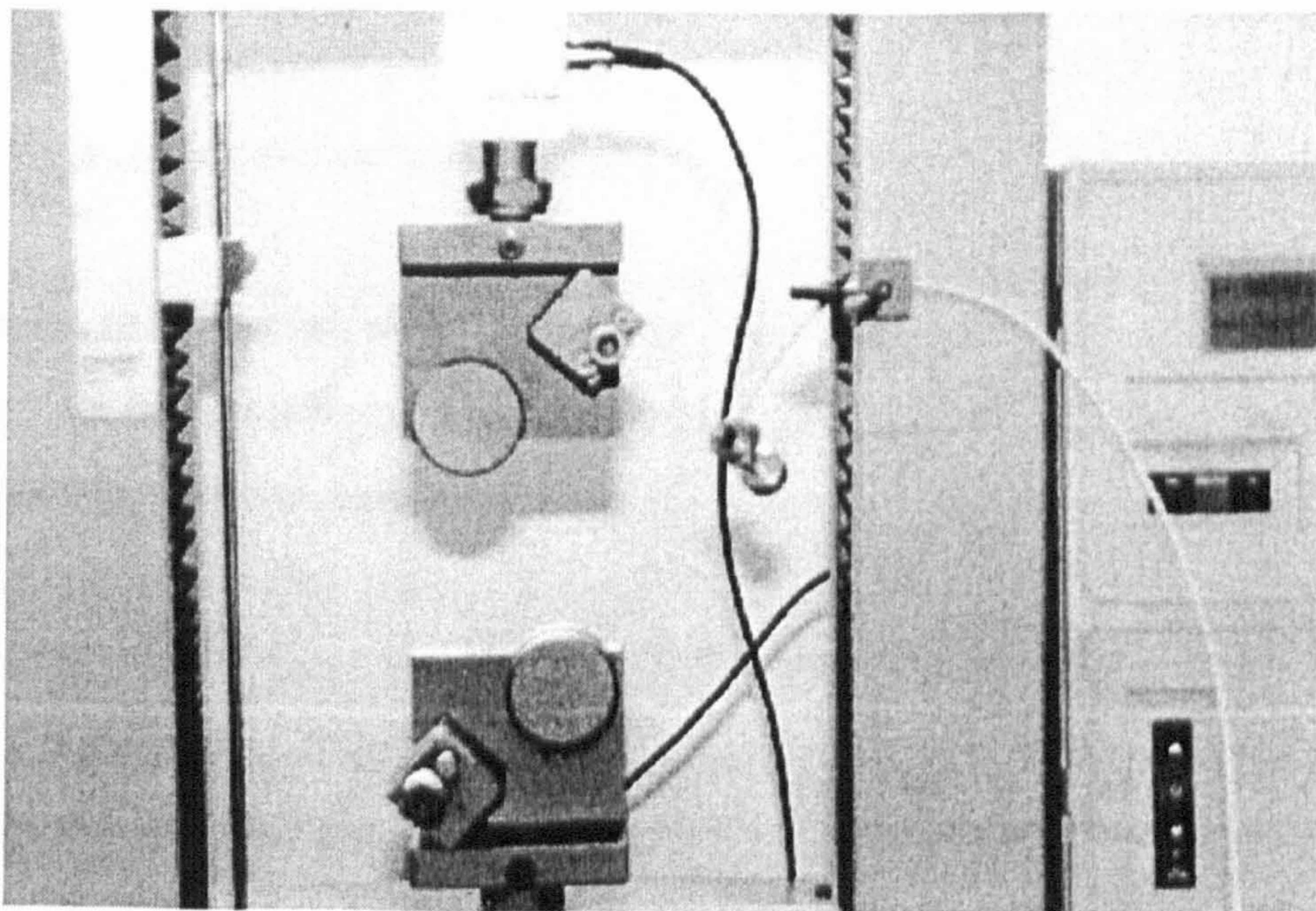


Figure 4.5: 100 kN Lloyds Machine used for filament testing.

4.5.2 18mm sub-rope

Three methods of termination were carried out for 18 mm sub-rope, splice, Parafil and Vaseghi Stress Relief Sockets. They are explained below:

- A) Splice:** To measure the benchmark for each rope, it was first tested by the splice termination. The 18 mm sub-rope comprises 12 braided strands. 1.5 meter long the extra material of both sides of a sample was considered to make the splice eye. The tail was turned and inserted inside into the body of rope. The tail then tapered to release tension along the rope. The buried part was taped to stop the tail from moving apart.
- B) Parafil Socket:** About 4m of the sub-rope was cut to make a 3m sample. The sub-rope was pulled into the socket from its nose. The yarns were opened and the socket was put inside them. Depending on the termination make up, heatshrink tubing, half socket or resin were applied. It was ascertained that the rope be passed through the heatshrink tubing before the spike was placed. A heat gun was used to shrink the heatshrink tubings. The spike and rope covered with heatshrink were pulled back inside into the socket. To add polyester resin (commercially called paralock) on the top, the socket was placed vertically. Sometimes it was necessary to apply some placticine in the socket nose to stop the resin leakage. The test was done in an hour after the resin was completely frozen.
- C) Vaseghi Stress-relief socket:** The only differences between the “Vaseghi Stress Relief Socket” compared with the previous method, Parafil socket, are the extra reinforcing material and changes in the socket geometry. The socket geometry stayed the same when testing 18mm sub-ropes while extra volume considered for 44mm rope as original socket had no more room for extra material.
- It is proposed that if the failure position is moved from inside to outside of the socket, the effect of termination could be ignored. This helped to develop the idea of the Vaseghi Stress Relief Socket. About 75 cm of the same rope was cut and inserted inside the rope in each end. The tail of extra material was tapered similar to the splice method. Then this piece of rope was considered as the sample. The

same procedure, as rope termination by normal socket, was applied from here to terminate the rope.

4.5.3 44mm Viking7 rope

Three methods of termination were carried out for 44mm rope. Splice, Parafil and Stress-relief socket.

- A) **Splice:** The rope comprises 7 individual sub-ropes. Each sub-rope is spliced as an individual rope. The only attention here is that each sub-rope should not be inserted into its own body because if it happens, the splice eye would bulge. The arrangement is shown in Figure 4.6. When each sub-rope is spliced, pieces of rope are tied around the complete rope to keep the splice together.

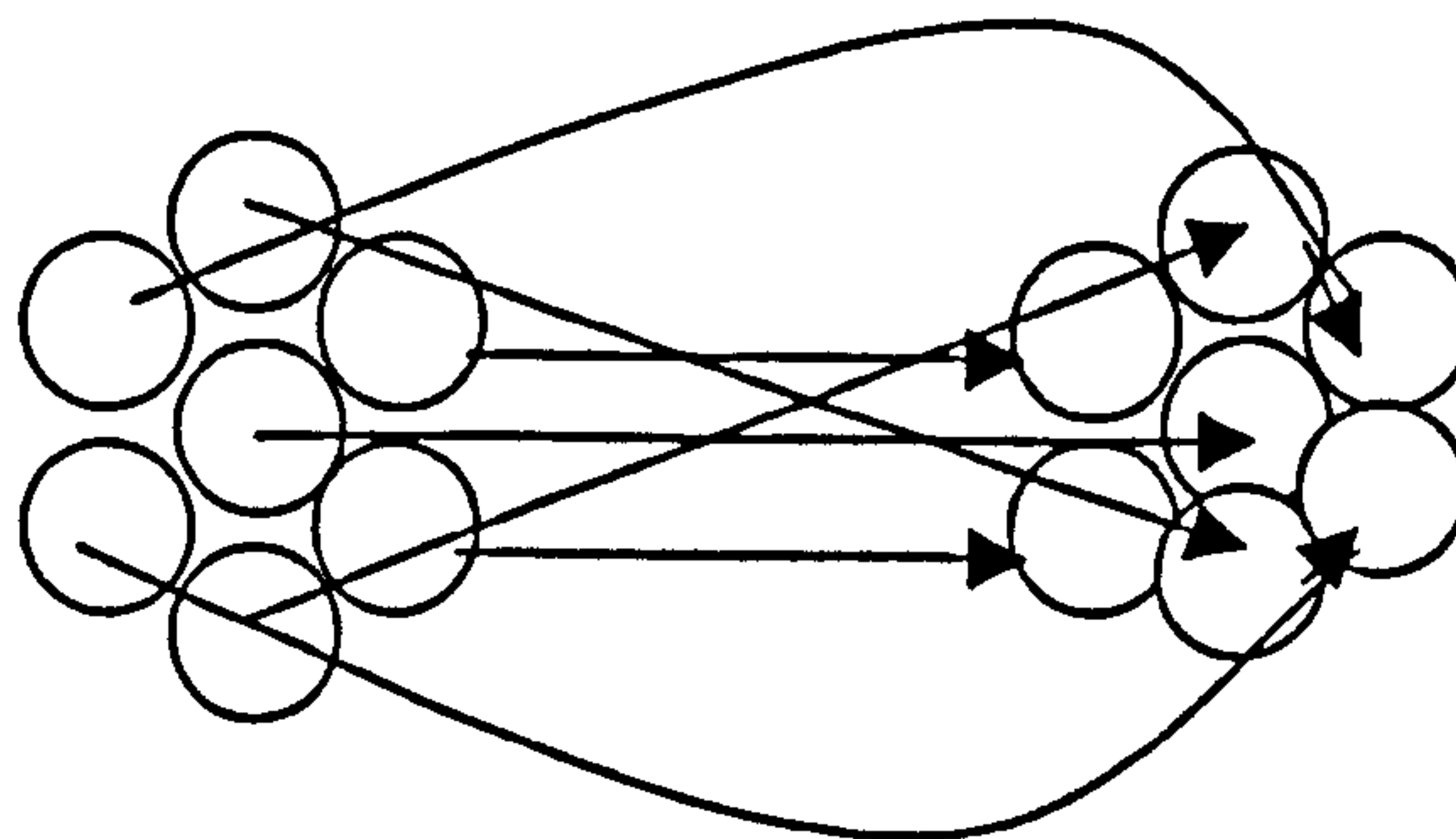


Figure 4.6: Arrangement of sub-ropes in 44mm Viking7 rope for splice makeup.

- B) **Viking7 Socket:** Viking7 socket (Figure 4.3) is an enlargement of Parafil socket for 44mm Viking7 rope because there is no socket for that size of the rope. Viking7 socket and its spikes are made in The Bridon International for this project. A three meter rope was cut and one meter of the jacket from each end was unbraided. The spike was put inside each sub-rope and it was covered by heatshrink. The whole assembly was covered with a big heatshrink. The whole assembly was pulled inside the socket. 100 kN pre-load was applied. The sample was then unloaded and sockets were taken from the machine and mounted vertically. Resin was added on top of the socket to lock the fibre from any movement. The resin should be added gradually in order to wet the fibres. Also the resin should fill all gaps inside the socket precisely to stop any part of the assembly from any individual movement. As resin gel time is about 15 minutes,

extra care should be taken to complete the resin in this time before it starts to freeze.

- C) **Vaseghi Stress Relief Socket:** As the idea of reinforcement of material inside the socket was raised, the design of the Viking7 socket was changed to incorporate the extra reinforcing material. The internal volume of the socket was increased although the same spikes were used. A three meter rope was cut and about a meter of jacket from each end was unbraided. To reinforce the sample ends, one meter of the sub-rope was inserted into each end. Tapering of the rope was carried to avoid stress concentration along the rope. The spike was put inside each strand and it was covered by heatshrink. The whole assembly was covered with a big heatshrink. The rope was pulled inside the socket and 100 kN pre-load was applied. Resin was added on top of socket to lock the fibre from any movement similar to the previous procedure.

4.5.4 120mm rope

The procedure is the same as that for 44mm Viking7 rope. But because of the rope diameter, every thing has been scaled up to 120mm.

Both ends of the rope were made and reinforced by 75% extra material, in Marlow Rope Company. A 10 meter rope was cut for each sample. Apart from that, a 6 meters rope, with the same construction, was cut to reinforce both ends. The reinforcement was done on each end with 3 meter ropes.

About 4 meters of rope was unbraided. Sub-ropes were taped to keep the yarns together. A 3 meter sub-rope, with the same construction, was inserted inside the rope end and tapered right to the end. Tapering was done in 1.5 meter length of the reinforced area to the tail. Each sub-rope, having the reinforced material in its core, was tapered and then another jacket was covered on top of all.

A new design for socket, on the basis of the stress relief socket, was used as termination. The assembly socket for 120 mm rope was designed in Bridon International. The socketting process was the same as 44mm rope in the stress relief

socket. The rope was pulled into the socket and the jacket was opened. The spike was placed inside each sub-rope and taped. The pre-load was applied by aid of hydraulic jacks and a frame designed for this project. The figure of frame and other parts has been shown in Figure 4.7a and 4.7b. The rope was pulled in the socket and uncovered while it was lifted by a crane to a certain level. 1.5 m of extra material was inserted in each sub-rope. Then each sub-rope was covered with heatshrink tubing and the whole assembly was pulled inside the socket. The crane lifted the socket into vertical position and 40 litres of the resin was poured in the socket. To stop the resin leaking out, some plasticine was applied between sub-ropes where the rope came out from the socket. The socket was left in the same position for about 24 hours until the resin solidified. The same procedure was done for the other end and the sample was lifted by a truck to NEL where the test was run.

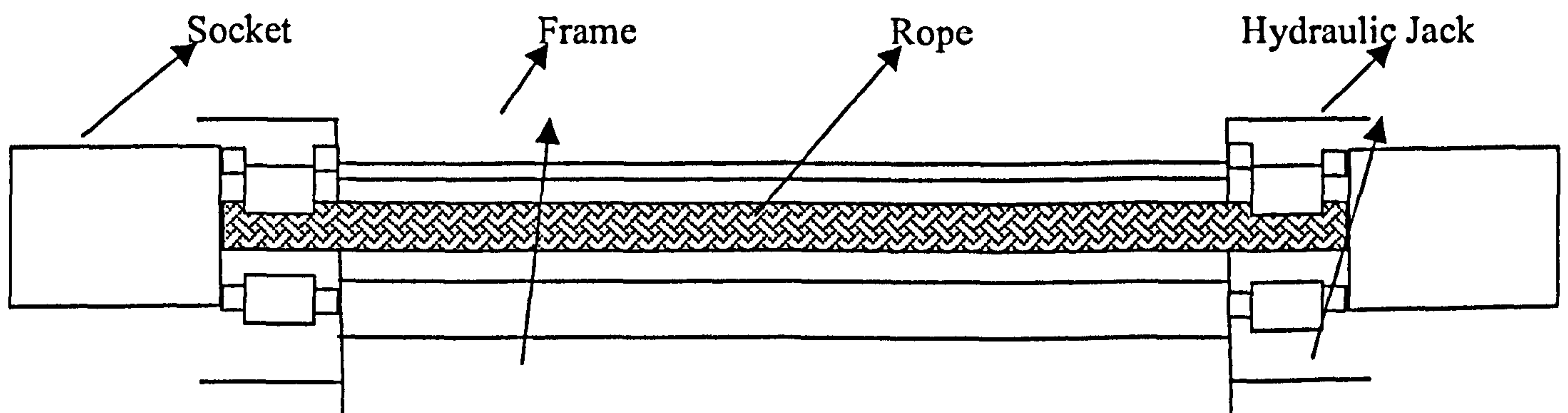


Figure 4.7a: Frame made for pre-tension of 120 mm Viking7 rope.

Length of sockets' face to face	= L_{total}
Length of marked area (Transducers)	= L_t
Slippage from socket 1	= B_1
Slippage from socket 2	= B_2

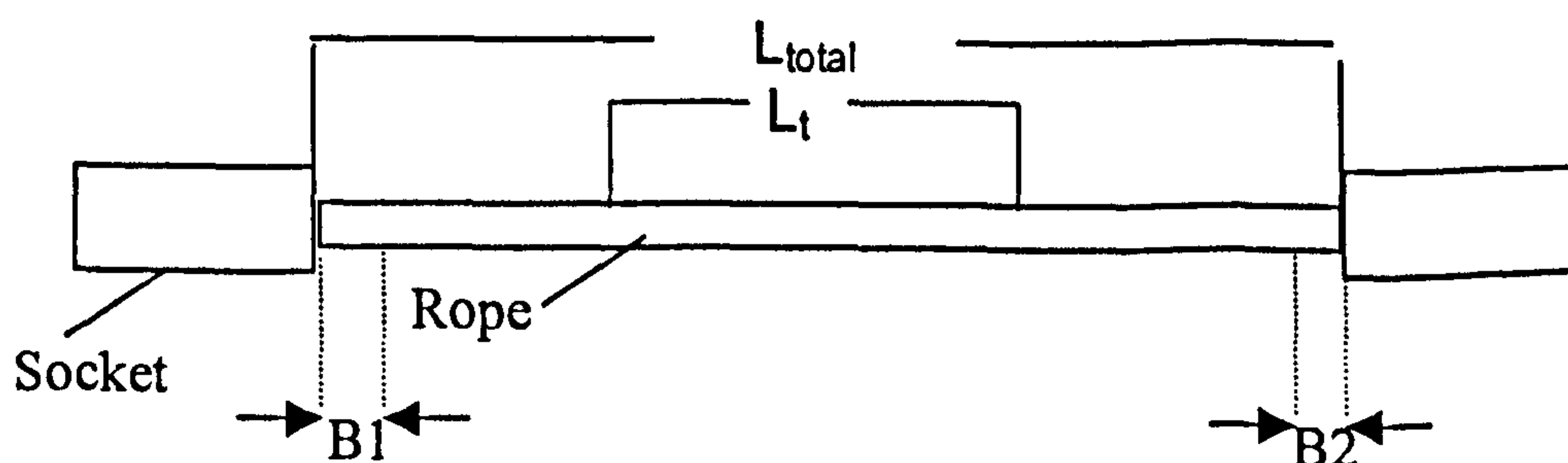


Figure 4.7b: Schematic layout of specimen and measuring instruments.

4.6 Testing facilities

4.6.1 Fibre test equipment

1- The Lloyds tensile machine: The rope sample was wrapped a total of four times around the top and bottoms bollards (Figure 4.5) and then clamped at each end to prevent slippage. The crosshead speed was kept constant at 150 mm/min throughout the test. The following data were taken from the computer connected to the machine in each test:

1. Breaking Strength
2. Extension
3. Tenacity
4. Stress/Strain graph

The data were collected by a PC and Microsoft Excel software was used to calculate the results and draw the graphs.

For each test, at least, 12 samples of each material and construction were tested and the average of data was considered to be the breaking load of the fibre. The samples, with partial breaking, were discarded.

2- The Denison 500 kN tensile machine: The 500 kN Denison horizontal test machine (Figure 4.8) Serial No: BF1 was used to test the sub-ropes. The machine had been designed to take up to 500 kN load. Different adapters were designed to fit any termination. The most usual one was the splice, which fitted in identical pins. The next method of testing was the socket. To measure the movement of the material in the socket, (socket-draw) the rope was marked. After some preliminary small loads and cycling, in about 10% of the breaking load, another mark was put on the sample and then it was considered that no further movement took place inside the socket. The elongation was counted on the basis of the second marks. Because the machine was hand-controlled, it was not possible to calculate the elongation at failure. Therefore, the tensile process was stopped before the rope broke and elongation was measured in

different stages. The rope was pulled until it broke and the breaking load was considered as the ultimate strength of the rope. Sub-ropes had no cover.

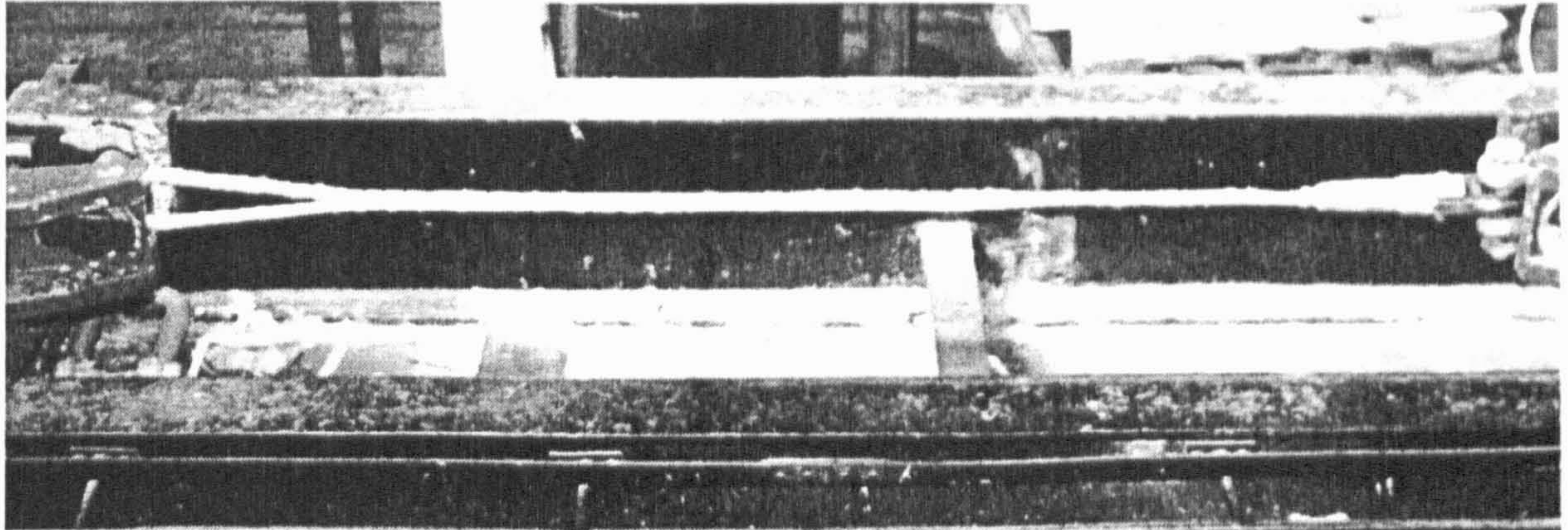


Figure 4.8: **500 kN Denison Machine used for sub-rope testing.**

To get a similar figure, samples with a partial breaking feature and breaking point inside the socket, were discarded.

3- The Bridon 1500 kN tensile machine: The Digital Monitor 1500 kN tensile machine (Figure 4.9), was used to test the 44mm Viking7 diameter ropes. The machine had been assembled in Bridon Marine to test the ropes with a breaking strength of up to 1500 kN. The digital monitor locks on the highest at failure. A plotter draws the stress-strain curve.

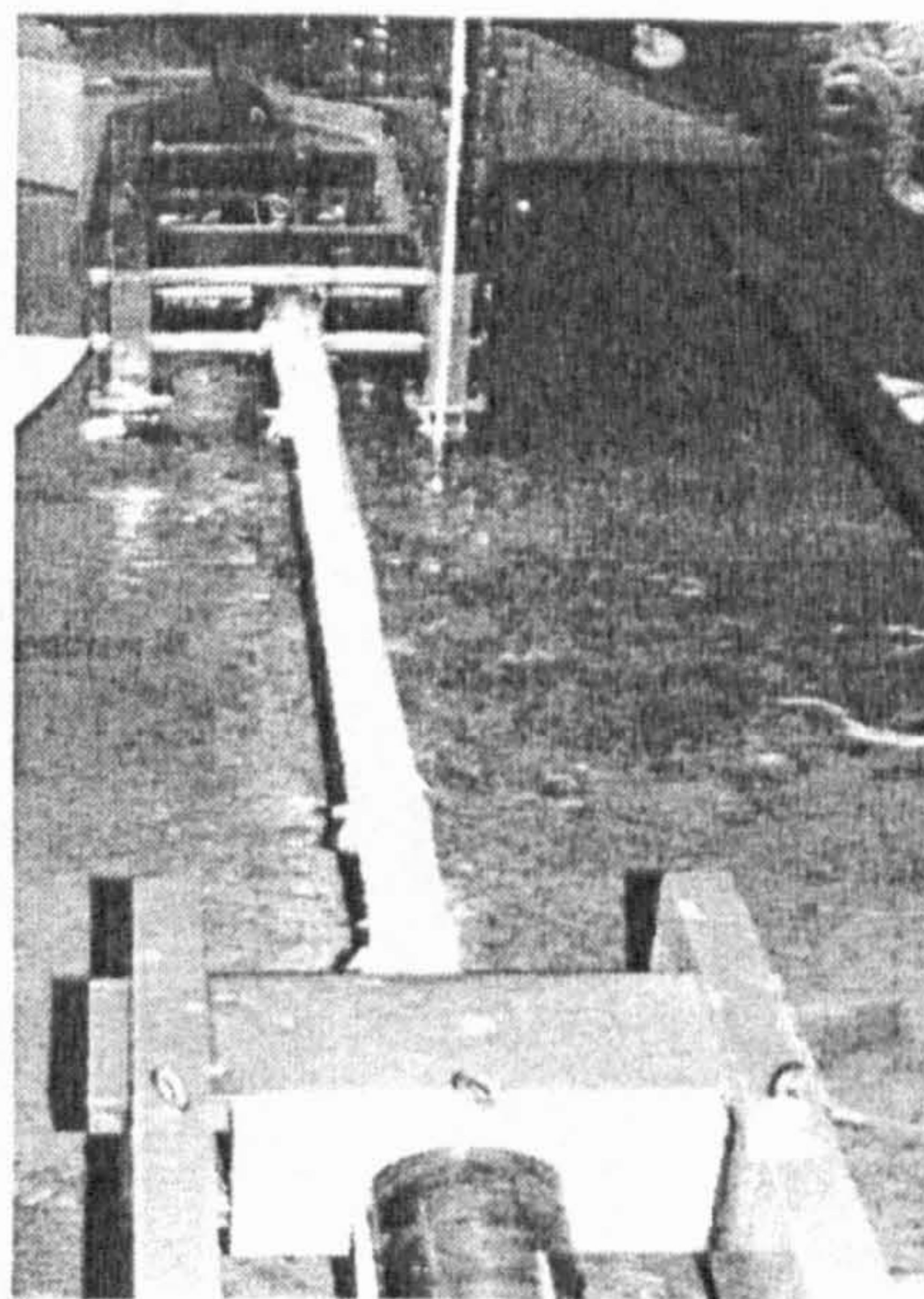


Figure 4.9: **The 44mm Rope mounted in the 1500 kN tensile machine used for rope testing**

To hold the assembly socket, some adapters were made (Figure 4.7a) as the original setting could not take the assembly socket. The adapters were designed and made in The Bridon International (Doncaster).

The machine could also perform the fatigue cycling test. The number of necessary cycles could be programmed into the machine. It could also be left on to break and the number of cycles could be measured. The movement of the ram was indicated by a digital monitor and gave its position in each second. Also another digital indicator could monitor the stress in each second.

4- NEL 30 MN machine: To test the 120mm rope, the 30MN machine (Figure 4.10) from NEL (National Engineering Laboratory in Scotland), was used. That was a 30MN horizontal two-space servohydraulic-testing machine. Eight hydraulic actuators applied force to a common moving crosshead. The applied force was derived from the summation of the transducer outputs and display on a digital voltmeter scaled in increments of 1mV equivalent to 10kN. A full scale reading of 3 volts corresponded to an applied machine force of 30MN.

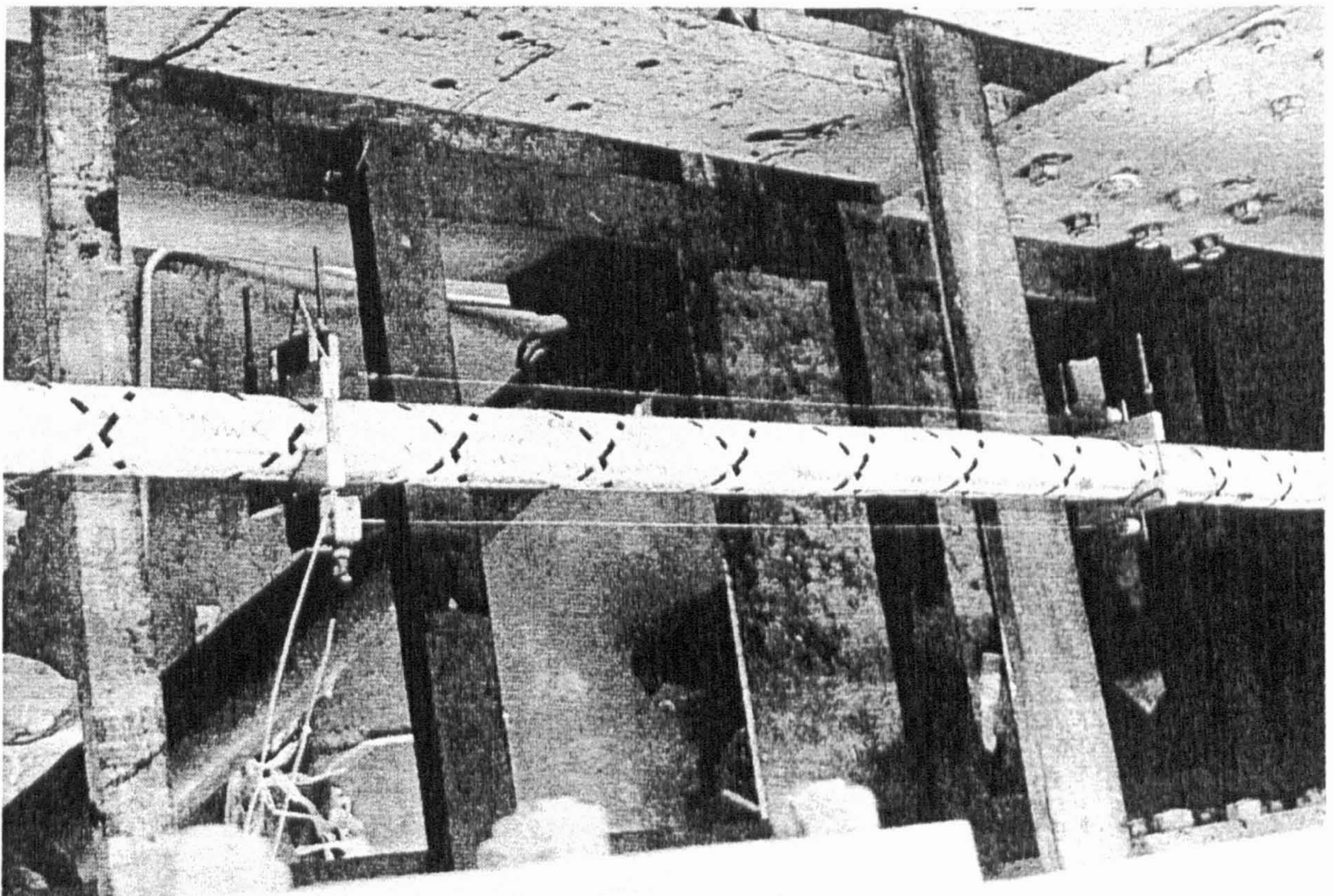


Figure 4.10: The 120mm rope mounted in NEL 500 kN tensile Machine.

4.7 Testing procedures

4.7.1 Tensile

1- Filament

The 100 kN Lloyds machine with identical bollards was used to measure the breaking strength and elongation of filaments. The weight/length of material was measured and used as an input to the computer. Apart from strength at break, the computer calculates “Tenacity, (breaking load/filament weight)”, which was being used to compare the strength of different ropes and constructions.

In each set of tests, at least, 12 samples were taken and the average of results was recorded as the breaking strength of the filament. The breaking strength of the strands was also measured with this method.

2- 18mm Sub-rope

The 500 kN Denison machine was used to test the sub-ropes. The sub-rope was assumed to break around 100-120 kN. The sample was put in the machine by using identical adapters. Around 30% of the initial pre-load was applied to the samples to remove any inequality in the strands’ length, which could happen during the termination procedure. The pre-load also adjusted the spike in the socket. The length of sample was measured for elongation calculation. The load was increased to break the sample. The breaking point and the final load was recorded.

3- 44mm “Viking 7” rope

All tests were done in 1500 kN machine and the data were recorded as the final breaking point and the stress/strain graph. The initial length of the sample was measured. Before the final load application, a pre-load of 100 kN was applied to remove any inhomogeneity in the individual ropes. Then, the sample was loaded to break and the final breaking load was recorded from the digital monitor. Elongation could be traced via the stress strain curve.

4- 120mm “Viking 7” rope

To test the 120mm rope, the 30MN machine from NEL (National Engineering Laboratory from Scotland) was used.

The initial length of the sample, stress drop during 30min holding time, extension under different loads, and breaking load were monitored by a computer and printed.

i) *Static Tensile Testing*

Strength or tenacity gives a measure of resistance to steady forces. It will thus be the correct quantity to consider when a specimen is subject to a steady pull, as for example, in a rope used for hoisting heavy weights. The breaking elongation gives a measure of the resistance of the material to elongation. It is thus important when a specimen is subjected to stretching. All samples were tensile tested immediately after the environmental conditioning. Acoustic emission activity was monitored on most tensile samples. Extension was measured from the machine cross head movement. The rope sample was wrapped a total of four times around the top and bottoms bollards and then clamped at each end to prevent slippage. The cross head speed was kept constant at 100 mm/min throughout the test. In most physical and engineering applications, load is replaced by *stress*. The SI unit of stress is Newton per square metre (N/m²), which is also called a Pascal (Pa). Since the area of the cross-section is not well defined, a relationship between the mass and the load is used in the textile technology and it is called the *Specific stress*. It is defined as:

$$\text{Specific Stress} = \frac{\text{Load}}{\text{Mass Per Unit Length}} \quad \text{Equation 4.1}$$

The consistent unit for specific stress is N m/kg (or Pa m³/kg). However, in order to fit in with Tex system for linear density, it is better to use Newton per tex (N/tex), which is 10⁶ times larger than N m/kg. For comparing different materials, the value of the specific stress at break is used and is called *tenacity* or *specific strength*.

ii) Efficiency

Efficiency is simply defined as the proportion of differences between the tenacity of each sample compared with the tenacity of initial filament divided by the tenacity of initial filament. The equation is as follow:

$$\text{Efficiency \% } (\sigma) = (T_R - T_i) / T_i \times 100 \quad \text{Equation 4.2}$$

T_R = Sample Tenacity

T_i = Filament Tenacity

Initially load was applied from 0 to 2500 kN. It was expected to have some socket draw at this stage although pretension had been applied before. This was investigated by comparison of machine displacement with transducers.

L_{total} = Sample length (socket face to socket face)

The following equation was used to calculate the extension of the rope:

$$\% \text{ extension} = 100 \times L_t / L_{\text{total}} \quad \text{Equation 4.3}$$

L_{total} Socket face to face

L_t Transducer distance

The socket draw was calculated by subtracting machine displacement from transducers measurement:

$$\Delta L_{SD} = \Delta L_{MD} - \Delta L_{\text{total}} \quad \text{Equation 4.4}$$

Where:

ΔL_{SD} Socket draw

ΔL_{MD} Machine displacement

iii) Socket draw

Initially load was applied from 0 to 2500 kN. It was expected to have a long socket draw at this stage. This could be investigated by comparison of machine displacement with transducers'. It is also considered that most of the socket draw will be removed after this stage and there should be no more socket draw for the rest of the test.

The socket draw could be calculated as follow:

$$\Delta L_{SD} = \Delta L_{MD} - \Delta L_{total} \quad \text{Equation 4.5}$$

ΔL_{SD} Socket draw

ΔL_{MD} Machine displacement

iv) Total extension in the rope

The total extension in the rope is calculated as follow:

$$\Delta L_{rope} = \Delta L_{total} - \Delta L_{SD} \quad \text{Equation 4.6}$$

v) Strain

Total strain in the rope could be calculated as follow:

$$\epsilon_{total} = \frac{\Delta L}{L} \quad \text{Equation 4.7}$$

vi) Elastic Modulus

Although elastic modulus for synthetic rope is not a valid expression because it does not exactly obey the linear law, the behaviour of rope under tensile load is very close to linear especially for polyester in parallel construction. The elastic modulus of the rope is calculated by:

$$E = \frac{\sigma}{\epsilon} \quad \text{Equation 4.8}$$

4.7.2 Fatigue cycling test procedure

Fatigue cycling tests were performed on the 44 mm rope in the Bridon 1500 kN tensile machine. The top and bottom load could be programmed into the machine. Because of ram momentum, the load should be adjusted by 20-30 kN difference. It also could be programmed by constant extension.

Two methods of fatigue testing were done as follows:

1- OCIMF Guidelines

The following test is done based on Oil Companies International Marine Forum (OCIMF, 1992) procedure.

The samples were sunk in tap water for 24 hours. Some pre-loads were applied to adjust the sub-ropes and then the test process started. To keep the sample cool, water was sprayed during the cycling (Figure 4.9).

1000 cycles were done at 60% of breaking load. Then the load was increased to 70% of the breaking strength for 1000 cycles. If the rope did not fail during cycling in %70 loads then the load is increased to 80% of the breaking strength. The number of cycles that the rope resists in 80% of breaking strength was then referred to the equation 4.9 that gave a number for each rope, Cycles to Failure (CTF).

The following equations have been derived during several cycling tests on ropes (OCIMF, 1992):

$$1000 \text{ cycles at } 50\% = 251 \text{ cycles at } 60\%$$

$$1000 \text{ cycles at } 50\% + 1000 \text{ cycles at } 60\% = 215 \text{ cycles at } 70\%$$

$$1000 \text{ cycles at } 50\% + 1000 \text{ cycles at } 60\% + 1000 \text{ cycles at } 70\% = 113 \text{ cycles at } 80\%$$

CTF is calculated as follow:

$$\text{CTF} = \text{Number of Cycle at } 80\% \text{ to break} + 113 \qquad \text{Equation 4.9}$$

- **Determination of thousand Cycle Load Level**

For each rope the load level at which failure occurs in 1000 cycles is calculated. The thousand cycles load level (TCLL), as a percentage of New Wet Breaking Strength (NWBS) is calculated by the following equation (OCIMF, 1992):

$$TCLL = 100 - \frac{6.91(100 - TLL)}{\ln(CTF)} \quad \text{Equation 4.10}$$

TLL: Test Load Level

CTF: (numbers of) Cycles To Failure

NB: instead of NWBS, the breaking strength of dry ropes has been used. The ropes, in this method, were mostly experiencing wet environments. That's why most of the calculations were done on the basis of the rope in wet conditions.

TLL is the test load level, percentage of NWBS, the load level at which CTF was determined. Figure 4.14 presents the above formulation in a chart.

- **Experimental procedure**

The sample was soaked in water for 24 hours. About 70 kN pretension was applied to adjust the sub-ropes.

The rope was cycled at 50% of NBS for 1000 times in 1500 kN Denison machine. The same procedure was applied at 60, 70 and 80% of NBS until the rope broke. The data were collected by a digital monitor as well as a plotter.

- **Processing of data**

The load-extension data was imported from the graphs via digitiser software. The data format is normally text and they were then exported to Microsoft Excel software to analyse the data and draw graphs e.g. load-extension.

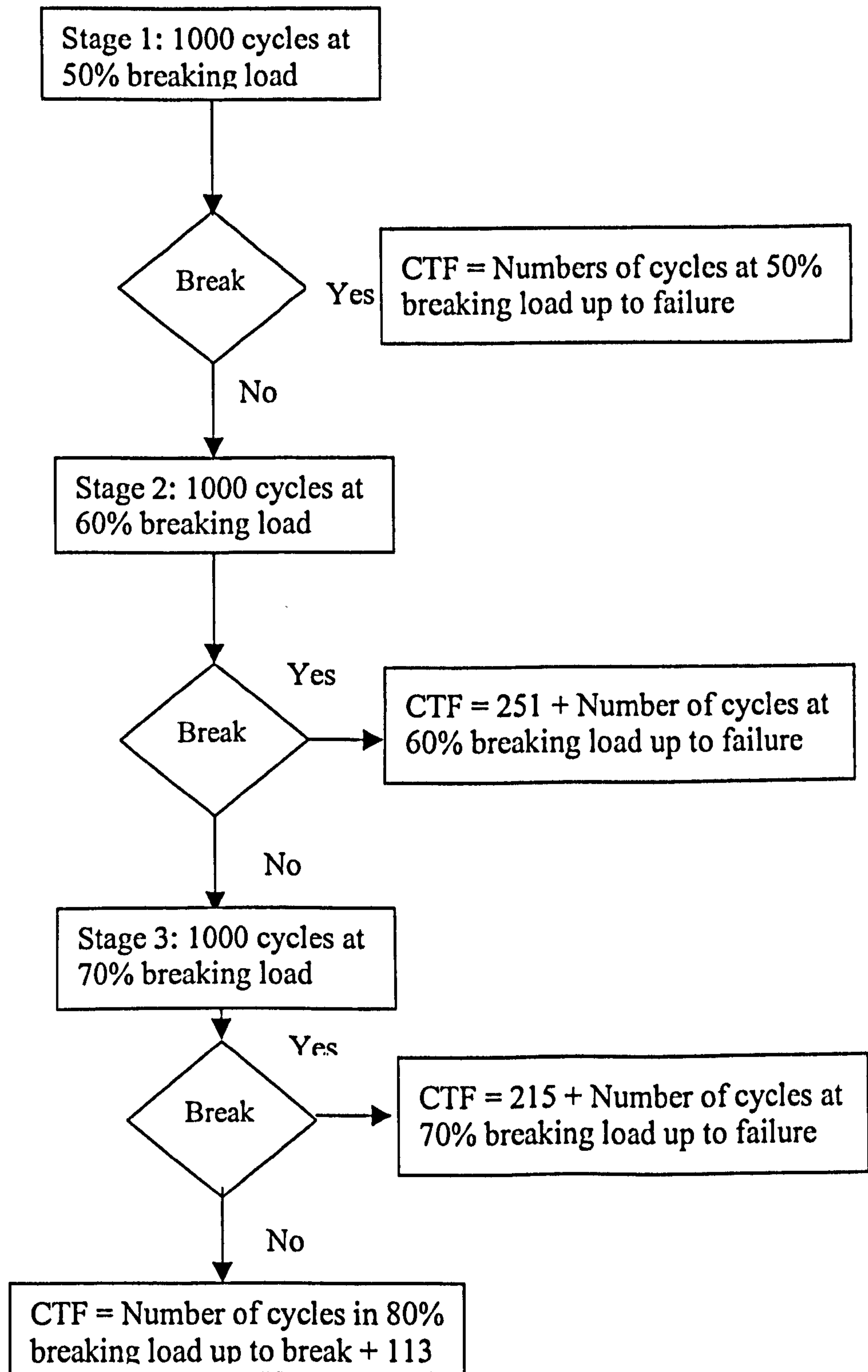


Figure 4.11: Schematic layout of OCIMF guidelines for calculation of CTF for each rope.

2- Petrobras method

Cyclic load testing should preferably be done at load levels where ropes would normally experience in service. The Brazilian Company, Petrobras suggested this type of cycling test. Therefore it is considered that the Petrobras method is based on rope cycling at low load.

About 50 - 80 kN pretension was applied to adjust any inequality in lengths of sub-ropes.

The sample was sunk in water for 48 hours before the test started.

The sample was mounted in the Bridon 1500 kN Tensile machine. Water was sprayed on the rope during testing.

The upper limit of the tensile machine was set to 290 kN to achieve 320 kN because of machine momentum. 320 kN was about 40% of the mean of the breaking load, which was chosen before. The lower limit was set on 190 kN to achieve 160 kN which was about 20% of the mean breaking load.

A load-extension figure was taken during the cycling process every 100 cycles.

The test was continued until the number of cycles passed 200,000. This means the run-out number of this rope was achieved.

Residual stress was measured after the run-out number of the cycling of the rope (Dunn, 1995).

4.8 Acoustic Emission Monitoring of Fibre materials

Several NDT techniques are available for use in conjunction with both wire and synthetic ropes. However, the most readily available is acoustic emission. The principle has already been successfully applied to composite materials and wire ropes. But very limited work has been conducted on synthetic fibre ropes and virtually none on the small diameter high performance synthetic fibre ropes. Hence the choice was clear. The second major reason was the simplicity of the use. The only equipment needed was the acoustic emission analyser, PC, sensor and silicon grease. The most difficult parts of the process were the placement of the sensor and the post processing and analysis of the results.

In this section, a detailed description of the technique used for AE testing of samples is given, and the basic principles of operation of AE analysers are discussed. A parameter called the "AE load delay" is defined, as the tensile load producing a specified low baseline level of AE activity.

Acoustic emission was used in this project in order to:

- Investigate the micromechanical events that occur during the loading process.
- Investigate AE load delay for each rope.
- Predict the maximum breaking load on the basis of AE load delay.

Acoustic emission analysis was performed during the following mechanical tests.

- Static tensile of different rope sizes from filament to rope.
- Residual strength of pre-loaded samples.

The data gathered by the transducer were quantitative rather than qualitative. Since the whole system was not calibrated to a specific standard, the results should not be used quantitatively which means that if another transducer with different frequency spectrum were used, the values could not be compared but would yield a comparable plot profile.

4.8.1 Acoustic Emission Analyser Used

The acoustic emission equipment used was a MR1004 AE analyser, which consisted of a single channel system with event counting and ring-down analysis capability. Tables 4.8-4.11 describes the system specifications and Figure 4.12 shows the equipment set-up. The system was interfaced to an IBM compatible Pentium P90 computer with 16 MB RAM and 1GB hard disk. In this way the data was collected sequentially and in a chronological order, in real time and stored on the hard disk from which it could be retrieved for the post-test analysis.

Model	Testometric Micro 350, Extended Frame
Manufacturer	Testometric Testing Machinery Co.
Manufacture Date	1994
Cross Head Speed Range	0.1 to 1000 mm/min
Last Calibrated	February 1997
Number of Bollards	Two
Diameter of Bollards	41 mm
Load Cell (N)	2500
Load Range (N)	4.00 to 2500
Frequency	375 kHz

Table 4-5: Specification of Testometric tensile testing machine.

In this work, attention was paid to the analysis of ring down counting (RDC) rather than other AE parameters. An AE event in this unit, defined in terms of the instrument threshold, had a fixed “*dead time*” of 100 microseconds. If the “*dead time*” elapsed since the last threshold crossing, the next threshold crossing was taken as the beginning of a new event.

The threshold voltage was adjustable from 10 mV to 69.18 mV, which corresponded with levels 0 to 7.0. The AE event amplitude was defined as the maximum AE signal level relative to 10 mV. The amplitude detector unit of the MR1004 sorted the AE events into 25 levels, each 2.4 dB wide. Level zero corresponded with the amplitude above 10 mV and below 13.18 mV. Events with amplitude larger than 10 volts were registered in level 25 (over-range). For ring-down counting, the amplitude of the signal was compared with the threshold voltage, and the number of times the signal amplitude exceeded the threshold level gave the total ring-down count for each event. Throughout the whole period of this project the same AE analyser and transducer were used.

4.8.2 The AE Transducer

In order to find the most suitable position for the AE transducer, several experiments were conducted. The most common technique was to attach the transducer directly to the sample. However, the most obvious problem was the physical size of the rope samples. The first approach was to attach the transducer directly to the rope by using one of the following:

- Masking tape
- Paper clips
- Bulldog clips

In none of the techniques used, did the transducer stay in contact with the rope sample at all times during the loading cycle. And in all the cases the rope always failed at a lower breaking load and under the transducer.

The choice was to attach the sensor onto the test rig. By keeping the transducer at the same place throughout the whole research, it was possible to maintain consistency and accuracy.

The acoustic coupling of the transducer to the surface of the test rig was achieved with a thin layer of silicon grease. Couplant is very important; nearly 100% of the energy incident normal on a metal/ air interface is reflected. A Couplant with the appropriate acoustic impedance will greatly improve the energy transfer from material to transducer.

In this study, the same PZT5 (MRTB-500) piezoelectric transducer and silicone grease, i.e. RS454-124 silicone grease, were used through making the comparison of all the results possible.

4.8.3 Processing of Data

The AE data used to analyse the behaviour of the ropes were obtained using two techniques:

- Real Time Data collection
- Post Processing

a) Real Time Data collection:

The data was logged, real time, using the Testometric machine software, Universal Materials Testing (UMT), via the RS232 port. The load was recorded directly from the 2.5 kN load cell. The data were logged into the computer in the data and text format. The UMT used the data files to plot its own load extension plots and make the calculations based on the data inputted into the system at the beginning of the test. The text files were used in post processing.

The stress waves generated due to the loading process were picked up by the MRTB-500 piezoelectric transducer and fed into the MR1004 Acoustic Emission analyser via the MRP-01 Preamplifier through the RS232C port. They were then displayed as histograms of events occurring as the loading continued (Figure 4.12).

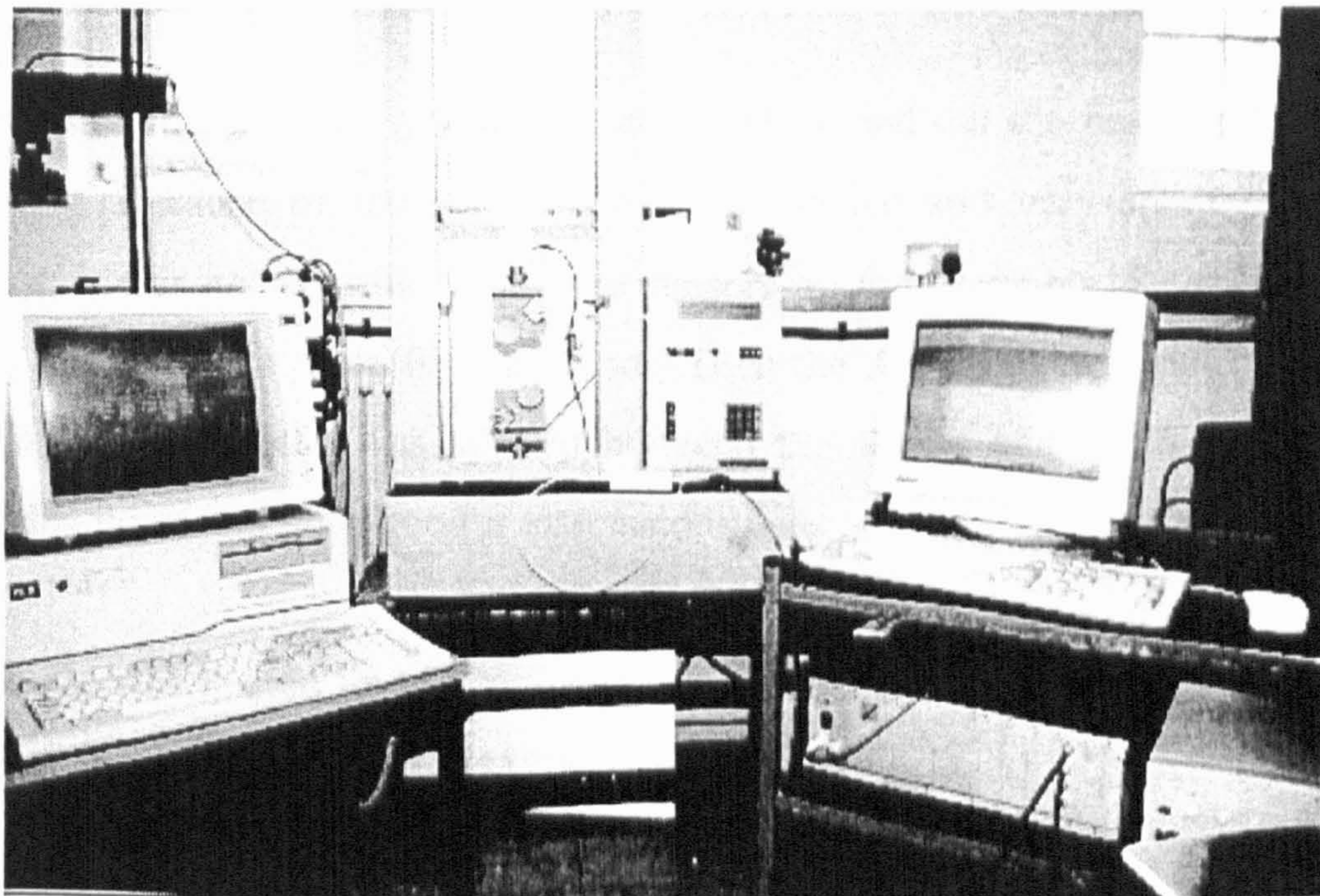


Figure 4.12: Acoustic emission test facilities a tensile machine.

b) Post-Processing:

In order to make use of the UMT and MR1004 results some post processing had to be done. The first step was to import the text files into Microsoft Excel and convert them into XLS format. They were then plotted in graphs against load extension results. The acoustic emission data had to be converted into a recognisable format for the Microsoft Excel. Thus they were converted into Comma Separated Values (CSV) format using the MR1004 software and then imported into Excel to change them into XLS format.

The graphs were constructed using time verses ring down count obtained from tests. The software uses counts from the experimental events and reports this as a number which is called the ring down count.

4.8.4 Sample preparation

- **Filament**

The filament consisted of 210 fibres of Akzo 877TN material. The samples were mounted in Testometric 10 kN computer control tensile machine in Bournemouth University. The original yarn consisted of 30 filaments, which had to be unlaidd. Identical grips were used to test the sample.

Sensor Position: Different positions were tried to find out the best position for the AE sensor. Because of the sensitivity of the device and very small diameter of filaments, it was not possible to put the sensors on the filaments. Several tests were done to find the right place for the sensor. Then the AE sensor was put on the upper grip. The silicon grease was applied between the sensor and the metal surface to remove the noise and get a good transmission.

The sample was loaded up to break and AE wave was detected at the same time as load-extension curve was recorded.

- **Sub-rope**

The sample preparation has been explained in section 4.5.2. The sensor was placed on the termination.

- **Rope**

Sample preparation has been noted on 4.5.3 and 4.5.4 as they were used to make the samples for static tensile tests. In both cases, the sensor was placed on the terminations as it was considered the best position to detect the noises.

4.8.5 Definition of parameters

AE values: AE value, in this study, means the ring-down counting in each second minus this number in the previous second.

Load percentage: Load percentage was the proportion of load at any time to the highest load in the test.

Extension percentage: Extension percentage was the proportion of extension at any time to the highest extension in the test.

4.9 Finite Element Modelling

ANSYS 5.3 software was used to develop the model. ANSYS includes its time-tested, industry-leading applications for structural, thermal, mechanical, computational fluid dynamics, and electromagnetic analyses, as well as solutions for transient impact analysis. ANSYS software solves for the combined effects of multiple forces, accurately modelling combined behaviours resulting from "multiphysics" interactions. The software also features advanced non-linear material simulation and the best solvers money can buy. Industry software vendors state that the criteria for an "Analysis for Design" product are:

- Have a user interface that looks familiar to the CAD user;
- Work off of the CAD geometry database;
- Support the same computer platforms as the CAD design system;
- Simplify the analysis system for use by a designer.

The software was run in Microsoft Windows environment and this helped to get all figures and data directly transferred to other softwares e.g. Microsoft Word. The software configuration has been set-up to understand the load application into nodes or element. Elements were chosen if the input data was pressure. However, if force was the initial input, it must be applied only into nodes or keypoints.

Solid modelling was done on the basis of the initial 100 kN Parafil socket manufactured by ICI for Parafil ropes. AutoCAD software was used to measure the dimensions of the socket. The measurements included the location of the keypoints and different areas as well as the angles. The first step was to make a model on the basis of existing geometry. Several methods could have been applied to make that. In this model, the model was made using the area rotation around the X-axis. At the end, the additional volumes were subtracted from the back of the socket.

The meshing process of the model was the second job to develop this model. Bricks with 8 nodes were chosen for the uniform parts of the model, like the socket body.

Bricks with 8 nodes were the simplest element, which was thought to be fitted into this model. A tetrahedron 10 node with rotation was used for a non-uniform part, like the back of the socket in forklift and clevis pin area. There were some distorted areas during the meshing process, which were ignored because the elements were too small compared with the actual shape.

The solution was done on three element types. The first element type was a brick with 8 nodes. Two sets of solutions, nodal & element, were done on this element type. To investigate the accuracy of the model two more element types were investigated. The first one was 4-nodes tetrahedron element and the second was 20-nodes bricks.

The last step was done to simplify the model in the solution phase. Contact elements were applied to tie three different models, rope, spike and socket. Two types of material were used in the modeling of the termination, one for the socket and spike and another for the rope.

Conclusion

In this chapter, the material and test facilities used for this study were discussed, as well as the finite element software and the software for Acoustic Emission data collection. In detail, the following issues were elaborated on: rope materials and constructions, termination types and parts, sample preparation for different ropes and terminations, testing facilities for fibre, sub-rope and rope, testing procedures in the case of tensile and fatigue cycling using the patent from chapter 3, acoustic emission and finite element modelling. In the next chapter, the results for using the facilities and materials in this chapter will be presented.

Chapter 5: Results and Discussion

5.1 Background

This chapter includes solutions to existing problems in rope termination mentioned in chapters 1 and 3. Based on a new method of termination, the “Stress Relief Socket”, it is predicted that rope performance could increase up to 13% compared with the best of existing terminations methods in industry.

The load carrying capacity of synthetic fibre ropes is usually limited by the strength of their termination. Therefore, the inherent tensile strength of ropes is not fully utilised (Flory *et al*, 1995). The main objective of this study has been to develop an optimum method of termination for high strength synthetic fibre ropes used in marine environments, and to achieve a better tensile performance compared with the existing methods. Macroscopic failure analysis carried out in this study has provided important ideas about modes of failure. In order to achieve the aforementioned objectives, about 550 samples were tested under tensile loading.

The following tests were carried out during this study:

- Static tensile test on Polyester - Akzo D877TN - 300 samples from filament to 44mm rope
- Static tensile test on Polyester - Akzo D855TN - 85 samples from filament to 44mm rope
- Static tensile test on Polyester - Hoechst - 150 samples from filament to 44mm rope
- Cyclic test on Polyester - Akzo D877TN - 44mm – 4 samples
- Cyclic test on Polyester - Hoechst - 120mm – 1 sample
- Residual strength measurement on Polyester - Hoechst - 120mm after cyclic loading – 1 sample
- Acoustic emission monitoring during filament tensile test on Akzo – 180 samples
- Acoustic emission monitoring during filament tensile test on Akzo yarn – 180 samples
- Acoustic emission monitoring of 44mm sub-ropes and ropes during static tensile tests.
- Finite element modelling – 2 models

The tensile test was the first conducted to satisfy the requirements of the manufacturers and end users. It is often the case that if a rope is approved in the tensile strength testing regime, further investigations, such as cyclic fatigue and creep

tests, will be performed. In this study, the tensile strength of different rope components was measured to investigate how it relates to different failure mechanisms. The different components tested included filament, yarn, sub-rope and rope.

In addition to tensile testing, cyclic fatigue performance is the next property that concerns the end users of mooring lines. Mooring lines are under constant cyclic loading due to the inherent behaviour of marine environments.

Two commercial methods of cyclic testing were performed in this study, namely OCIMF (Oil Companies International Marine Forum) and Petrobras. The guidelines for the former guidelines suggest a testing regime based on high loads and relatively low numbers of cycling. The latter is based on low loads and high numbers of cyclic loading.

In an attempt to elucidate failure mechanisms, in filament, yarn and rope, acoustic emissions were monitored during tensile testing.

A finite element modelling of the socket and filament were performed to investigate the stress concentration areas in Parafil socket, which indicates the areas where the rope should be improved to prevent the failure and also prove that the load stay constant in the fibre when loading.

5.2 Parameters affecting the quality and reliability of results

As this study involved many experimental findings, it was imperative to limit the parameters that affected the quality and reliability of results.

It is believed that the following parameters could have adversely affected the results.

- 1- **Termination preparation skill:** During the preliminary stages of this study, it was found that different labour skills would result in different rope strengths. Therefore, all the samples were prepared by the same person using an identical procedure.
- 2- **Quality of as received rope filaments:** All as received batches of filaments were routinely checked for visible defects, after discarding the first 10 meters of the filament.

- The samples used were taken from bobbins with no initial processing defects. However, the samples used may have included some minor faults, which seemed impossible to detect. But this could represent the true nature of the supplied materials. This is in addition to the quality check carried out by the production personnel.
- 3- **Pretension:** In order to avoid the effect of socket draw and equalise the rope elements lengths, all samples with socket termination were pre-tensioned prior to testing. However this procedure may have caused partial breaking of some filaments, which could not have been visible.
 - 4- **Termination effects:** Although samples with failure inside the termination were discarded, termination effects were not negligible in all samples. However, minimum termination effects were found on samples using the Stress Relief Socket as failure points were far from the socket.
 - 5- **Sample number:** For economical reasons, a small number of samples was used to test larger diameter ropes. Therefore, the results may not be statistically representative. However, the past experience of previous tests has shown that the results are reproducible.
 - 6- **Rope jacket:** The jacket was applied to 44 and 120mm rope to protect and keep all sub-ropes together. It was assumed that the jacket had no influence on the rope strength. However, when the jacket was used in the termination process, it may have improved the breaking load.
 - 7- **Socket resin:** The resin used to impregnate the filaments inside the socket, should have penetrated all fibres equally. Therefore, dry filaments would have decreased the reliability of results.
 - 8- **Heatshrink:** The heatshrink process involved high temperatures that could have damaged the fibres, which in turn could have affected the results.

Care was taken to minimise variability in the procedures. Therefore, it is claimed that the experimental results, presented in this thesis, are accurate and reproducible.

5.3 Static tensile test

The behaviour of rope under applied force and break type is the most important feature of ropes. The reaction of the rope to applied force is a combination of material properties and construction. Its reactions, thus, depend on the structure of the fibre and material used. Moreover, the prediction of rope strength based on material used is somehow useless if termination effects are not considered.

A rope is a fairly complex arrangement of fibres in a multi-helical structure. The rope fibres are arranged in helical structures whose axes form further helices in a larger structure. Often the larger structure is again arranged in a larger helical structure. These helical structures stretch fairly easily by becoming longer and thinner, as a spring does under tension. They snap back when the tension is removed. At the same time, the structural deformation causes stresses in the fibres to which they respond by stretching. The fibre stretch reaction depends entirely on the load-elongation properties of the fibres used.

In a rope composed of material having very low elongation, nearly all the stretch of the rope will be structural. In a rope constructed by highly stretchable fibres, the material stretch would be an important percentage of the rope elongation. It can be up to 50% of the total elongation. Rope structures usually tighten in use after several loading, but they open by action of the material used, such as swelling or shrinking processes after being immersed in water or exposed to heat. The fibre material itself behaves in a viscoelastic manner, and thus changes dimensions and its load-elongation behaviour due to loading processes and environmental influences.

At the same time, these changes interact with the arrangement of the fibres in the rope structure. Fibre ropes change their dimensions and load-elongation properties in use. Therefore, as-received and conditioned ropes should be discussed separately. Most of the time, available test data from rope manufacturers usually deal with new ropes only; load-elongation curves mainly show the reaction of new ropes under standard test and environmental conditions. Small ropes show higher strength efficiency than large ropes as, the number of fibres in a rope increases with the square of the diameter. They also exhibit greater inclination with respect to the rope axis, and thus suffer a drop in strength efficiency.

The load-extension curves obtained from static tensile test results from previous studies show three stages of the mechanical behaviour of ropes:

- **Zone 1: Initial non-linear behaviour**

This zone is defined by the non-linear rise in the load. The main reasons for the non-linear rise are thought to be:

1. If socket termination used, rope socket-draw will be an important factor in this region. Rope socket-draw is mainly affected by care in preparation as socket termination is very dependent on the care taken during assemblage.
 2. The alignment of fibres into a uniform assembly. This is congruent with the literature that during the loading history there is structural realignment of the fibres, especially in the initial stages when the fibres have room to move.
 3. The cover extends more than the core, due to the differential extension between the core and the cover, but it takes less loads. Therefore the rise and fall in load could be due to slippage. It is due to some surface fibres failing as a result of internal abrasion, fibre fatigue and hysteresis. This process of differential extension continues until the cover starts to grip. From this moment onward the core and the cover extend at the same rate, which is the start of the second zone.
- **Zone 2:** A pronounced knee region, when the curve shows an inflection. The rope cover and the rope construction are thought to affect the shape and behaviour of the rope.
As the load rises, the cover continues to grip the core. The friction between the fibres leads to an increase in the heat generated. The heat and the radial pressure of the cover will cause the fibres either to fuse together or become very compacted, which is the start of Zone 3.
 - **Zone 3:** A complete linear region which proceeds to the catastrophic failure of the rope material.

Transition from zone 2 to zone 3 is very important since it is the transition from a stage where rope can bear increasing loads, with growing damage, to a stage where the rope fails in a sudden and catastrophic manner. This zone is the linear part that extends from the end of Zone 2 (the curved section of the graph) to the point at which the rope fails. By the time that this stage starts, every fibre in the load bearing section of the rope has compacted together. In other words, the rope has begun to behave like

a single uniform rope. As the failed end recoils, the released stored energy is quickly converted into heat. But the cover prevents this heat from being lost to the environment. This heat causes the fibres to fuse together and increase in rope stiffness [Koohegilani, 1998].

5.3.1 Tensile strength of filament and yarn

This section presents the behaviour of filament and yarn under tensile loading.

The following comparisons could be made between these two materials:

I) Efficiency

Figure 5.1 shows efficiency of these two materials from Tables 5.1 & 5.2.

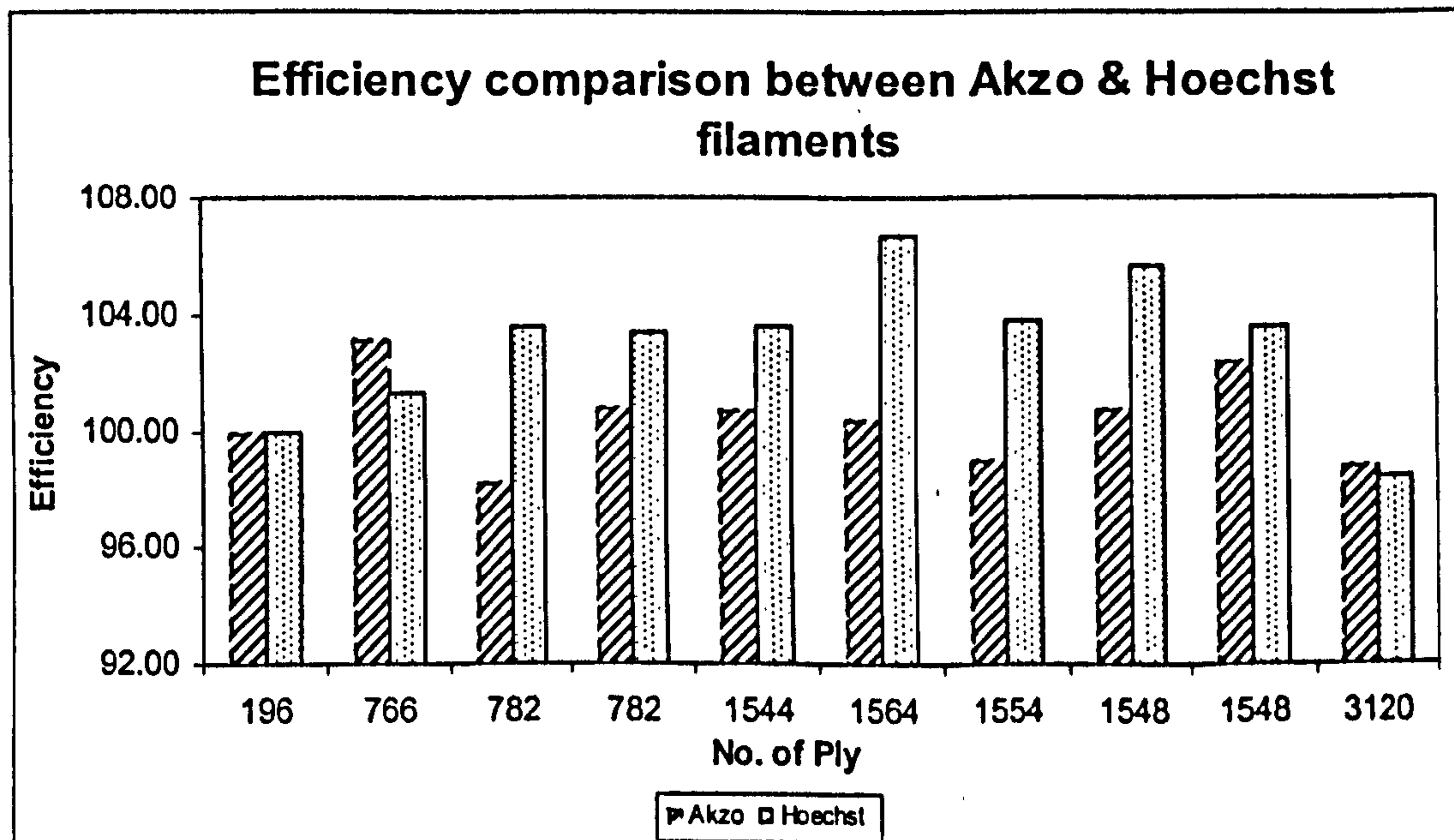


Figure 5-1: The schematic layout of construction efficiency for Akzo and Hoechst materials from table 5.1 & 5.2.

Construction	Size (Tex)	D (mm)	BL (N)	E (%)	T (kN/Tex)	ζ (%)
Untwisted 1 Ply	196	0.5	133	28.32	678.07	100.00
Untwisted 4 PLY	766	0.9	535	26.77	699.36	98.16
Twisted (S) 4 PLY	782	0.9	520	26.93	665.53	100.77
Twisted (Z) 4 PLY	782	0.9	536	27.06	683.22	106.05
Untwisted 2x4 PLY	1544	1.4	1053	27.42	682.66	100.69
Twisted (Z) 2x4 PLY	1548	1.4	1056	30.26	683.02	100.37
Twisted (Z) 8 PLY	1548	1.25	1074	29.21	694.69	99.01
Twisted (S) 8 PLY	1554	1.25	1042	29.41	671.30	100.74
Twisted (S) 2x4 PLY	1564	1.4	1063	29.23	680.52	102.46
Untwisted 2x8 PLY	3120	1.90	2076	28.30	670.05	98.83
Twisted (s) 4x4 PLY	3134	1.95	2052	31.82	655.44	96.67

Table 5-1: Number of filaments, Diameter, Breaking Load, Elongation, Tenacity, and Efficiency percentage of Akzo filament and yarn.

Construction	Size (Tex)	D (mm)	BL (N)	E (%)	T (kN/Tex)	ζ (%)
Untwisted 1 Ply	122		84	18.18	692.81	100.00
Twisted (S) 2 Ply	250	0.4	175	17.50	701.46	101.25
Twisted (Z) 2 Ply	250	0.5	179	17.13	717.36	103.54
Twisted (S) 4 Ply	500	0.7	485	19.94	716.12	103.36
Twisted (S) 4 Ply	500	0.7	504	22.32	717.16	103.51
Twisted (S) 8 Ply	994	1.0	734	20.02	739.04	106.67
Twisted (S) 8 Ply	1000	1.0	718	21.53	718.99	103.78
Twisted (Z) 8 Ply	1000	1.0	731	19.61	731.99	105.66
Untwisted 2x8 Ply	2004	1.5	1437	23.46	717.80	103.61
Twisted 2x8 Ply	2002	1.6	1363	23.27	681.48	98.36

D = Diameter

BL = Breaking Load

E = Extension to break

T = Tenacity

ζ = The Construction Efficiency

Table 5-2: Number of filaments, Diameter, Breaking Load, Elongation, Tenacity, and Efficiency percentage of Hoechst.

The results show (Table 5.1 and 5.2) that the most efficient filament collection consisted of 4 plies for Akzo and 8 plies for Hoechst samples with the assumption that 1 ply filament is 100% efficient. In addition, consistency in the efficiency results for Hoechst was more than that in Akzo.

Fluctuation in results could be because of improving effects in some fibre collections if experimental errors are ignored. It is thought that fibre collection, in some cases, could increase the tensile properties. No real figure for this improvement could be given and it is only seen in some experimental data.

II) Twist angle

The differences in the results of tenacity, for S and Z turns, in the twist of yarns are presented in Figure 5.2. The literature states that there is no clear evidence on tenacity difference between S and Z constructions (Hearle *et al*, 1969; Oplatka *et al*, 1996; Rebel, 1996; Pan, 1996).

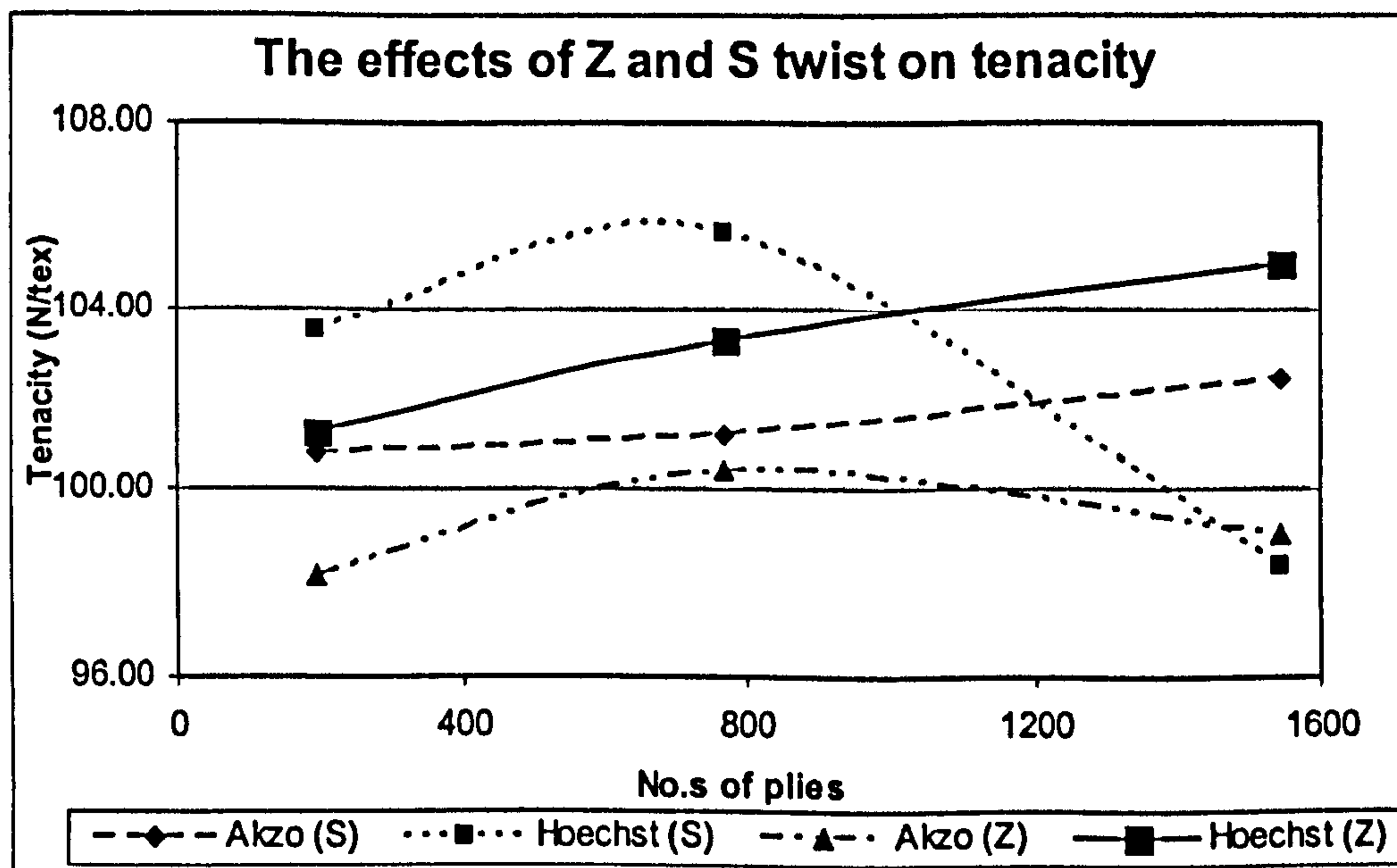


Figure 5-2: The effects of S and Z turn in the filaments for Akzo and Hoechst

The results of the resent study indicate that Akzo samples give relatively identical tenacities data regardless of their construction. However, Hoechst samples in Z twist denotes a superior tenacity relative to the Hoechst S twist. As it has already been discussed, there should be no major difference in the results and this simply could be as a result of experimental errors.

III) Tenacity behaviour of filament

A typical Tenacity-Strain curve, for filament, is shown in figure 5.3. Lower tenacity in Hoechst is due to construction differences as Akzo consists of more fibre compared to Hoechst (Section 4.3). When comparing differing collection of filament, it is necessary to ensure that each filament has a similar weight.

Hoechst did not show any clear knee region but a small change was noted in Akzo. Non-linear region did not reflect the rope behaviour under tensile for both materials after 100 kN/Tex. It is thought that the non-linear region in filaments was mostly due to the alignment of fibres in the initial stage of load application.

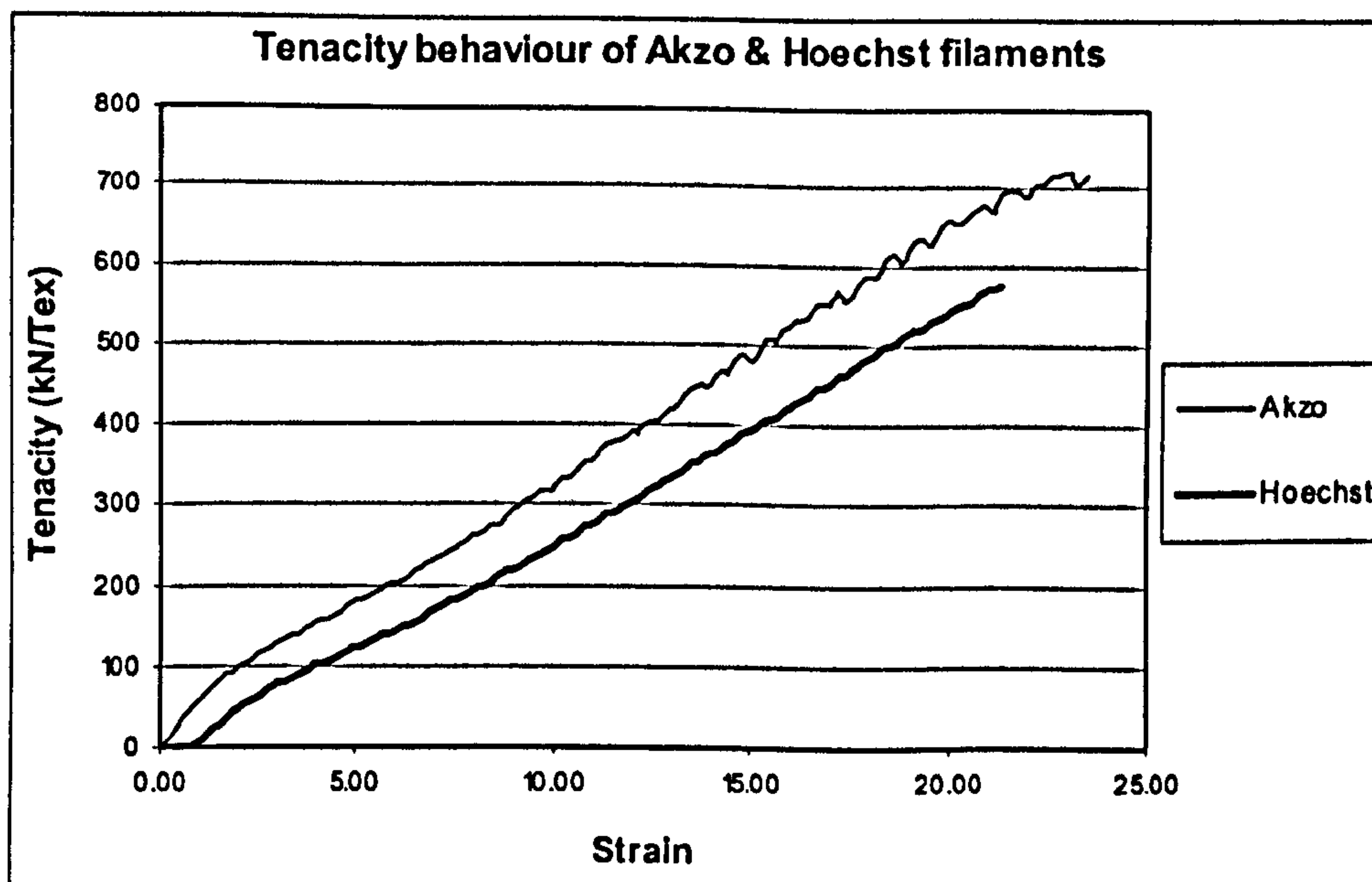


Figure 5-3: A typical Tenacity curve for Akzo and Hoechst filaments.

Tensile test for filaments does not match the results for as-received materials (Table 4.1). This is due the differences in constructions of two materials.

IV) Tenacity behaviour of strands

A typical tenacity-strain curve, for Akzo and Hoechst strands, is shown in figure 5.4.

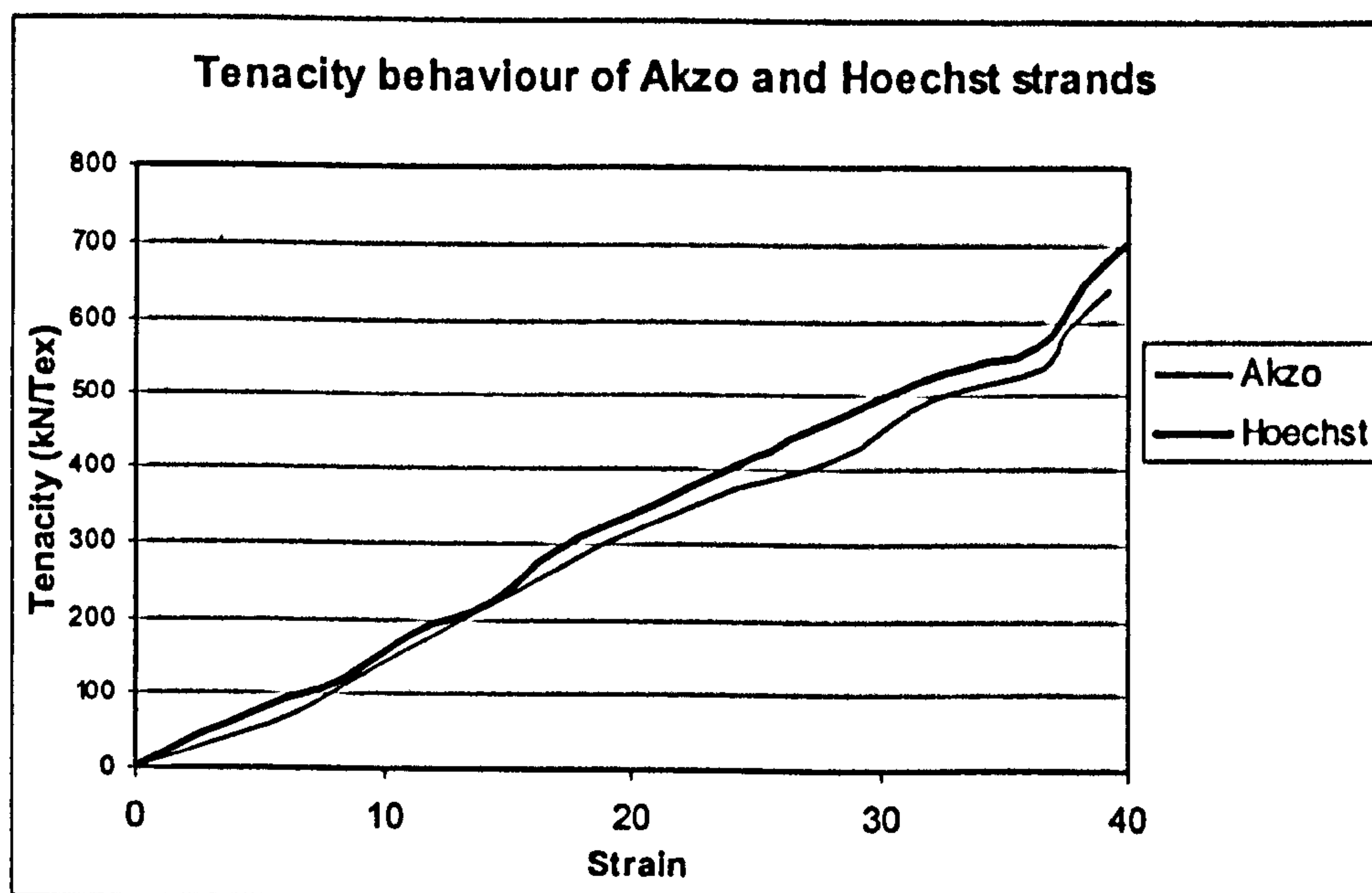


Figure 5.4: A typical Stress-Strain curve for Akzo and Hoechst strands.

The dominating effect in tensile properties of strands, compared to single filaments, is filament twisting, as strands are made of twisted filaments. When the load rises, the friction between the fibres leads to an increase in the heat generated. The heat will cause the fibres either to fuse together or become very compacted. There is a relative decrease in the rate of tenacity in both materials at similar extensions before they break that is happened around 32-36 percent of strain. There is a decrease in the loading properties when filaments melt. When melting, filaments tend to fuse together and behave like a uniform bar that result in increase in the final breaking tenacity.

Comparing similar strains in figures 5.3 and 5.4 indicate that the strand showed relatively high strain compared to the filament. This could possibly be justified for the following reasons:

1. The filament consists of an assembly of single fibres such that there will not be relatively friction. Twisting to make the strand, could build up a structure that tend to create friction under load. Changes in the strand curves after 30% strain could be a result of heat build-up in the fibres that leads to plastic deformation of the filaments which results in a larger extension.

2. The machine frames is elastic and hence could extend more in the strand compared to the filament tests. In the twisted structure of the strand there may well be an elongation required to insure that each filament is in tension. This can be detected in figure 5.3.
3. Differences between structures of filament and multifilament (strand) which is a twisted structure of filaments inevitably change the load-extension loci. When the load is applied, the strands can tend to untwist that result in greater extension.

5.3.2 Tensile strength of sub-rope

The reaction of fibre ropes to applied forces, energies, and deformations is their most important technical property. Ropes as textile structures, react to applied stresses showing a combination of constructional and material deformation. Their reactions thus depend on the structure of the fibre material used in them. The structure of ropes is a crucial feature affecting their behaviour under applied loads.

In the present study, 18 mm sub-rope of the two polyester grades, Akzo and Hoechst, were tested using different methods of termination, Parafil, stress relief socket, and splice. Also different arrangements of spike, inside socket, were examined. Poor data, which were due to partial failures, were discarded. The rated values of the strength for Akzo and Hoechst sub-ropes were calculated from the strength of a single filament by multiplying the number of filaments in the sub-rope, without considering the effects of the twist, the termination, or the construction or other defects (e.g. cover, test method and so on).

1. Spike arrangements

In order to find out the best method of socket termination, different spike lengths and preparation were tested. The average results are presented in Table 5.3.

Sample Configuration	Breaking Load (kN)		Tenacity (N/Tex)		Efficiency (ζ) (%)	
	Akzo	Hoechst	Akzo	Hoechst	Akzo	Hoechst
HS+H+R	100.04	106.20	529.79	529.17	77.85	76.37
FS+H+R	102.06	111.39	538.55	555.03	79.43	80.11
FS+R	101.56	108.45	535.92	540.38	79.04	77.99

Table 5-3: Average data from Akzo & Hoechst 18mm sub-rope tests using different spike arrangements.

HS: Half Spike H: Heatshrink R: Resin FS: Full Spike

The results are presented in Tables 5.3 and Figure 5.5. It appears that the best method of termination for this rope type, terminated with Parafil socket, is Full Spike + Heatshrink + Resin. Half spike arrangement donates the lowest results compared to the others. This could be as a result of less contact areas between socket and spike and a smaller amount of gripping properties. Heatshrink tubing plays a softening role inside the socket and allows fibres to adjust themselves when pulling. Post-mortem comparison between full spike, with and without heatshrink tubing, proved that more fibres fused and failed inside the socket when heatshrink was not used and resulted in a lower tensile strength (Figure 5-7).

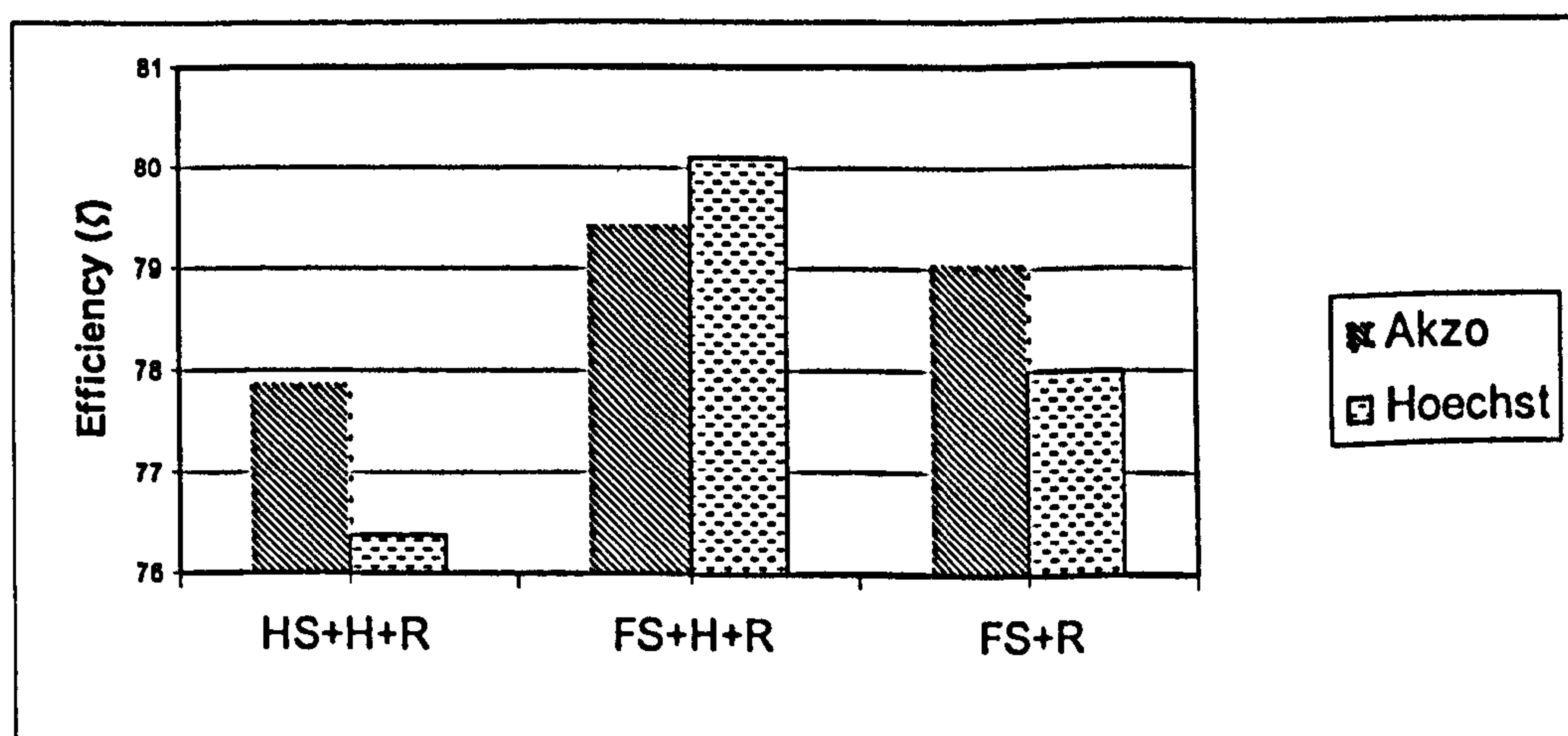


Figure 5.5: Tensile efficiency of sub-rope with different arrangement in an identical termination.

As FS+H+R was proved to be the most consistent method of termination to measure tensile strength, it was chosen as the testing method for the rest of tests.

2. Termination methods

As mentioned (section 3.1), the use of different termination methods led to significant differences in the loading performance of the sub-ropes.

The following results present the behaviour of two material types under tensile load using different termination types:

Sample Configuration	Breaking Load (kN)		Tenacity (N/Tex)		Efficiency (ζ) (%)	
	Akzo	Hoechst	Akzo	Hoechst	Akzo	Hoechst
Parafil Socket	101.31	111.39	534.61	555.03	78.85	80.11
Splice	107.39	113.43	566.70	565.16	83.58	81.57
Stress Relief Socket	109.69	100.15	578.83	499.01	85.37	72.03

Table 5-4: Average data from all Akzo & Hoechst 18mm sub-rope tests.

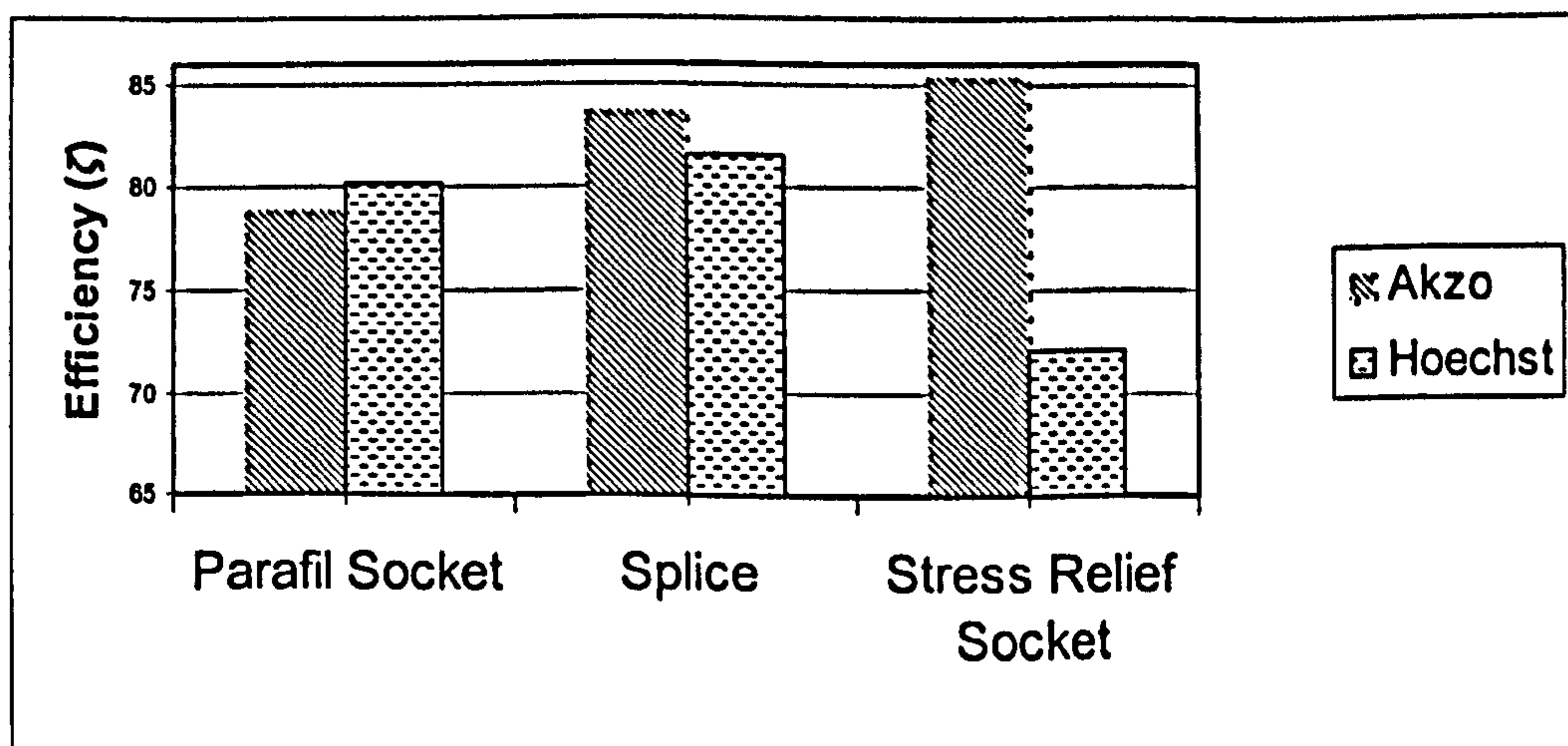


Figure 5.6: Tensile efficiency of materials tested in different termination configurations.

The Stress Relief Socket showed an improvement in tensile property for Akzo while Hoechst showed a sharp decrease in tenacity.

It is thought the surface coating on Hoechst fibres could cause fibre locking. As the Stress Relief socket is based on application of extra material inside the socket, fibres must have relative movement to adjust during the initial load application process. Sticky fibres cause fibre fusion followed by premature failure inside the socket.

Post-mortem assessment of the Hoechst rope inside the socket showed that fibre were stocked and fused together (Figure 5.7).



Figure 5.7: **Hoechst Fibres inside the socket after failure.**

3. Tenacity behaviour of the sub-rope

The tenacity-strain figures of the Akzo and Hoechst sub-ropes are graphically shown in Figures 5.8 and 5.9.

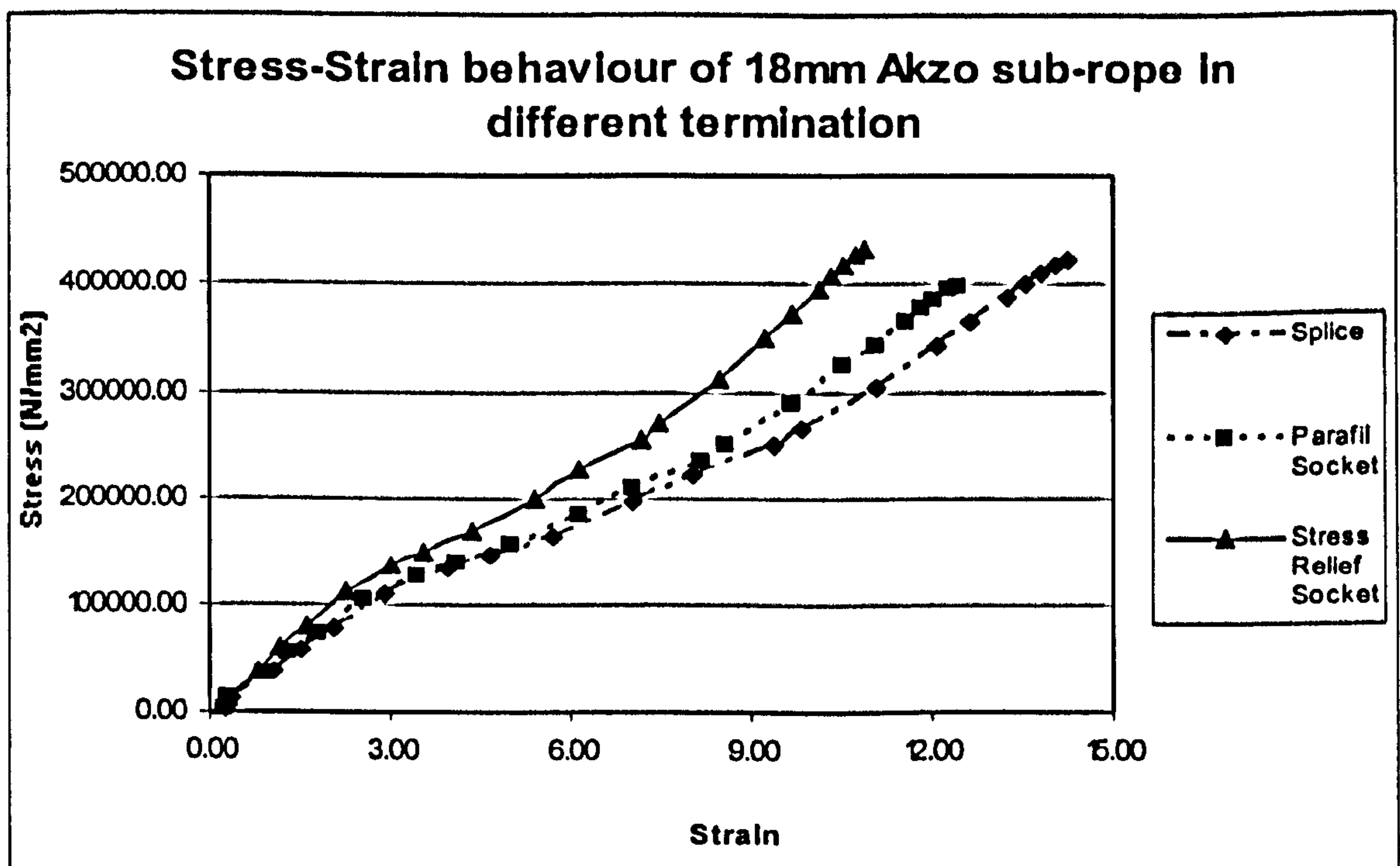


Figure 5.8: Tenacity behaviour of 18mm Akzo sub-rope tested with different termination type.

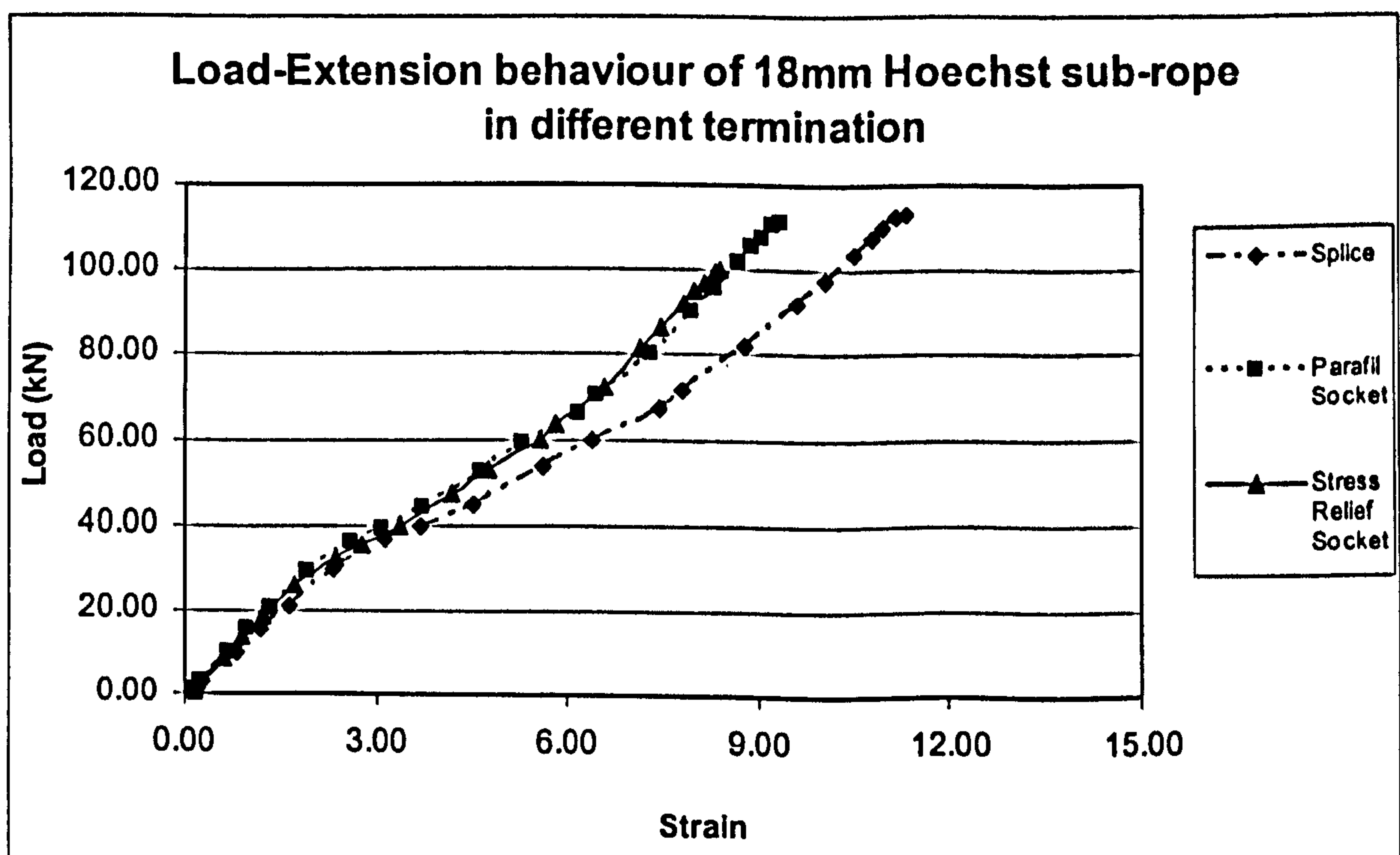


Figure 5.9: Tenacity behaviour of 18mm Hoechst sub-rope tested with different termination type.

Comparison between Figures 5.8 and 5.9, suggests that the rope tenacity for the splice termination is poorer than those of Parafil and the Stress Relief Socket. The lower strains tolerated by the Hoechst material is because of the same surfactants that caused the material to give the poor stress relief socket performance.

4. Extension to failure

Different termination methods have various effects on the extension to failure of sub-ropes. The extension to failure of rope using the Parafil socket was higher than that in the splice while using the Stress Relief Socket appeared to produce the lowest extension in ropes. It should be noted that extension in the Parafil and the Stress Relief socket is a combination of the socket-draw and rope extension, while in the splice slippage happens in the buried parts of the rope. It appears that the slippage in splice is smaller than the socket draw in the Parafil socket.

The least rope extension occurred in the Stress Relief Socket. It is believed that extra reinforcing material caused fibre-locking and results in lower extensions. Also, the smaller socket-draw in the Stress Relief Socket could be due to the bigger assembly inside the socket because of the extra material used.

Moreover the extension has been shown to be dependent upon the material type. The Akzo sub-rope extended 30% more than the Hoechst sub-rope under tensile loading regardless of the termination method used. The use of the Hoechst fibres in the Parafil socket led to slightly larger extensions when compared with the splice and the Stress Relief Socket. This difference was partially due to the extension differences in the as-received materials listed in Table 4.1. The as-received filament material for Akzo had 53% more extension to break than the Hoechst material (Akzo, 1997).

5. Failure mechanisms in sub-ropes under tensile loading

Perhaps one of the most important elements, in premature failure of the rope, is dissimilarity in the filaments' length in the fibre. However, with regard to the sub-rope, numbers of elements (e.g. termination, braided structure fibre melting and fusion) could have important roles in the failure mechanism.

Ideally, the role of termination is to distribute the load uniformly among the filaments and the strength of the rope is dictated by the strength of the filament. However, any non-uniformity in the load transfer between the termination and the other rope constituents will result in a reduction in the total rope strength. If a termination is

badly designed, or manufactured, the failure takes place within the termination vicinity.

When one of the load bearing elements (yarns) fails, the cumulative load is transferred to the remaining elements. Therefore, partial load for each element usually exceeds the breaking strength of the element. The result is a catastrophic failure before reaching the final expected load. This results in partial failure in the rope, which is the most common type of breaking. Fibre melting and fusion seems not to affect the sub-rope as there is no cover, and the heat generated could be easily released.

6. Failure Mechanism related to splice termination

When considering the performance of the splice termination, it can be argued that several parameters can have detrimental effect on the loading performance. These include:

- Internal eye angle (Leech *et al*, 1993, Edvold *et al*, 1996)
- Pin diameter
- Rope diameter
- The contact area between eye and pin material
- The stress concentration between the tapered end of splice and the rope, which can be caused by changes in the geometry of the buried part of splice.

In this study, although the effects of the abovementioned parameters were not specifically investigated, the splice used was carefully designed and prepared according to the British Standards for testing (BS 73234, 1991). In all samples used, the failure took place at the end of the buried part of the splice tail, as a result of the stress concentration. In every case, care was taken to ensure that the effect of the burial rope geometry be minimised to improve the sample quality.

7. Failure Mechanism related socket termination

Two different mechanisms, internal and external effects, can potentially dominate the failure process in the socket termination. The different influencing factors are as follows:

- The stress concentration between rope-termination components. Therefore local rope failure takes place when the local stress level exceeds that of the rope material strength. In this process the interaction between all the components (including socket, spike, heatshrink tubing and rope) can affect the rope performance.
- Non-uniform resin impregnation in the socket can result in the partial failure of the rope filaments inside the socket. Since the polymer resin has to bond all the fibres together firmly, debonding prior to rope failure is undesirable. In the present study, post-failure observation of those samples which exhibited premature failure, showed that fibre-resin debonding was the cause of the problem.
- The modulus differences between socket and rope can cause differential movement in socket-rope structure, which can lead to failure in the socket, due to the internal abrasion of socket and rope material.
- The effect of the internal conical angle, which can influence the tensile loading direction. An angle of 3° can change the loading capability by 0.14% which is not significant.
- Arrangements of fibres in the socket can influence the failure process; non-uniform distribution of fibres in the socket can lead to non-uniform loading of fibres. This is especially important when, during the loading process, the fibres tend to move into a more fibre concentrated area of the socket. In this study, attempts were made to ensure regular fibre arrangements around the spike, but it was difficult to examine the reliability of the arrangement. This caused a catastrophic failure in high loads because the gripping between the socket and the spike decreased dramatically.
- Different fibre materials may have different influence on the socket loading performance. Fibre slippage inside the socket during the loading process can be a significant problem. The resin impregnation can potentially increase inter-fibre bonding of filaments. Therefore the fibre-resin bond strength can affect the

loading performance.

- Prior to testing, pretension (10-20% of breaking load) is applied to ensure that all rope filaments are of equal length. Therefore, it is probable that some filaments fail inside the socket. In this study, no attempt was made to detect the filament failure inside the socket.
- The length of socket draw is an important feature of the rope performance. In this study, when sub-rope was used, the application of pre-load took up most of the socket draw. Therefore, the rope movement inside the socket was minimised during the testing cycle.
- The flexible heatshrink tubing plays an important role inside the socket. Ideally, it should protect the rope material during the loading process. Therefore, it should be durable and fit the spike and socket. Post-mortem examinations of broken sub-ropes have shown that, in every case, the heatshrink tubing was damaged inside the socket. This indicates that premature failure occurred in the protective tubing resulting in rope-socket abrasion (Figure 5.9).

8. Heatshrink Tubings

Heatshrink tubing is used to ease the contact areas between the socket and the fibre. When the fibre is in contact with the metal socket surface, movement of the fibres inside the socket and the relative friction between the two elements might cause premature fibre failure inside the socket.

Advantages

1. Eliminates any roughness on the socket and spike contact points.
2. Reduces fibres' damages in the initial stage of loading.
3. Shows the uniformity of fibres around the socket before the spike is inserted.

Disadvantages

1. Slippage may occur as a result of the difference in roughness of the two materials, heatshrink and spike.
2. Distortion and failure may occur as a result of the softness and wedging forces.

5.3.2 Tensile strength of 44mm Rope

The tensile results of 44mm rope tested using different terminations are summarised in Table 5-4. Normal socket was designed, to accommodate 44mm rope, based on Parafil geometry.

<i>Termination Configuration</i>	Breaking Load (kN)		Tenacity (N/Tex)		Efficiency (ζ) (%)	
	Akzo	Hoechst	Akzo	Hoechst	Akzo	Hoechst
Viking7 Socket	625.24	720.45	453.07	512.77	66.82	74.01
Splice	669.26	779.98	484.97	555.14	71.53	80.13
Stress Relief Socket	753.48	819.70	546.00	583.42	80.53	84.21

Table 5-4: Summary of results from all tensile tests on Akzo & Hoechst 44mm rope.

1. Comparison between terminations' performances

It is assumed that stress concentration inside the socket is the main reason in failure. Failure modes of most broken samples indicated that rope failed very close to the socket nose. This proves the effects of termination on failure can not be ignored.

In splice, forces are divided between two legs that prevent failure happens in the legs. It is thought that the stress concentration areas, in the splice, are situated along the rope at the end of the buried part where failure usually happens. The observed mode of failure is similar in both materials, in which the failure consists of partial failure of the rope with at least one complete sub-rope failure. Complete failure of all sub-ropes is quite rare. The failure mode is highly dependent on sample preparation skills; therefore, care was taken to ensure that high quality. This mode of failure has been reproducible in every sample tested, and is acceptable in the splice structures. In every case, the location for the failure is immediately after the end of the buried section of the splice where the stress concentration is high.

The stress relief socket donated the best performance for this type of the rope. As it is expected, when stress concentration areas, inside the socket, is improved, it could even give a better results than the traditional termination method, splice.

2. Discussion on the normal socket

As noted, the normal socket is identical to the Parafil socket with larger geometry to accommodate 44 mm ropes. The socket was designed in Bridon Marine Company, Charlton, London and was made in Bridon Structural, Doncaster for this study (Figures 5.10 a & b).

- Termination Design

The idea of trapping the fibres around a spike by means of heatshrink tubing and then housing the 7 units into a tapered socket seemed to have a reasonable chance of making the final termination. The socket bore is 46mm to accommodate 44mm ropes and the backend is 104mm. The internal angle is 8 degree (Figure 5.10a & 5.10b).

The final design to termination would look very similar to the standard Mooring sockets presently used for steel rope and spiral strand terminations which are already accepted as the norm by the oilfield customers and classification authorities.

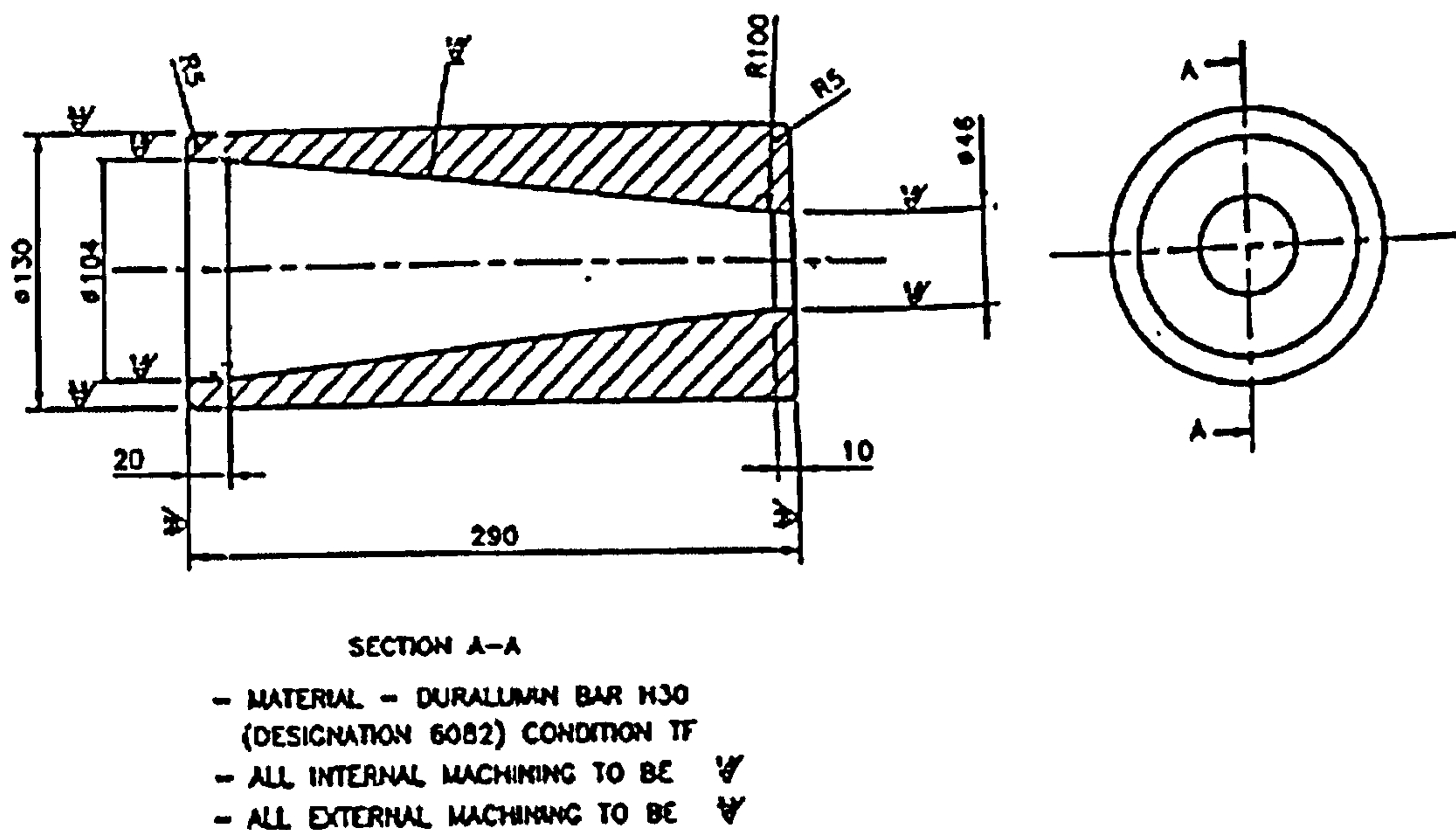


Figure 5-10a: Drawing of Viking7 socket (Bridon Marine, Charlton, 1997).

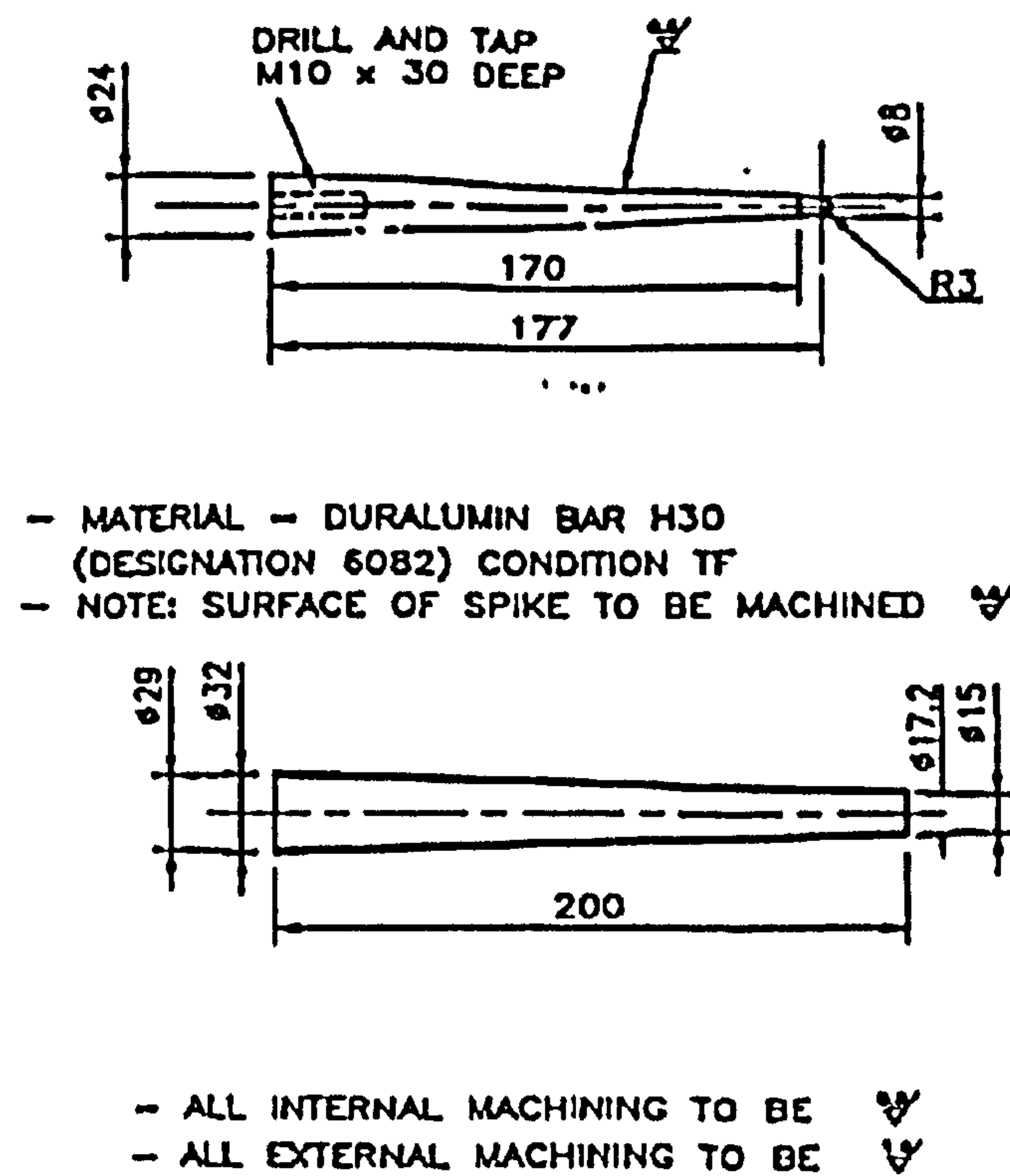


Figure 5-10b: Drawing of Spike and Metal Tube for Viking7 Socket (Bridon Marine, Charlton, 1997).

- Spikes' arrangements

It was thought that the heatshrink sleeves would be too soft and would tend to distort and fail, due to the wedging forces (Figure 5.11). In order to overcome this foreseeable problem, it was suggested to use a swaged thin wall conical tube in either steel or aluminium alloy giving the smooth bore necessary so as not to damage the fibres. After the spikes were inserted into the centre of the ropes, the conical tube could then be pulled over to trap the rope fibres, and then the whole 7 rope unit could be pulled into a tapered socket. In order to give the thin wall tubes support against the hoop stresses of the wedging action, the tube could be cast in a resin matrix within the socket. The tail ends of the fibres could also be cast into a resin capping to finish it off (Figure 5.12).

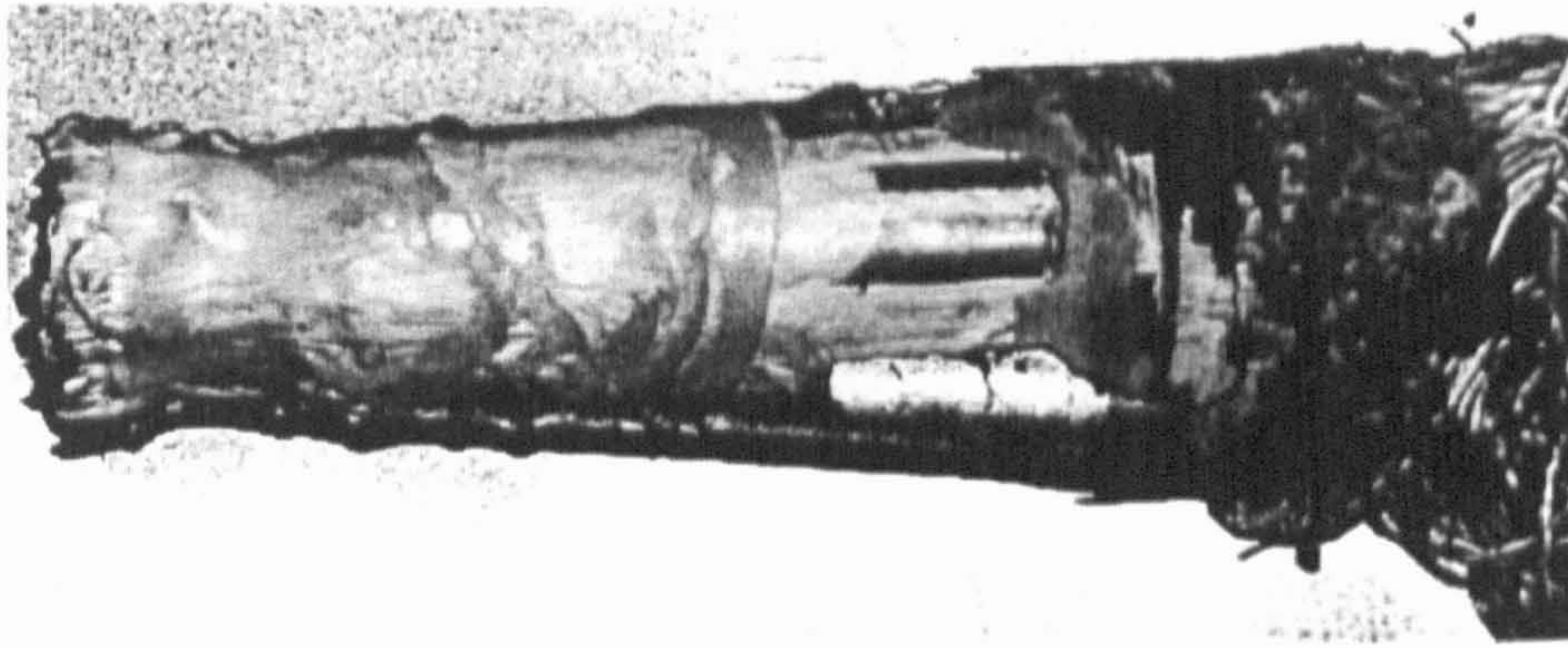


Figure 5.11: Photo of damaged heatshrink inside the socket after tensile testing.

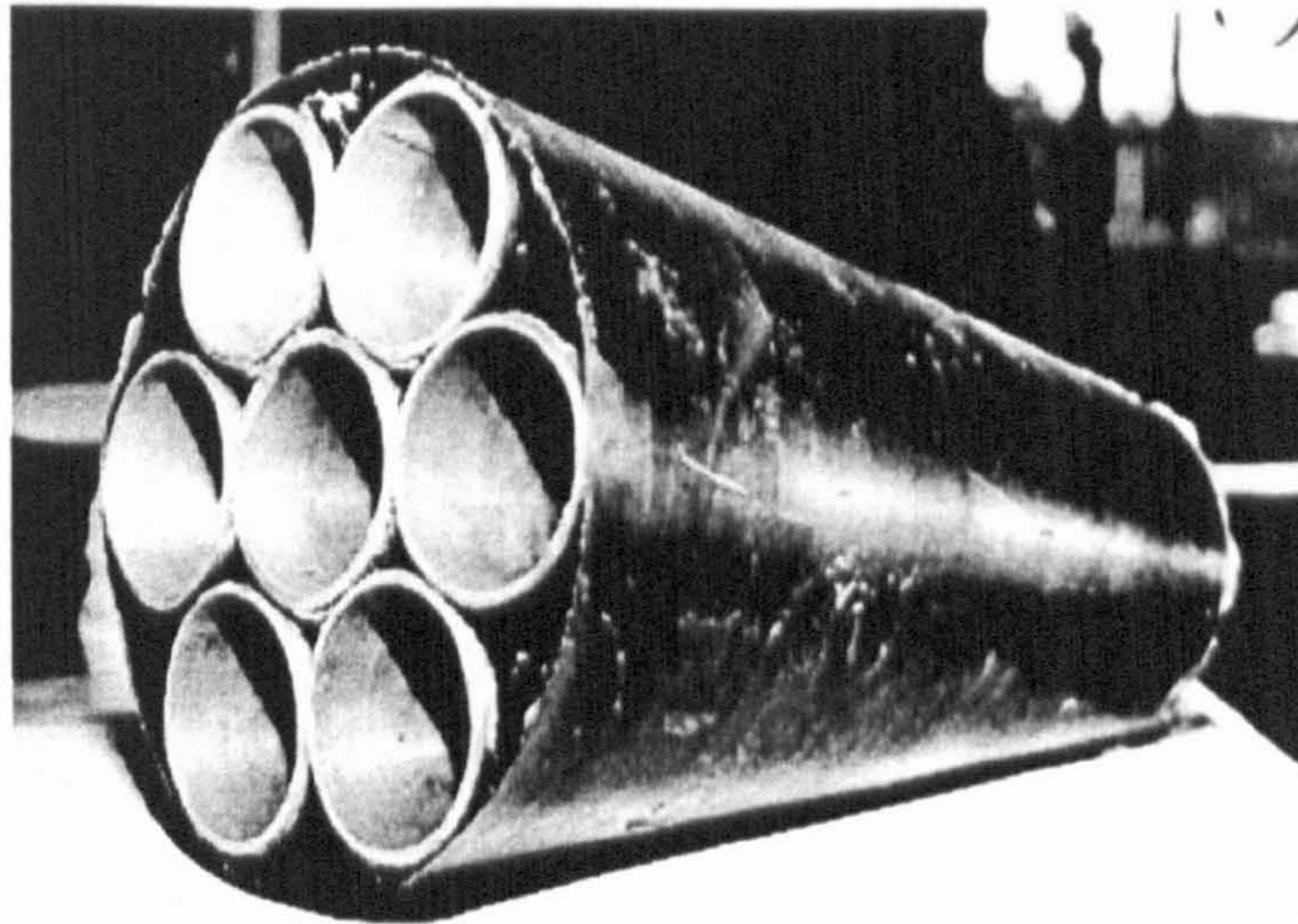


Figure 5.12: Seven individual metal tubes cast in resin.

- Results

The tensile testing results for the 44 mm rope/normal socket are listed in Tables 5.6.

No.	Termination Configuration	Breaking Load (kN)	Tenacity N/Tex	Efficiency (ζ) (%)	Mode of Failure
1	MT + R	489.74	369.19	54.45	Partial Progressive Failure
2	HS	499.09	376.24	55.49	Complete fracture at static end 30cm near to the socket
3	HS + R	506.27	381.65	56.29	5 sub-ropes broke close to socket Core did not break
4	HS + R	603.71	455.10	67.12	Complete fracture at static end 30cm near to the socket
5	HS + R	620.24	467.57	68.96	Complete fracture at static end 2 sub-rope broke near socket
6	HS + R	643.47	485.08	71.55	Complete fracture at static end One sub-rope broke near the socket
7	MT + R	633.53	477.58	70.44	3 strands broke - 4 strands left

HS + R = Heatshrink & Resin
 MT + R = Metal Tube cast in resin
 Table 5-6: Termination Configuration, Breaking Load, Tenacity, and Efficiency percentage of Akzo 44mm rope in normal socket termination.

The results for the first three samples (Table 5.6) were not taken into account due to inadequate experience in sampling. However, the observed failure modes for these samples gave a valuable insight into the failure process. The failure mode of the first two samples consisted of partial breaking of the sub-ropes in a progressive fashion. Number 3, led to partial failure of 5 sub-ropes near the socket with the core intact. In all these cases, the breaking load was less than expected for the rope. The reason for the partial failure was due to the non-uniform load distribution in the sub-ropes, which was caused by unequal lengths of the sub-ropes.

The results for the samples 4-6 (Table 5.6), that include heatshrink tubing with resin impregnation, showed complete fracture. However, post-mortem examinations of the samples showed that some sub-ropes broke near the socket nose (Figure 5.13). Therefore, it can be argued that the effect of termination on the rope load carrying capability is not negligible. The last sample (No.7) included metal tubes, instead of heatshrink tubing, surrounded by resin (Figure 4.4). The results for this sample show an unexpectedly high breaking load. However, with reference to the mode of failure, which in this case is the partial failure of all sub-ropes, it appeared that it was difficult to assemble all the sub-ropes in the same length and the result would not be reproducible. The fact that all the sub-ropes have been kept separately in the metal tubes, which limit the interaction between the sub-ropes, could be the cause of the high breaking load.

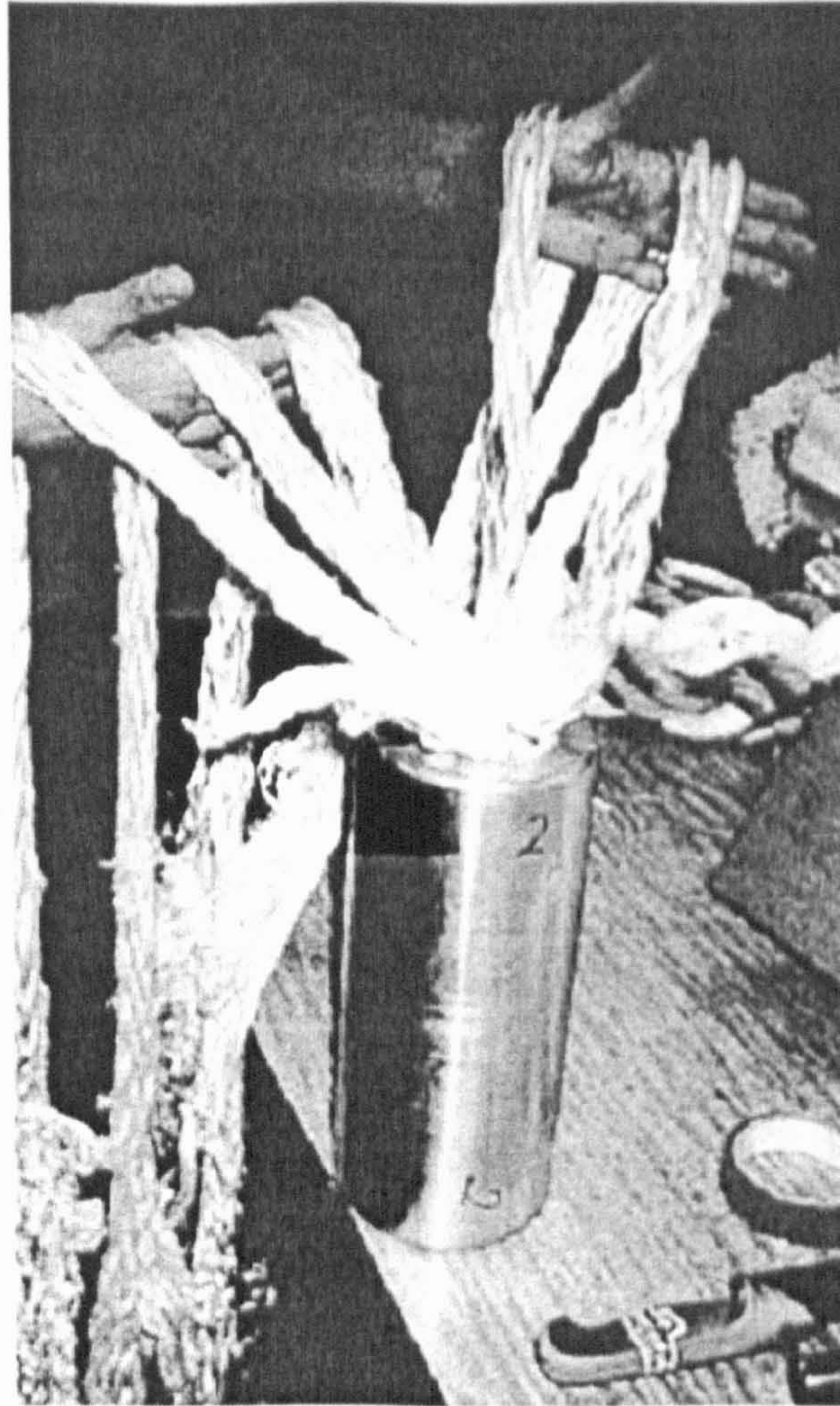


Figure 5.13: **Broken end with five sub-ropes out of seven still intact.**

Since the strength of sub-rope in Parafil socket was approximately 100 kN, it was theoretically expected to have a strength of 700 kN for the 7 sub-ropes in parallel structures. The strength value of 643.5 kN for the best heatshrink tubing and resin socket was not different to a great extent from the ideal situation.

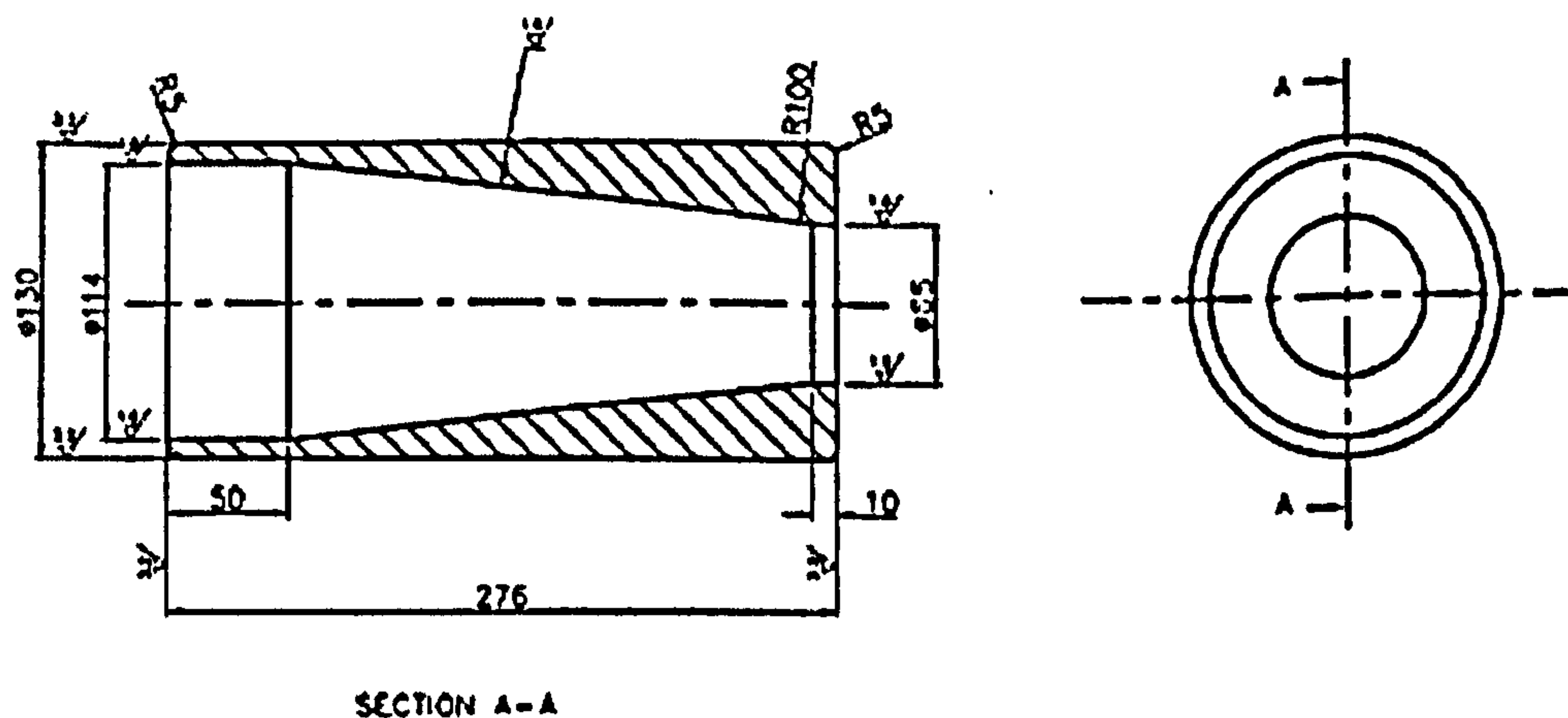
3. Discussion on Stress relief socket

The major differences between the Stress Relief and the Viking 7 sockets are the extra reinforcing rope material and changes in geometry of the socket.

- Modification in Termination Design

Spike geometry seemed to have direct effects on termination performance. If successful, this would reduce the severities of abrasion at the nose of the spike, thus increasing rope lifetime. McTernan (1986) noticed an increase in lifetime of a factor of 10 when modifying the spike for a 60 tonne rope cycled between 5% and 50%

The main concern in this study was to design a socket that could accommodate about 50% extra fibre material inside the socket. This led to redesigning the socket geometry. The overall external diameter did not change. The fittings and adaptor designed to accommodate this socket and change the external diameter could have caused some problem in the total setup. The socket backend increased to 114mm from 104mm while the front-end socket opening increased to 65mm from 46mm. The spike geometry also changed based on changes in the socket. The total length increased from 177 to 253mm. The backend diameter changed from 24 to 32mm and the front-end from 8 to 10.5mm (Ref. Figures 5.10 & 5.14).



- MATERIAL - STEEL EN16 CONDITION 'R'
- ALL INTERNAL MACHINING TO BE 'Ra'
- ALL EXTERNAL MACHINING TO BE 'Ra'

Figure 5.14a: Drawing of Stress Relief Socket (Bridon Marine, Charlton, 1997).

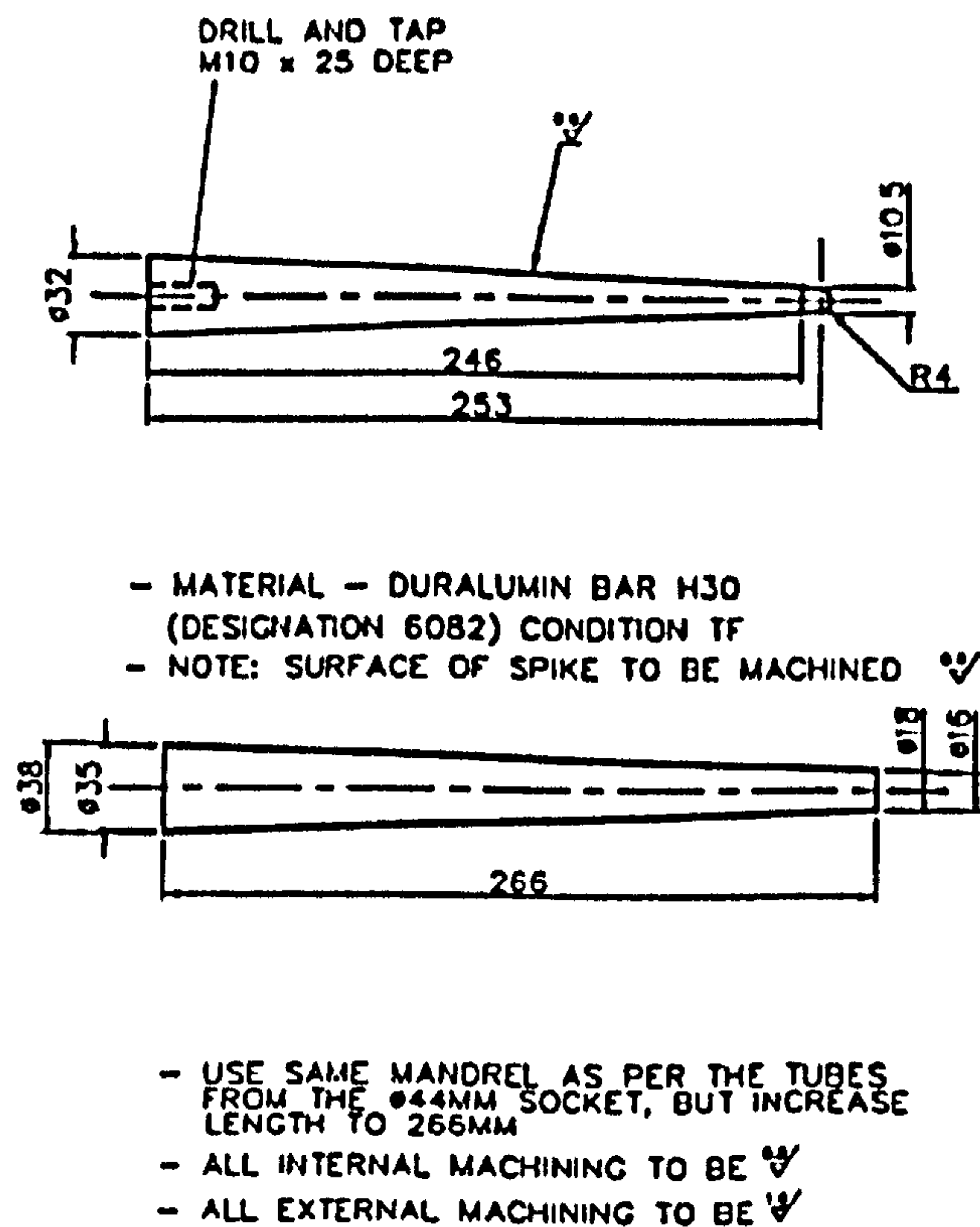


Figure 5.14b: Drawing of Spike and Metal Tube for Stress Relief Socket (Bridon Marine, Charlton, 1997).

- Results

Tables 5.7 and 5.8 present the results of the static tensile testing for the 44mm Akzo and the Hoechst materials using the stress relief socket. Based on previous experiences and more consistent results, most tests were concentrated on the termination made with socket, spike, heatshrink and resin.

Termination Configuration	Breaking Load (kN)	Tenacity N/Tex	Efficiency (ζ) (%)	Mode of Failure
HS + R	701.93	499.60	72.11	Partial failure happened Resin penetration was not complete
HS + R	772.20	549.61	79.33	1 sub-rope failed before rope failure sub-ropes broke near the socket
MT + R	802.42	571.12	82.43	Failure near the socket 1 sub-rope was loose
HS + R	808.03	575.11	83.01	5 sub-ropes broke simultaneously 2 sub-ropes did not break
HS + R	811.47	577.56	83.36	One sub-rope pulled out Resin action was not good
MT + R	818.85	582.81	84.12	6 sub-ropes broke simultaneously 1 sub-rope did not break
HS + R	857.73	610.48	88.12	Clear break far from the socket

HS = Heatshrink

MT= Metal Tube

Table 5.7: Termination Configuration, Breaking Load, Tenacity, and Efficiency percentage of Hoechst 44mm Rope in “Stress Relief Termination”.

Termination Configuration	Breaking Load (kN)	Tenacity (N/Tex)	Efficiency (ζ) (%)	Mode of Failure
MT + R	668.17	484.18	71.41	5 sub-ropes broke close to socket 2 sub-ropes did not break
HS + R	723.29	524.12	77.30	Bad resin penetration caused some sub-ropes broke near the socket
HS + R	757.83	549.16	81.00	Clear break far from the socket
HS + R	761.97	552.15	81.44	Clear break far from the socket
MT sr R	770.83	558.57	82.38	Clear break far from the socket

Table 5.8: Termination Configuration, Breaking Load, Tenacity, and Efficiency percentage of 44mm Akzo Rope in “Stress Relief” Termination.

The summary of the results (Table 5.4) shows that the Stress Relief Socket has led to a superior tenacity as compared with the splice and the normal socket. Improvements of about 5 to 13% were seen using the Stress Relief Socket compared with the splice and the Viking 7 Socket. It is interesting to note that the breaking load for the stress relief socket, regardless of the material used, far exceeded that expected by consideration of the theoretical estimation for the sub-rope strength of 100kN (7 x 100).

Termination made from heatshrink and resin, produced more consistent results. With regards to the failure modes, the best results belonged to the tests having clear breaks. Mode of failure for the Hoechst indicated that although some sub-ropes had not broken or pulled out during the tensile process, reinforcement materials played an important role in driving away the stress concentration areas from the socket.

- Comparison of different terminations under tensile loading for Akzo

The tenacity behaviour for Akzo materials in the Stress Relief Socket is graphically shown in Figures 5.15a, b & c. The Vaseghi Stress Relief Socket and the metal tubes behave fairly similarly under tensile loading and the metal tube final break is slightly higher than that of the Stress Relief Socket. It is thought that these two types of termination reflect the most reliable rope tensile strength and the effects of termination is lower than those of the other types. This is due to the similar behaviour of the two termination methods.

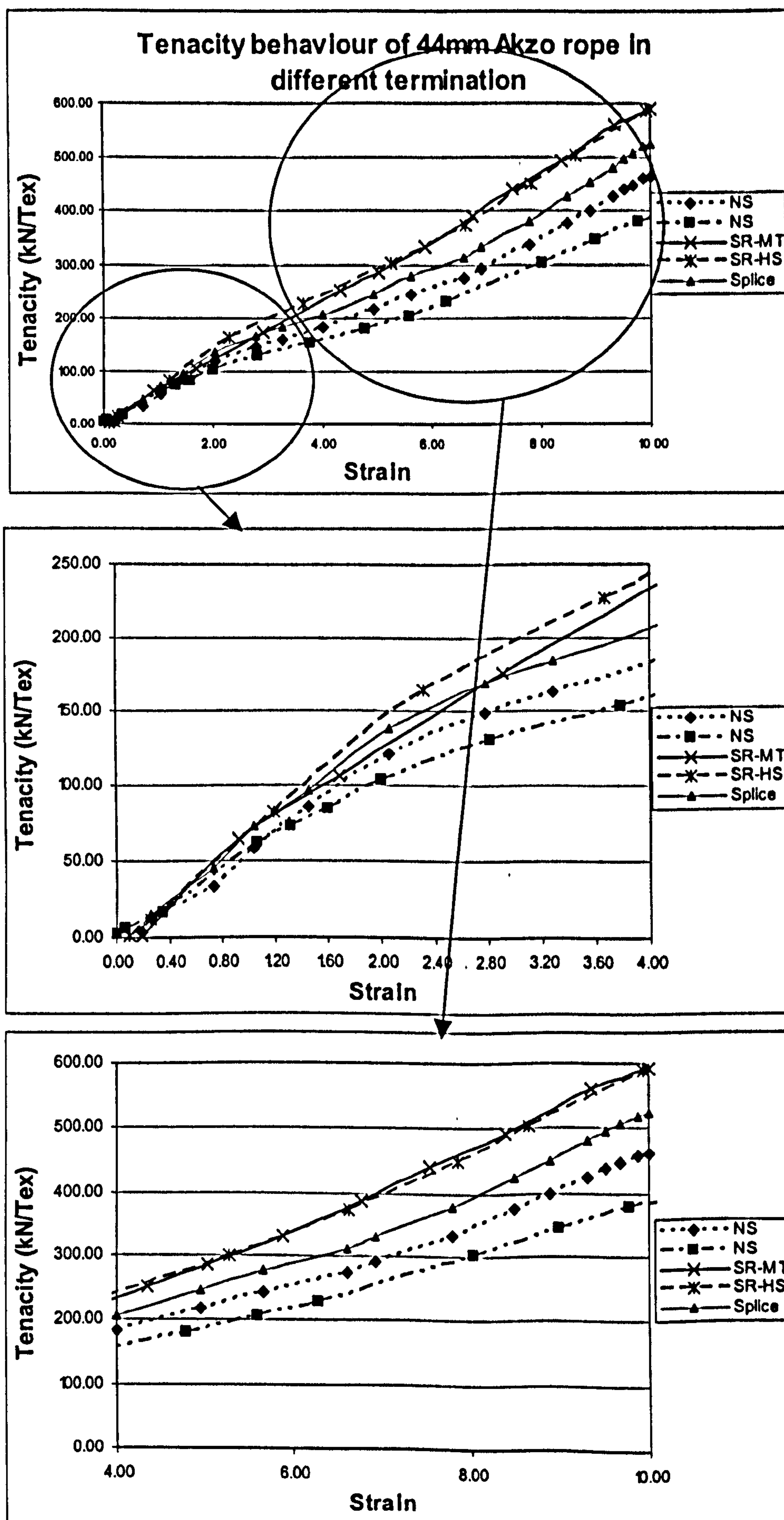


Figure 5.15: Comparison of 44mm Akzo rope tenacity behaviour with different rope termination.

(NS = Normal Socket (Viking7 Socket), SR+MT= Stress Relief Socket+ Metal Tube, SR+HS= Stress Relief Socket +Heatshrink)

The Stress Relief Socket shows very small non-linearity compared with other methods. Zone 2, a pronounced knee region, is more visible in the normal socket. The Splice pattern resides somewhere between the two sockets, the normal and the Stress Relief Socket. It showed a fairly similar knee point to the normal socket which was slightly higher in load. The lowest results belonged to the normal socket. The negative effect of termination on the final rope failure was obvious in the normal socket as most samples broke near the socket with some sub-ropes intact.

- Comparison of different terminations under tensile loading for Hoechst

The tenacity behaviour for Hoechst materials in the Stress Relief Socket and splice is graphically shown in Figures 5.16a, b & c. It is noted that a normal socket was not used for Hoechst material as it was rejected in Akzo compared to superiority of stress relief socket.

Metal tubes showed higher load in similar extension compared to heatshrink although the final results are fairly similar. This could be because of flexibility of heatshrink compared to metal tubes. It is thought that flexibility of heatshrink lets fibre to adjust when pulling compared to metal tubes and result in higher extension measured.

Metal tubes load showed a jump in low extension around 0.3%. It showed higher load in most areas compared to splice and heatshrink and then curves are converged in breaking point.

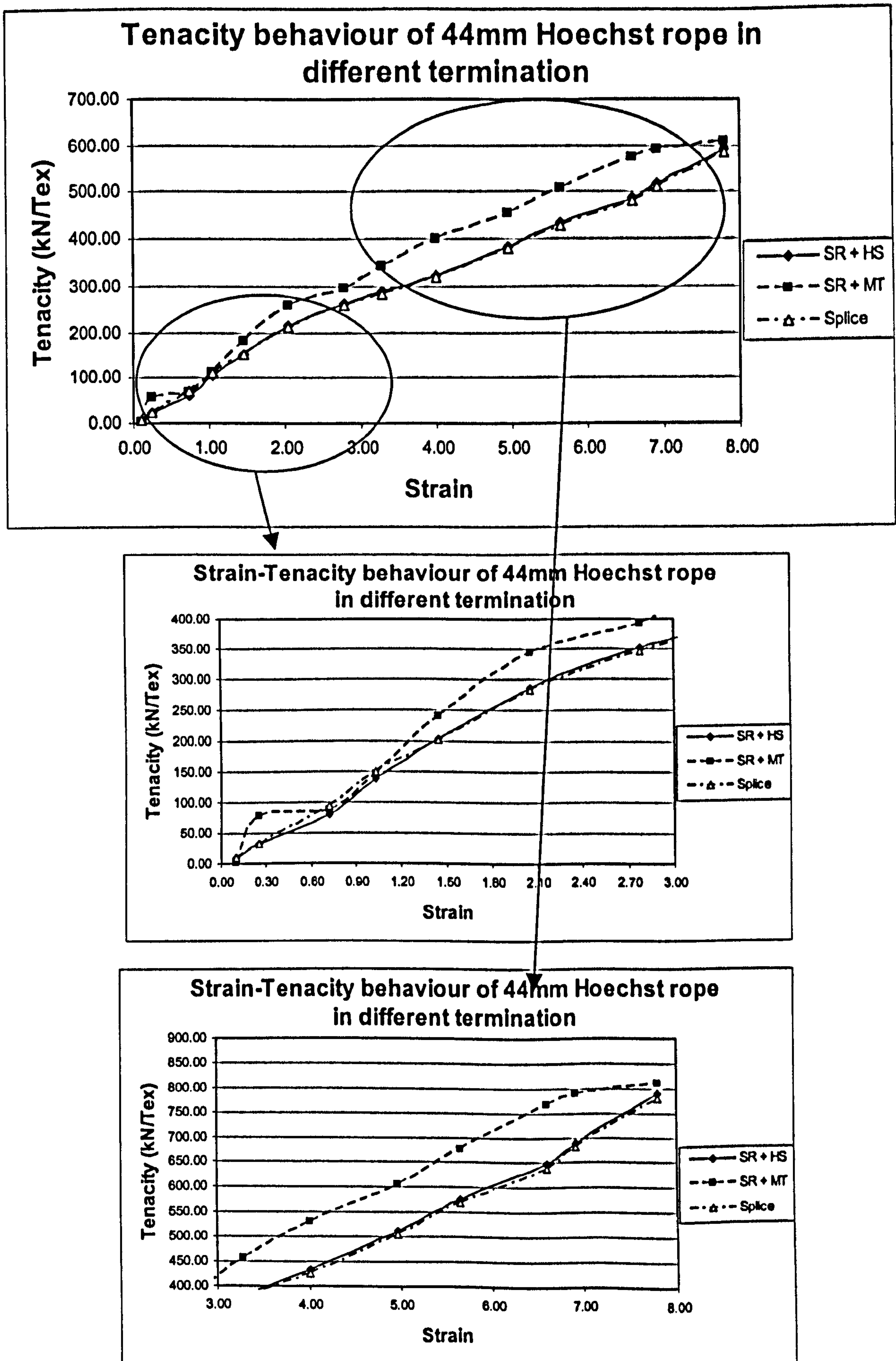


Figure 5-16: Comparison of 44mm Hoechst rope tenacity-strain behaviour with different rope termination.

(SR+MT= Stress Relief Socket+ Metal Tube, SR+HS= Stress Relief Socket +Heatshrink)

Higher load in metal tubes compared to heatshrink could be because of flexibility of heatshrink. It is thought that flexibility of heatshrink allows the fibre to adjust when pulling compared to metal tubes and result in higher extension measured.

At 0.3% strain the metal tube appears to be subjected a 50kN/tex tenacity (compare tube and non tube graphs in Figure 5.16). If this is not an experimental error, it could be a result of gripping properties in low loads. Gripping happens in initial stage of loading. When the load increased, it overcomes gripping forces.

It could be argued that convergence of curves between 0.5-1.0% strain is because the load/extension behaviour is not sensitive to termination in the initial stages of load application.

Metal tube termination showed higher load compared to heatshrink and splice between 1.2-7.5% extension. This could be because of less extension in metal tube compared to the others in similar load. Metal tube gripping forces is higher than splice and heatshrink which tend to decrease the rope extension as part of socket draw is included in that.

- Discussion about different rope behaviours in various terminations

The Non-linear region, in the tenacity pattern, is thought to be mainly due to fibre realignment and socket-draw during the initial loading process. In Stress Relief Socket, because of its bulky construction, there is a lower mobility of the whole assembly inside the socket which results in a vague knee region in its tenacity pattern. However, the loading process always progresses with more socket-draw and realignments in the normal socket and results in a clear knee region. In the Splice, although there is no socket-draw, some sub-ropes slip inside the buried part. It can be argued that the knee region produced is a result of fibre realignment and fibre slipping. Smaller knee regions compared with normal socket could be explained by lack of socket-draw in splice.

The total extension of the rope, during the loading regime, is expected to be a combination of the socket draw, the sub-ropes' realignment during the pre-loading stage, and the actual rope material extension. So if machine displacement is

considered to measure rope extension, socket-draw and fibres' realignment should be excluded to have a correct figure of extension.

- Comparison of different materials

To compare both materials in the Stress Relief socket, a typical tenacity figure of the 44mm Akzo and Hoechst ropes, tested in stress relief socket including heatshrink tubing and resin, is shown graphically in Figure 5.17. The socket-draw has been excluded. The Akzo curve showed a clear knee point before complete linear region while Hoechst tenacity pattern did not illustrate the same pattern before linear region to failure.

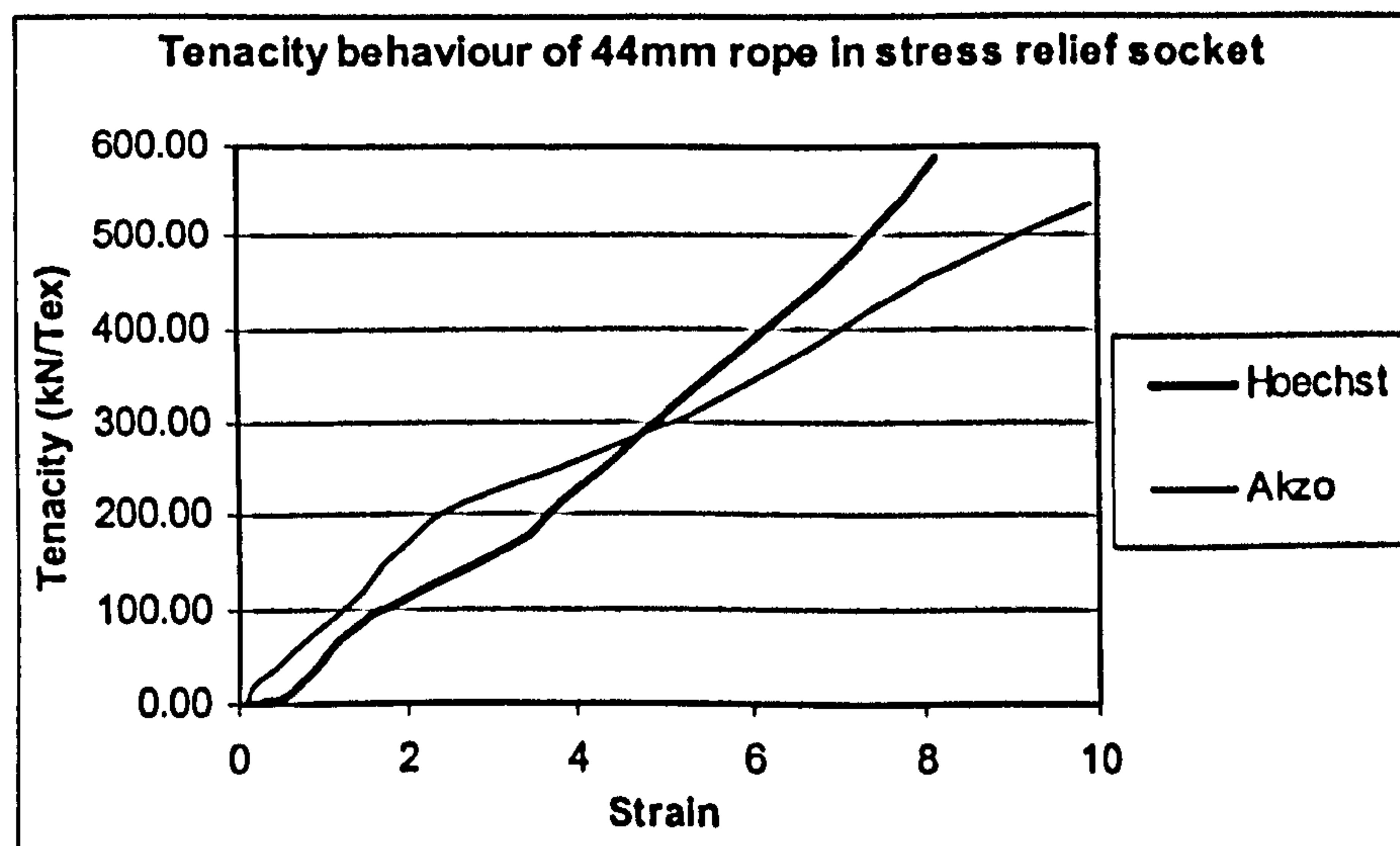


Figure 5.17: Typical tenacity behaviour of 44mm Akzo and Hoechst rope tested with Stress Relief Socket, heatshrink tubing and resin.

As mentioned (Section 5.3.2), application of some fibre coating caused fibre sticking in the Hoechst rope. This could be the reason why there was no clear knee point in the Hoechst curve.

- Extension behaviour

In the splice termination, since there is no socket interference, the total extension consists of the sub-ropes' realignment and the actual material extension. For this reason, it is difficult to compare machine displacements for the socket and the splice terminations. However, if differences between splice and sockets are measured, the

figure could give some idea about the socket-draw because rope realignment and extension is similar in both methods.

Considering socket terminations, if socket-draw is excluded, the Akzo rope tested using the splice termination showed 1.8% less extension than the Viking 7 socket and 0.35% more than the Stress Relief socket. As the rope was similar in these three testing methods, it was expected to have similar extension. It can be argued that the differences could be as the result of experimental errors because they were very small and negligible.

- **Comparison of terminations' behaviour of 44mm rope in tensile test**

The reliability and accuracy of the tensile strength results in the Parafil socket are more dependent upon the sample preparation skills. However, this problem fades when using the Stress Relief Socket, as the extra material compensates malpractice in the termination preparation and provides for a higher breaking load.

Figures 5.15 & 5.16 showed the typical tenacity behaviour of Akzo & Hoechst ropes tested with different terminations. The most consistent graph and the highest tensile strength belonged to the Stress Relief Socket using heatshrink tubing.

It can be seen from the curves that tenacity plots behave similarly until around 150 kN/Tex. Changes in load-extension behaviour after this point leads to different slopes in the curve.

The Stress Relief Sockets which include heatshrink tubing behave more linearly up to the final breaking points than do normal socket curves. The Splice curve behaviour stays in the middle of these two methods. The most non-linear curve in these series is exhibited by Metal tubing.

The main reasons for the non-linear behaviour in the Viking7 rope are fibre adjustment, realignment of filaments and socket-draw which can be observed in all curves. By removing the spurious effects of the rope, i.e. fibre realignment and

adjustment, and use of different termination methods, it is expected that more consistent rope behaviour would be achieved.

Extra fibre material in the stress relief socket can potentially cause differences in the rope performances in the tensile test because all other parts are the same. It may well be the case that when the amount of reinforcing fibres increases in the socket, the rope behaviour tends to be more linear. The linearity of the metal tubing method could be due to the more rigid nature of the termination provided by the metal tubes inside the socket.

5.3.4 Tensile strength of 120mm rope

The main objective of all previous tests, in an industry project, is to reach a resolution for terminating the 120mm rope which is supposed to anchor oil platforms. As the testing procedure of 120mm rope is too expensive, previous tests are done to reach some estimation about 120mm rope.

I) Rope behaviour under constant load

The rope is terminated based on procedure in the Section 4.5.5. Then it was delivered to NEL (National Engineering Laboratory – Scotland) for testing.

The sample was pulled and kept in 2500 kN for 30min after a few cycles. Two sets of transducers were put on the rope to measure the displacement. The machine and the percentage of the near side transducers' displacements under 2500 kN load is graphically shown in Figure 5.18. It seemed that under constant load, machine displacement showed a greater value compared with transducers' displacement, which was mainly due to socket-draw. Although previous cycling aimed to remove the socket-draw and uncertainties in filaments' lengths, it was concluded that some socket-draws were not removed in the initial stage of cycling. Machine displacement showed a uniform pattern while transducers pattern seemed to present a non-uniform graph. Machine displacement was provided by a computerised system that fed load to

keep it constant, but rope under constant load tended to creep because of fibre adjustment in the socket. That's why transducers' pattern showed a non-uniform figure (Figure 5.18).

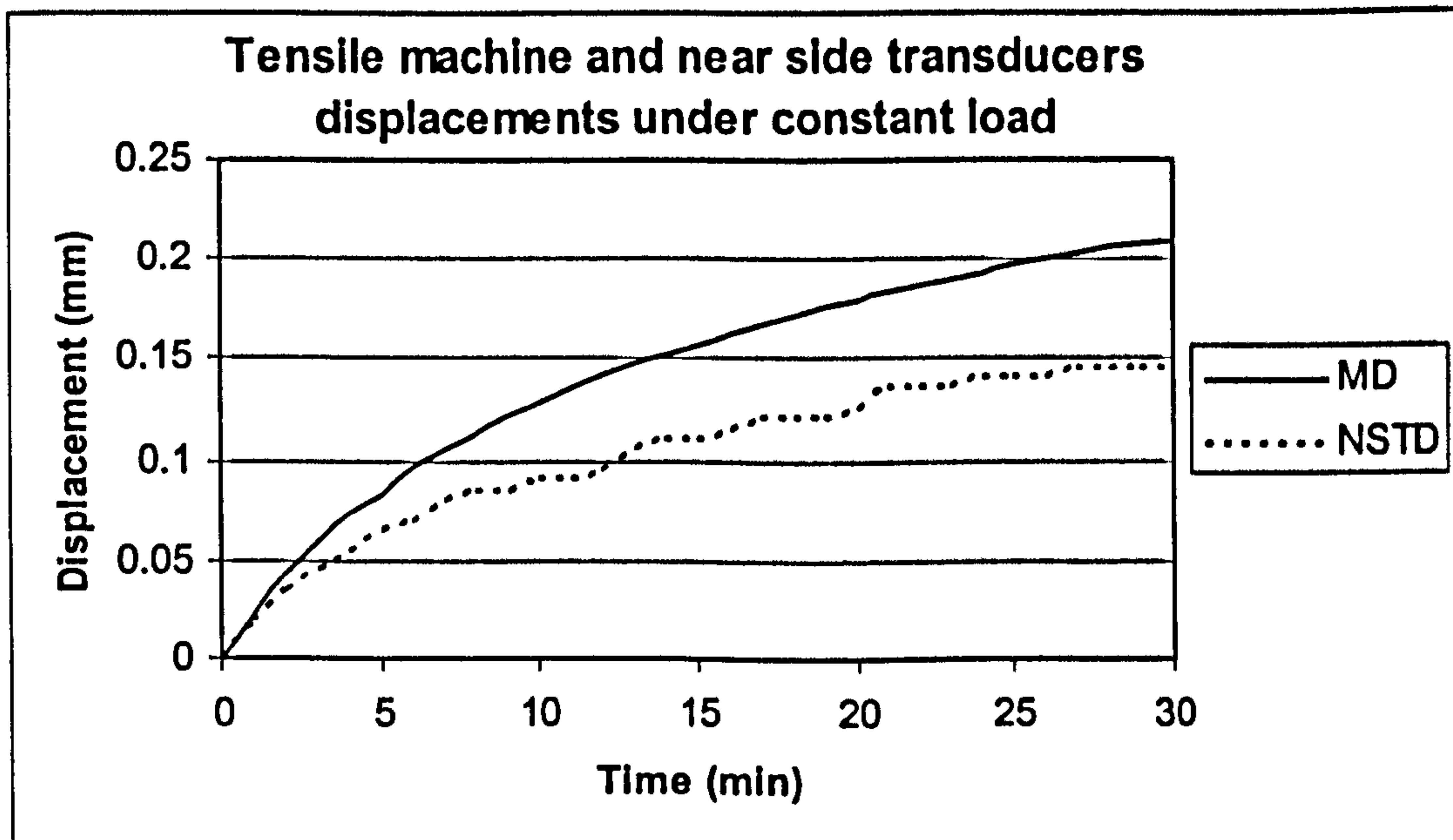


Figure 5.18: Machine and near side transducers' displacements percentage under 30min 2500 kN constant load for 120mm Hoechst rope.
MD = Machine Displacement NSTD = Near Side Transducers' Displacement

II) Breaking strength of 120mm rope

Breaking test was done based on section 4.7.2. A breaking load of 4778 kN for 120mm Viking7 rope was recorded. The result indicates that the breaking load for the 120mm rope is 5.8 times more than the 44mm rope while the difference in mass is 6.3 times. It is clear that when the rope size increases, the relative load bearing capability reduces. The relative efficiency for the different rope sizes is shown in Figure 5.19. The 120mm rope achieved a breaking load efficiency of 78% compared with the filament breaking load and this is a significant improvement compared with the previous data on polyester ropes with a breaking load of 1.5 times the strength of 8-strand polyester rope tested by German Standard for testing (Table 4.5). Normally a 50% reduction in efficiency is an acceptable figure in the breaking load (Yearley, 1996).

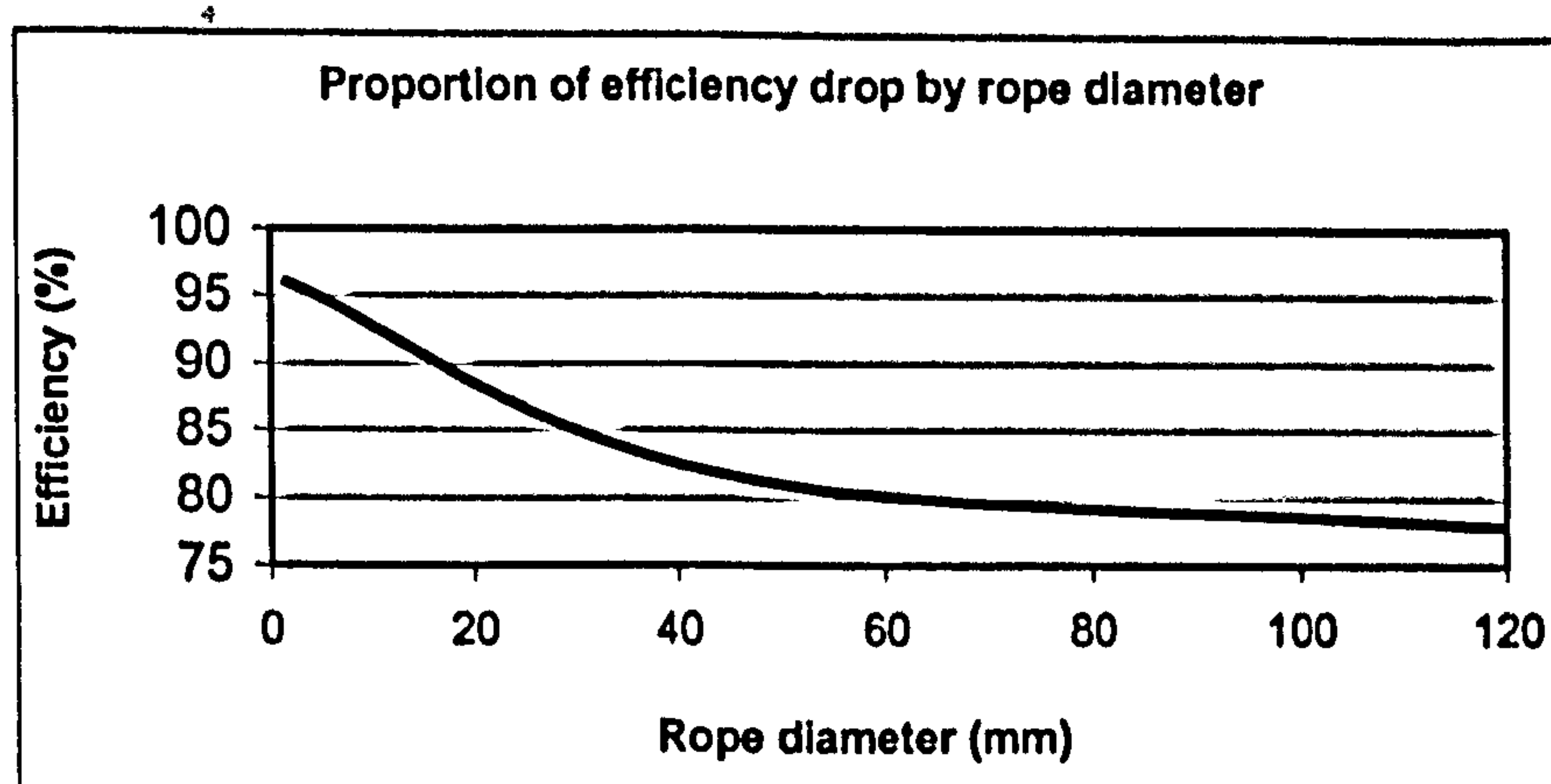


Figure 5.19: Tensile efficiency drop by rope diameter using the Stress Relief Socket.

It can be seen that efficiency is reduced at a faster rate up to 44mm rope size beyond which the efficiency levels off. Therefore, it is possible to predict the strength of larger ropes from the smaller 44mm size. This will save cost and time on testing.

The rope maker companies usually consider at least a 50% reduction in the rope efficiency from filament to rope. Although 50% reduction might not be an acceptable figure for safe working condition, it is a proper method to show the capability of the rope and the advantage of termination over the other methods.

The post-mortem examination of the rope indicated that 2 sub-ropes were still intact. Having some unbroken sub-rope could mean that more loads is expected if more care is taken in sample making and arrangement of the material in the socket. Considering the first test on this rope with this termination and some unbroken sub-ropes, the result is promising and further work on this method is recommended.

Some previous results, on the same diameter ropes, gave an assumption of 5000 kN for this rope. The result for 8 strands plaited rope (Viflex) is 2770 kN (Table 4.5). The construction is 50% polyethylene and 50% polyester. Some similar constructions, from Brazilian rope makers, gave the idea of a breaking load of about 5000 kN (Bridon Marine, 1996). The result is highly acceptable as this was the first test on this type of rope using the Stress Relief Socket.

III) Rated value

The tenacity against rated & experimental values based on tenacity of the initial filament is graphically shown in Figure 5.20.

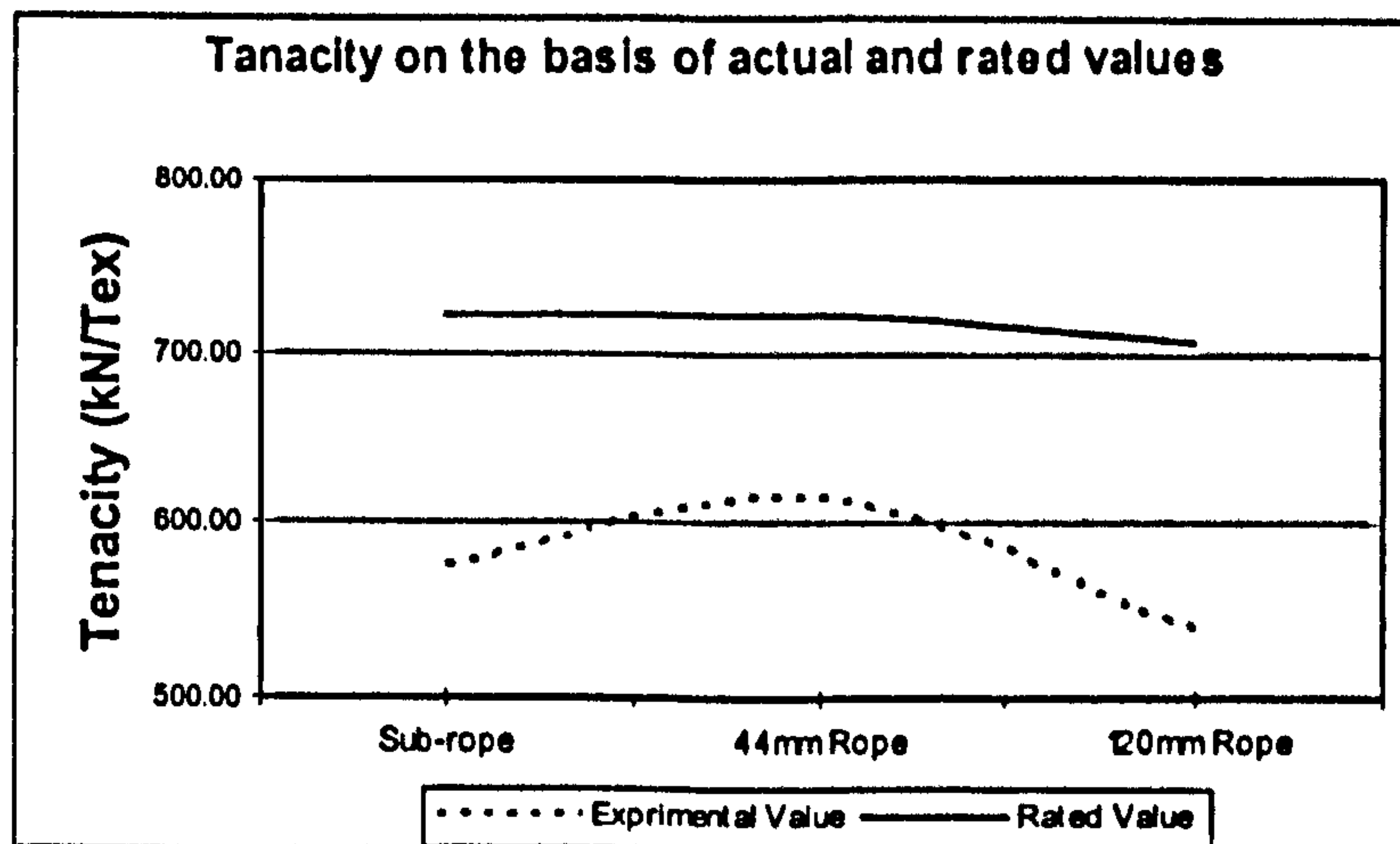


Figure 5.20: Comparison of actual and rated values for Hoechst material in different rope diameters.

The rated values are greater than the experimental ones because no fault is being considered when rated values are calculated. This suggests that the user should apply a considerable safety factor in design.

Lower results in experimental values are because of the twist angle, termination effects, and inequality in filaments' length. Effects of twist angle are predictable by measuring the lay length, which indicates the filament's angle. However, it is difficult to measure the effects of termination and any fault in the rope because experimental results have been restricted by their tests' methods and there is no way to find out the actual breaking strength of the rope to take as a benchmark.

Figure 5.20 shows the comparison between the rated and the actual breaking load for the Hoechst material. It is expected that when the rope size increases, the difference between the tested and the rated value would increase. Consequently the lowest gap appeared in the 44mm rope. The poor result in sub-rope was because of surfactant which causes the increased deviation compared to 44mm rope.

IV) Prediction of Strength on the basis of broken sub-ropes

Based on number of sub-ropes, the predicted breaking strength for 120mm rope will be 6800 kN considering 971.5 kN breaking load of each element (Bridon, 1996). It is assumed that the total breaking load is shared equally between all sub-ropes. Although this may not be practically acceptable for end users, it is important as part of the investigation to assess the role of limiting factors. Also this may contribute to further work to understand the ultimate strength capacity of the rope.

The predicted breaking strength is 8% higher than the rated value and 30% higher than the experimental value. These differences indicate the strength loss from the initial filament to the final product, i.e., rope.

V) Tenacity behaviour before Cycling

To investigate the tenacity behaviour of the rope and also to trace the socket- draw, three extension measurements were taken from the rope. The first was machine displacement that presented the displacement of sockets face to face. Two other measurements were taken by near-side and off-side transducers. The transducers were set up in 2m length of the rope. The test layout is shown in Figure 4.7a and 4.7b.

The results are shown in Figure 5.21. As the load increases, the machine displacement tends to increase faster than the transducers'. This is because the machine displacement is a combination of the machine stroke, socket draw, and rope extension while the transducers clearly show rope extension.

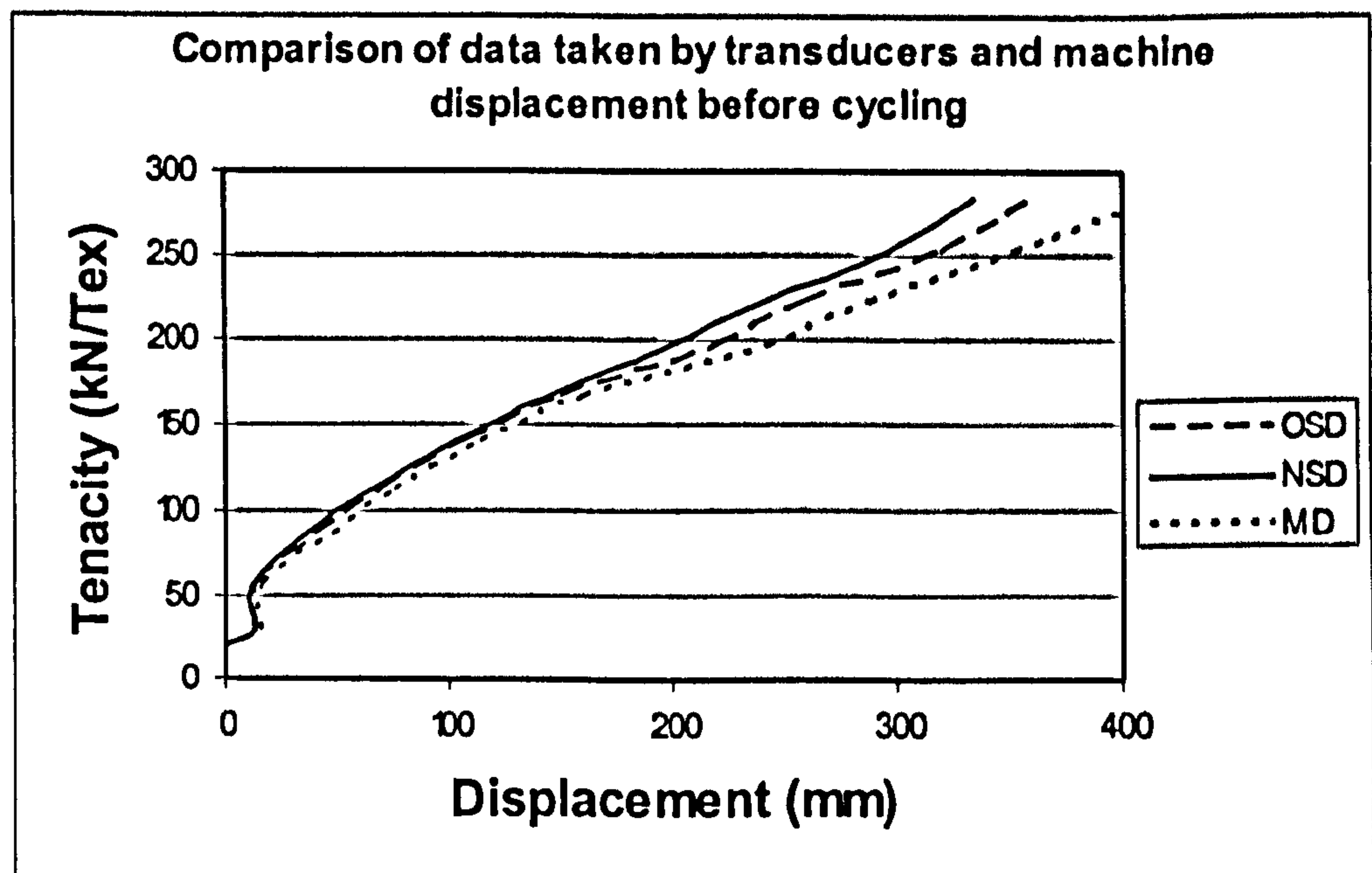


Figure 5.21: Tenacity curve for 120mm rope test layout with transducers attached in initial stage of loading.

MD = Machine Displacement - NSD = Near Side transducers Displacement - OSD = Off Side transducers Displacement

There is a load increase between 250-500N with no displacement. It seemed that the rope absorbed some tension, in the initial stage of the loading. The rope, as textile structure, reacted to an applied stress or strain with a combination of constructional and material deformations. Its reactions, thus, depended on the structure of the fibre material used. It is believed that rope response was mostly structural in the initial stage of loading. As a rigid structure, 120mm rope behaved like a metal bar when the loading started until the load was transferred to the sub-ropes. This could be the reason for the load increase with no extension.

Extension at constant load of 2500 kN for three ropes sizes is considered (Table 5.9), 28mm (120mm sub-rope) – 5.35%, 44mm – 3.04% and 120mm – 1.45%. Extension percentage decreases by 43% from 28mm rope to 44mm rope while this figure is about 72% if 120mm rope and 28mm ropes are compared. It is clear that when the rope sizes increase, the extension drops dramatically.

Rope Type	%Extension at 2500 kN
120mm Sub-rope	5.35
44mm Rope	3.04
120mm Rope	1.45

Table 5.9: Extension at constant load for different rope sizes.

VI) Tenacity-Strain behaviour

The figure for tenacity-strain to break is presented in 5.22. The sample broke at 4778 kN. Partial failure happened with two sub-ropes were still intact.

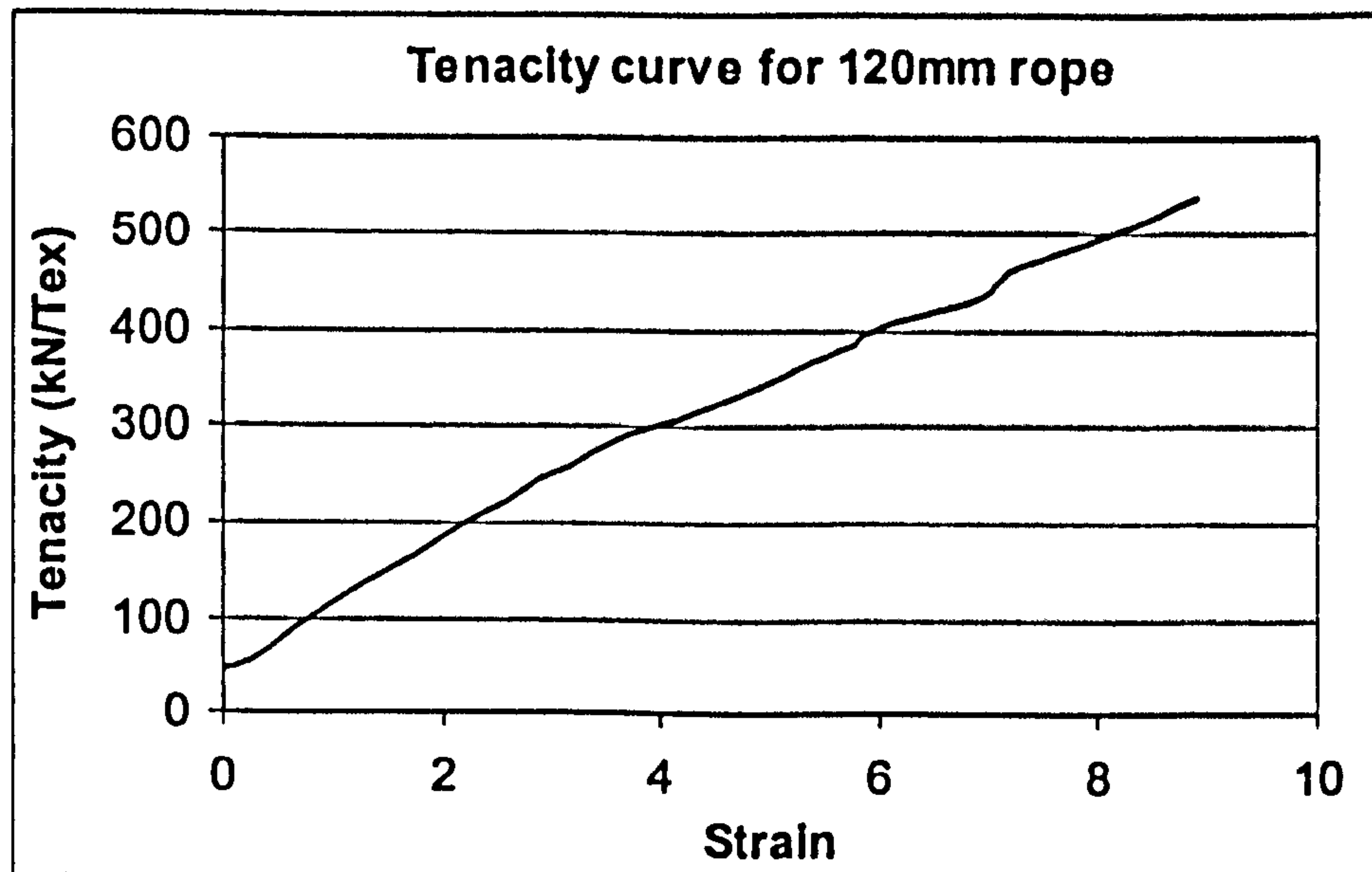


Figure 5.22: Tenacity curve for 120mm rope for final break.

There is no clear knee point in this figure. This is because most of the fibre realignments and socket-draw were removed in the previous cycling and tension treatments. When the rope was made, it was expected that most of the fibres' realignment be removed under the sub-ropes tension. Fluctuation in the graph around 400 kN/Text is due to machine breakdown.

The total extension in the rope was measured at 150.39mm. Socket face to face length after initial cycling was measured to be 334.22mm at 2500kN. A simple comparison between these two figures, indicate that most socket-draw and fibre realignments are removed during the loading regime before final break. Therefore the resultant extension could be considered as the actual extension of the rope excluding fibre realignments and socket-draw.

- *Effect of Cycling on Tenacity Behaviour*

The effect of cycling on fibre adjustment in the rope itself is obvious. In the presence of socket, some other effect, e.g. socket-draw and fibres' length adjustment in the socket should be included.

When the cycling is applied, the following effects happen:

- 1- Some dissimilarity in fibres length disappears.
- 2- Socket draw tends to decrease to a minimum.
- 3- Graph 5.16 has a uniform pattern with no fluctuation. It is believed that most of the socket-draw and fibre realignment has been removed during the rope preparation (e.g. cycling and application of constant load).

VII) Effect of filaments' number on strain

The results of the maximum strain to failure for the different filament constructions are shown graphically in Figure 5.23.

The results show that the maximum strain to failure is the same for all the small size filaments up to the strand construction. There is a sharp rise in the strand. This is due to the inherent increase in the twist in the construction. The reason for this phenomenon is that during the initial stages of loading, a significant proportion of the extension consists of untwisting before complete loading is taken up by the filaments.

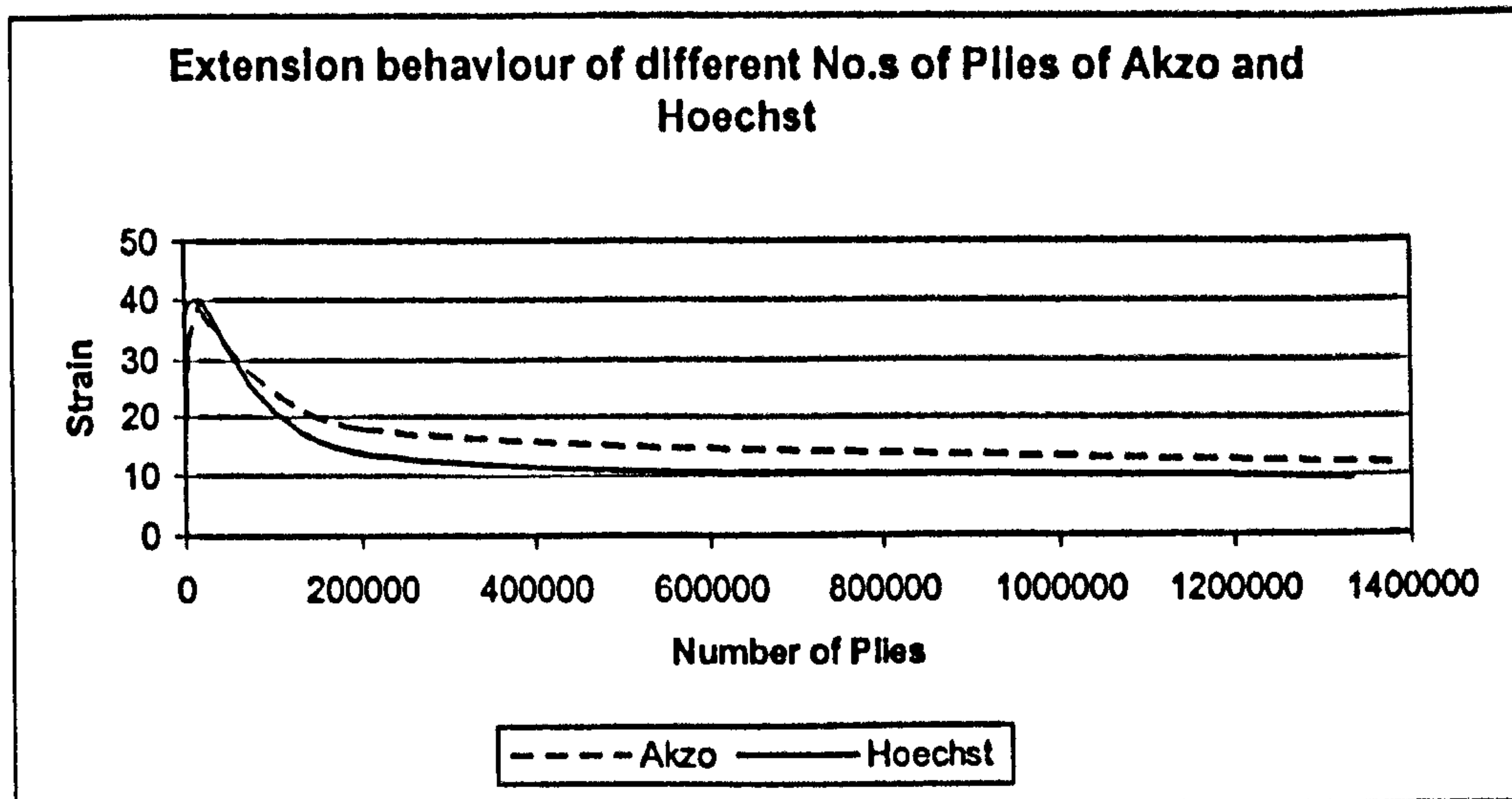


Figure 5.23: Strain at break for different number of plies of Hoechst and Akzo materials.

The above figure includes all tests referring to tensile strength of the ropes. Referring to figures 5.3 and 5.4, and the above figure we have previously fully explained the shape of this graph.

5.3.5 Conclusion

The “Stress Relief Socket” proved to achieve the best results in static tensile test for different sizes and types of ropes in this study. Comparisons with some previous results on similar rope sizes also proved that.

It is believed that the novelty of this method is in reducing the stress concentration areas around the socket and moves the high stress points along the rope. All previous methods suffer from premature failure around termination because of load concentration points.

5.4 Cyclic loading

In this section, the results of the cyclic loading tests on the stress relief rope-termination systems, using rope sizes of 44mm Akzo and Hoechst and 120mm Hoechst materials, are presented and discussed.

The two different cyclic loading methods performed on the ropes are as follows:

1. Cyclic tests according to OCIMF guidelines on 44mm Akzo and Hoechst materials which recommend a testing regime of high load and low number of cycles (Section 4.7.2 – 1).
2. Cyclic tests based on Petrobras requirements on 44mm Akzo and Hoechst and 120mm Hoechst materials, which suggest a testing regime of low load magnitudes and high number of cycles (Section 4.7.2 – 2).

5.4.1 OCIMF cyclic testing on 44mm rope systems

OCIMF is a practical test method for cycling large diameter ropes based on experience over many tests done in the past (Bitting 1980, Crawford 1983, 1985, Flory 1990). The focal point of this test is that if the rope is cycled 1000 times in 50% its breaking load + 1000 times in 60% + 1000 times in 70%, they should be equal to 113 cycles in its 80% breaking load. This is an experimental equation and obviously many tests have been done to work out such a figure. It is assumed that this figure is based on the mean result of tests done on different materials and rope sizes.

The results of the cyclic loading test based on OCIMF guidelines on 44mm Hoechst and Akzo are presented in Table 5.10.

Material	CTF	TCLL	BL (kN)
Akzo	222	74.42	748.50
Hoechst	213	74.22	804.50

CTF: Cycles to failure

TCLL: Thousand cycles load level (tonnes)

BL: Breaking load (tonnes)

Table 5.10: CTF, TCLL, and Breaking Load for 44mm Akzo & Hoechst rope in OCIMF cycling test method.

The results show that the both Hoechst and Akzo materials performed nearly similarly with respect to OCIMF cycles to failure. Cycles to failure (CTF) for both materials were very close and the difference was negligible.

Although at first sight the results indicate that it was difficult to compare these two materials with similar levels of cycles to failure, Akzo performed slightly better when CTF (Cycles to Failure) at 80% breaking load is considered. It can be suggested that the calculation based on TCLL formula can lead to a more realistic and closely related practical situation because it considers the breaking load level as well as the number of cycles to failure. The full analysis of the different approaches is given in Section 4.7.2.

I) Load-extension behaviour of the rope during cyclic loading

The load-extension plots for 44mm diameter Akzo and Hoechst samples are shown in Figure 5.24. The plots show the load-extension during final cycle of the cyclic testing regime for the relevant cycles ranging from 10-4100 cycles. Different load levels are also noted. A clear knee point is seen around 10 tonnes load in all plots until 4000 cycles. The knee point is disappeared in 4100 cycle's plot.

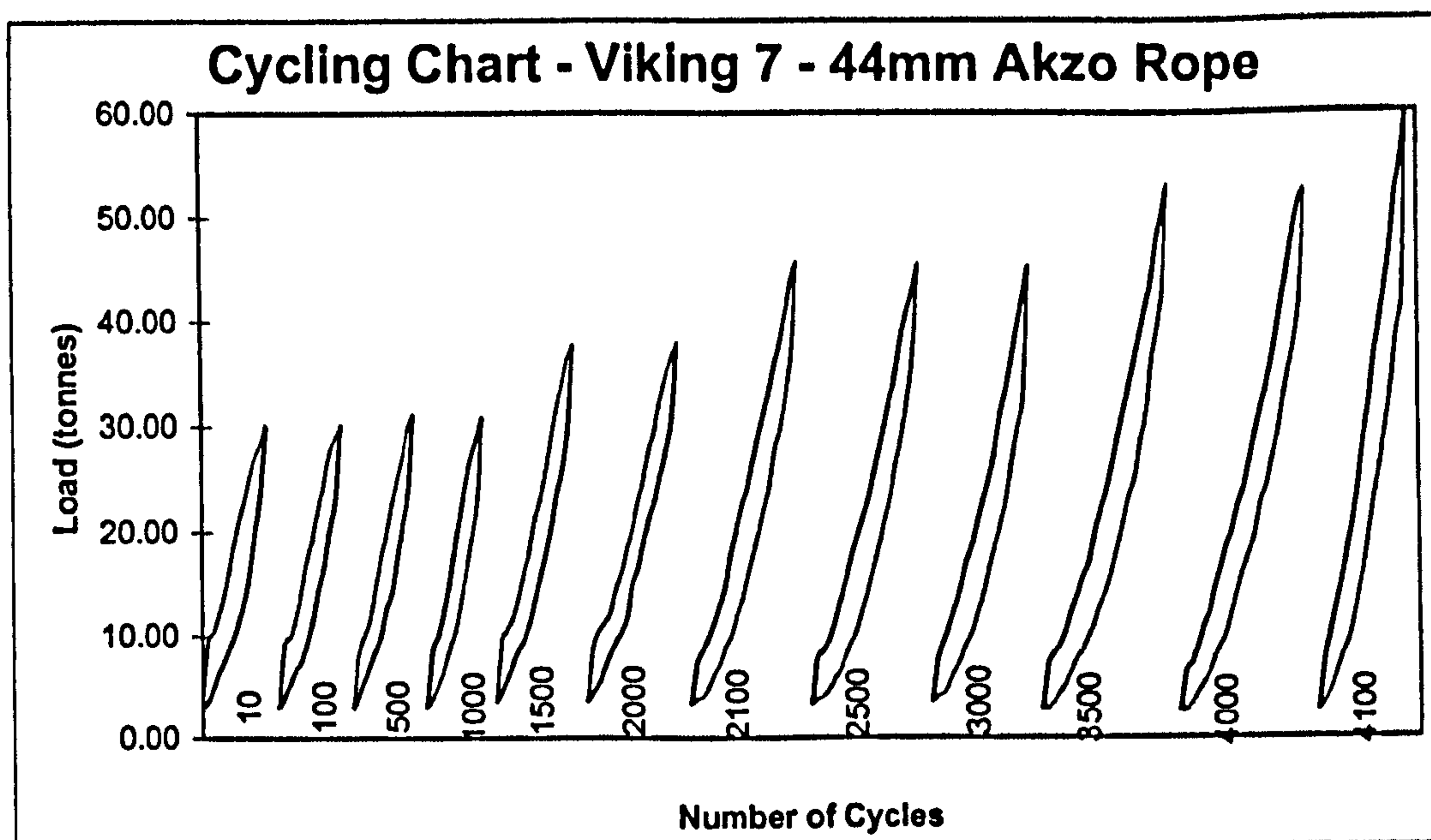


Figure 5.24: Load Extension behaviour of the 44mm Viking7 Akzo rope under cycling process (OCIMF method).

Existence of the knee points in a sample that had been experiencing cycling load for long time could not be due to socket-draw. It could be argued that fibre realignment is recoverable when load is removed. Therefore during the next loading process, the knee point could be due to fibre realignment that has been recovered in the return cycle. However we should also note that this effect is disappeared after 4100 cycles.

The results presented in Figure 5.24 show that as the number of cycle increases, the modulus of the ropes also increases due to changes in materials stiffness. Application of water spray on the rope, caused less heat generation during the testing procedure and resulted in lower increase in modulus.

It can also be seen that the load extension plots are more irregular at low number of cycles. This could be due to the fibres realignment in the rope during the initial stages of cycling.

II) Failure analysis

The failure observations during the test, which took 15 days to generate the data, indicate that the failure took place in a catastrophic manner. The final failure consisted of failure of one sub-rope, which preceded the total failure. The sudden final

failure resulted from an overload on the remaining sub-ropes after the first sub-rope failed. Post-mortem examination of the sample indicated heat generation during the testing regime as sub-rope fused together.

Moreover due to the relatively short length of samples used in this study, any differences in the length of sub-ropes would lead to the partial failure of the shortest sub-rope. It may not be a problem in actual line as it is very long and small inequalities in sub-ropes lengths inside the socket will not make a problem same as small samples.

III) Viscoelastic behaviour of rope

The failure in the rope consists of several stages including a linear stage of elastic behaviour followed by a non-linear stage that called plastic deformation as a result of viscoelastic behaviour. When the rope is cycled continuously, the viscoelastic behaviour dominates the deformation process. This will involve the generation of hysteresis heat, which will contribute to the partial failure of a sub-rope [Parsey, 1983].

Polyester as a filament shows viscoelastic behaviour and it is clearly reflected in the load-extension graphs. However, as a rope, the viscose behaviour tends to decrease because of the braided structure. Therefore, it is expected to recover most of the load applied to the rope during the tensile process. It is clearly seen that as the rope sizes increase, the load-extension figures tend to show more linear behaviour.

Rope diameter has a major influence on the total extension of the rope. The larger the diameter is, the less extension is produced. If both viscose and elastic properties dominate the behaviour of the rope, the viscose part seems to be very limited as the rope diameter increases and most of the tension applied is recovered.

5.4.2 Low load Cycling - Petrobras method

The second cyclic testing method carried out on the 44mm Akzo and the Hoechst rope and the 120mm Hoechst rope was based on the Petrobras requirement with a cycling programme of relatively low loads and high numbers of cycles (nominally greater than 200,000 cycles) between 180-320kN (10%-30% rope breaking load).

This test was conducted to determine the rope performance under low load and high numbers of cycling. This gives an indication of rope survival in service to be the endurance limit for the rope in the marine environment, beyond which the ropes expected to last a long life without deterioration of properties.

This cyclic performance is dependant on the rope material as well as the termination type.

I) Effect of cyclic loading on rope extension

It seemed that the first 14000 cycles produced 5% extension whereas further 6.2% extension in the rope was created by 200,000 cycles. The rate of increase in extension reduces as the number of cycles increases up to a maximum of about 100,000 cycles beyond which, increase in extension is insignificant. 200,000 cycles is a definite number at which the extension rise is negligible.

When fibres are cycled in fixed loading ranges, the typical pattern of the stress-strain is altered considerably during the initial cyclic loading. For example, the initial modulus for nylon 6.6 rope changes and the apparent yield at about 2% strain point disappears (Flory *et al*, 1988). The stress-strain curve subsequently comes closer to an elastic behaviour. The initial and total moduli also change as a function of the load applied. This indicates that the contribution of viscous damping decays significantly in a few cyclic loads and keeps constant.

II) *Residual Strength*

The residual strength of both the Akzo and the Hoechst 44mm rope was measured after 200,000 cycles. Each sample was pulled to destruction after cyclic history.

Details of breaking loads are presented in Table 5.11.

Material	Number of Cycles	BL (tonnes)
Akzo	200186	753.45
Hoechst	200150	812.46

Table 5.11: Cycle numbers and Breaking Load to failure for 44mm Akzo & Hoechst rope in Petrobras cycling test method using the Stress Relief Socket.

Both ropes broke simultaneously in all the sub-ropes and no sub-rope was left intact. The results indicate a superior cyclic performance with a minimal reduction in the breaking load. This shows only a 3.3% reduction in strength compared with 826.0 kN which was chosen as the breaking strength of the same rope with the same termination.

The residual strength showed about 3% reduction in strength for both materials. The literature also supports this finding as polyester material is resistant to low load cycling (Crawford *et al*, 1983).

5.4.3 Conclusion

It can be concluded that the “Stress Relief Socket” did not have any adverse effects on the rope performance in the cycling test. The resultant breaking strengths are comparable with straight breaking test. Defects in the termination were examined by checking the broken ends after rope failure. It was noted that very few broken fibres were observed in the termination.

5.5 Acoustic Emission

5.5.1 Background

The main objective of this section is to investigate the relationship between acoustic emission signals and damage behaviour in the rope using different methods of termination and investigate if there is any difference between the “Stress Relief Socket” and other methods of termination.

The following parameters were monitored using acoustic emission signals:

- a) To examine the relationship between the AE load delay and the breaking load of the rope.
- b) To compare the performance of different rope terminations, under tensile loading.

It is well established that a sharp rise in AE activities signifies a major damage process in the rope structure (Vanderveldt *et al*, 1983). Therefore it is assumed that any significant rise in the cumulative AE ring-down count would be related to the rope simultaneous failure. However, in most cases, a gradual increase in AE ring-down count is observed prior to the final failure. This is due to the partial failure of some filaments before reaching an ultimate load.

Two Load-Extension and the AE ring-down counts were superimposed. The idea was that is when the rope failed or any crack occurred, the AE detector would pick some signals. The numbers of signals pass the threshold depend on the magnitude of the crack that occurred in the rope. If the two curves are put together, there must be some agreement between them. To make the results more sensible, it was attempted to relate the highest point of the AE and load-extension curves together.

In large ropes, some of the AE signals could be due to fibre alignment in the bundle since it is not expected to have fibre failure in the early stage of loading. If the fibre alignment coincides with the filaments' failure, a drop in the load-extension curve with a simultaneous increase in as acoustic emission is observed.

When a specimen is loaded gradually from load zero, AE detectors start to detect noises at a particular time, which corresponds to a particular load. The corresponding load level is defined as the "AE load delay" as described in Section 4.8 (Vanderveldt *et al*, 1983). The advantage of the AE load delay is to make some estimation about the safe working load.

5.5.2 AE from Filament

The average of breaking load in 30 tests is 82.139 N. The results consist of 71.870 N minimum up to the maximum of 89.980 N. The standard deviation in these tests was counted to be 4.717.

The first set of results is about Akzo 210 filament fibres.

The samples were mounted in the tensile machine and AE sensor was put on the tensile machine.

The sample was loaded up to break and AE wave was detected at the same time.

The results that were given by the AE detector contain the number of events that cross different thresholds. One channel called ring-down channel and it adds up all events that have been taken from the other channels. The ring-down channel has been used as reference in this report. The count ring-channel add up all previous number plus the new event together. In order to find out the value of the peak, every number was decreased from the next number. This gives the absolute value of the result that has been picked by AE machine. The peak moment could be traced by this method.

It was tried to superimpose two Load-Extension and Ring down counts-Time on one curve. The idea is when the rope fails or any crack happens, AE detector starts to pick some noise and the frequency of wave depends on the magnitude of crack that has happened in the rope. If two curves from two machines are put together, there must be some agreement between them.

Failure in some filaments starts before the final breaking and it could be traced by AE detector although nothing appears in the Load-Extension curve. The advantage of these pulses is to detect the failure before it happens. Also it could give the some idea about the safety of rope in service and its safe life. In new lines the rope contains some AE detectors by them strength and safe life of the rope is predicted by the peaks that have been taken from the rope during the service.

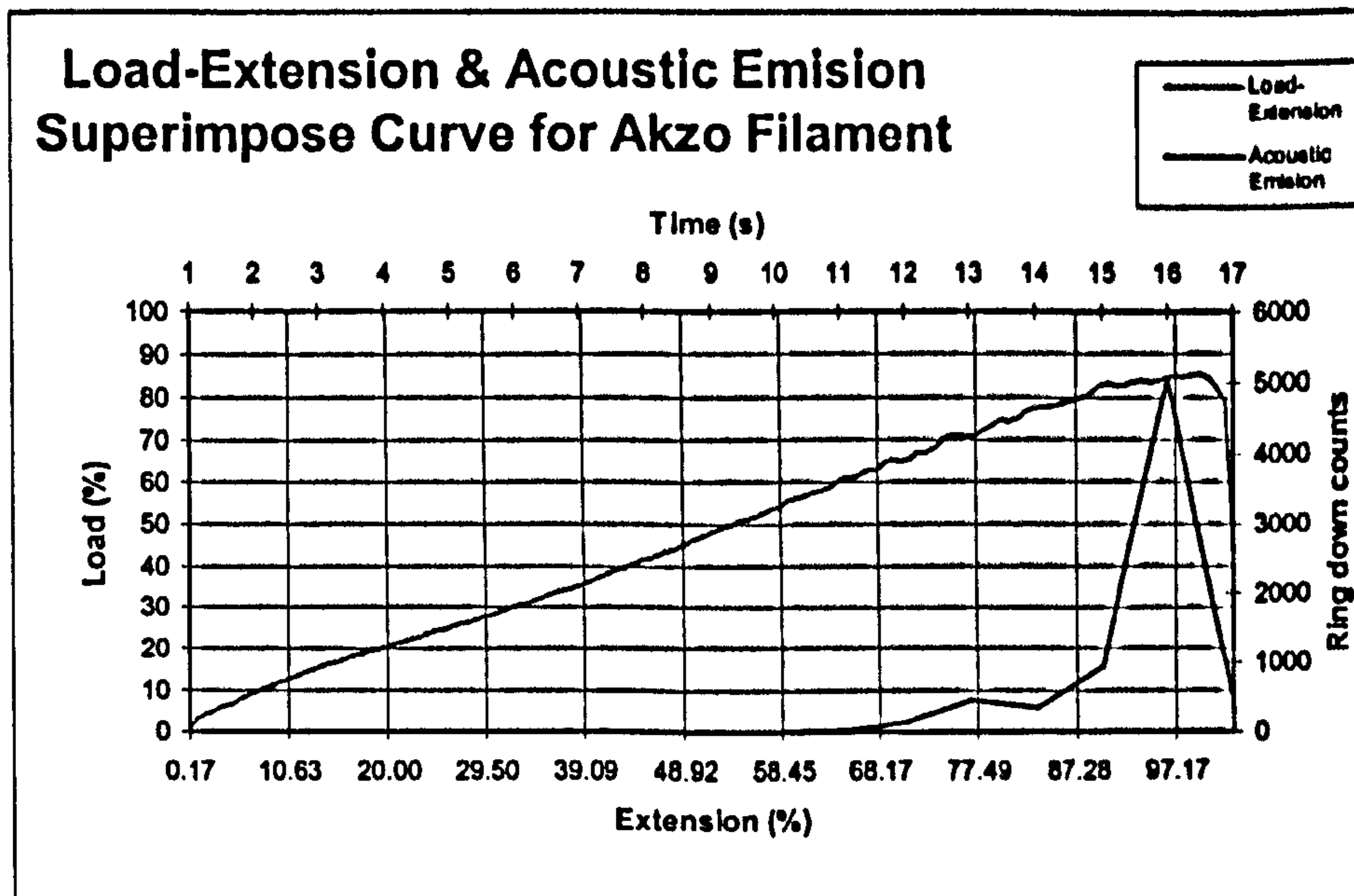


Figure 5.25: Detected failure from 65% of load.

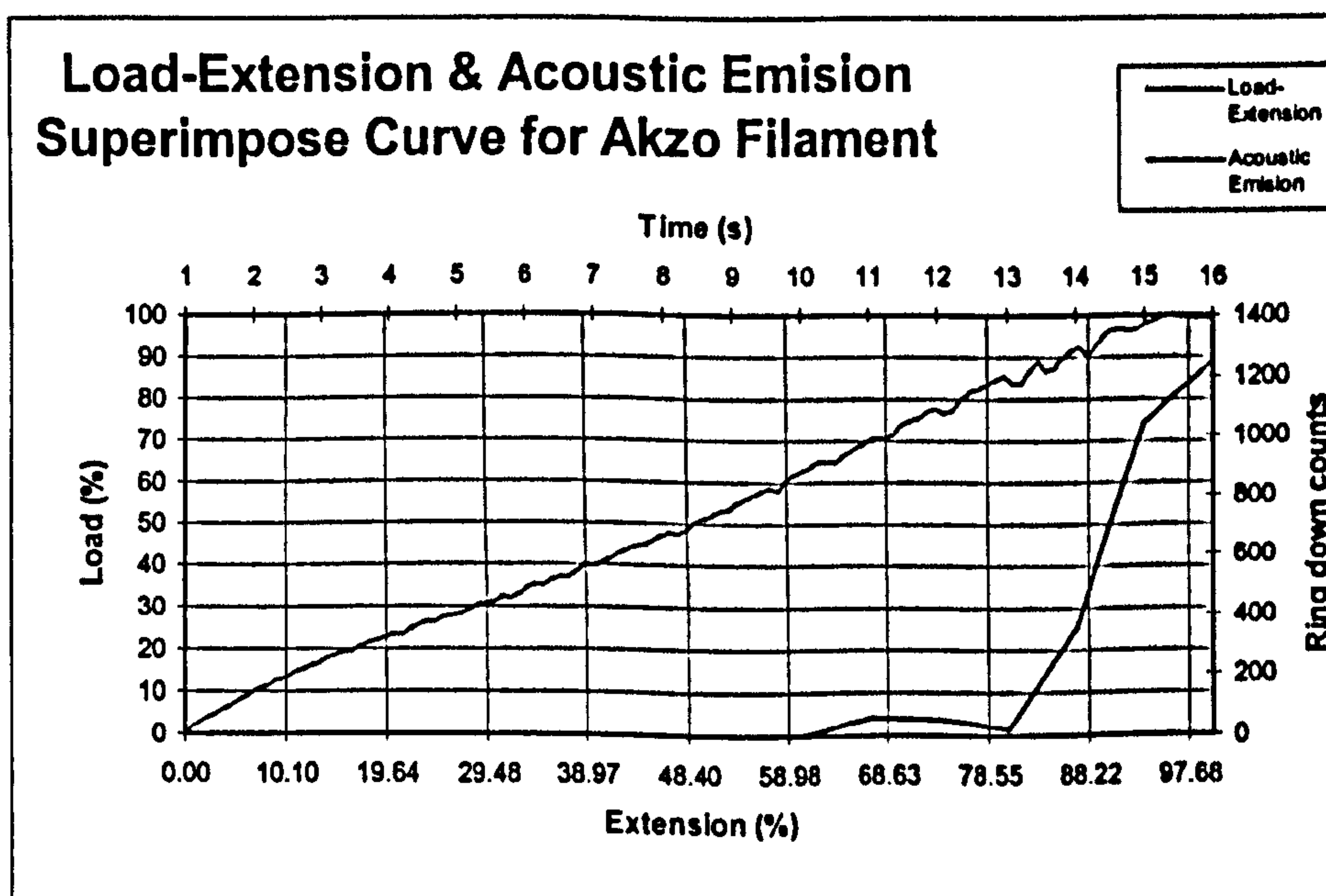


Figure 5.26: Some filaments broken at lower load between 60-80% load.

Some of the noises were picked up as result of fibre adjustment in the bundle because there have been no broken filaments in some cases but the Load-Extension curve shows some defects. If these defects were fibre breaking, the load peak was lower than the average breaking points.

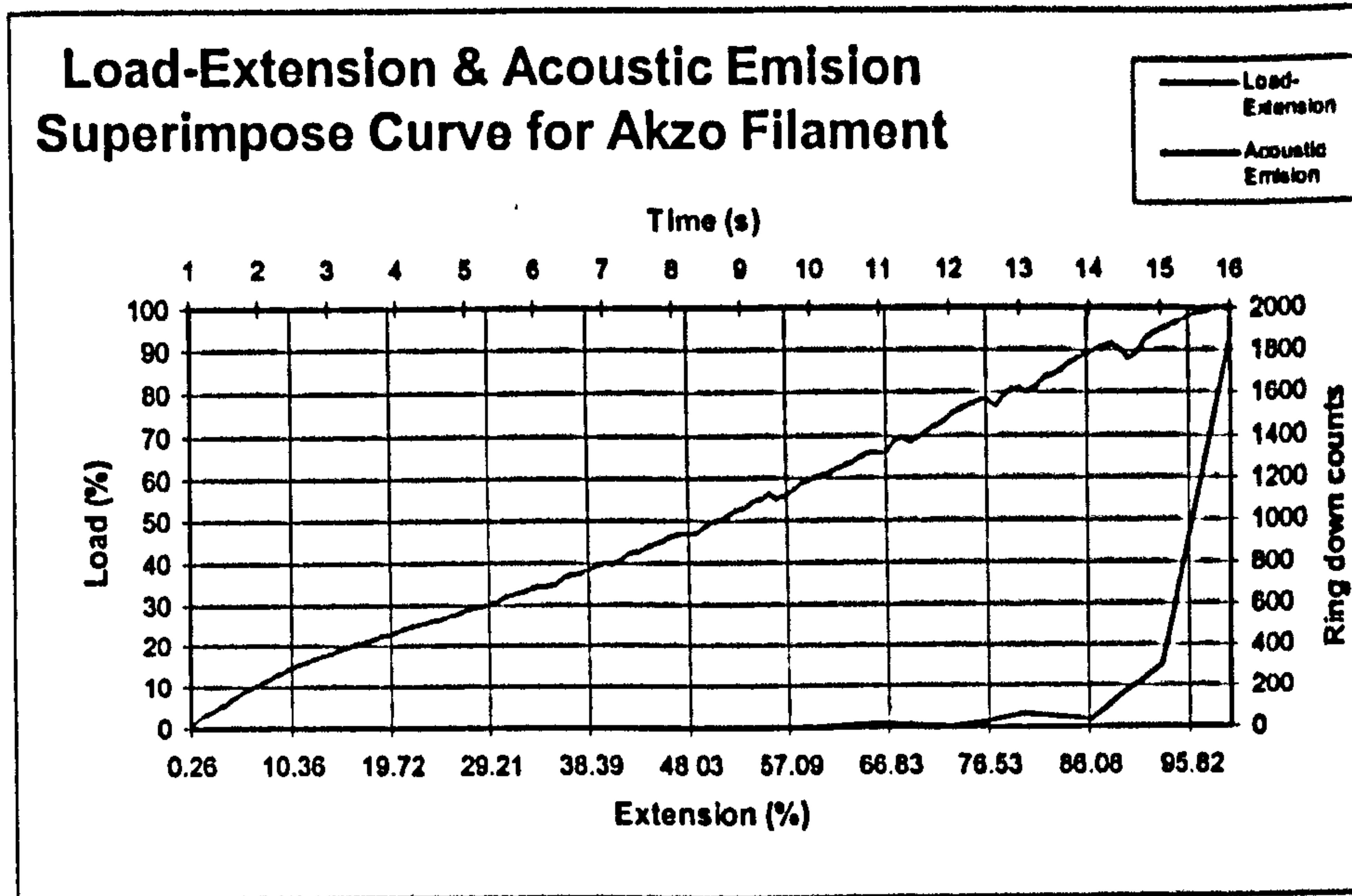


Figure 5.27: The Ring down counts picked up from 60% load as result of fibre adjustment.

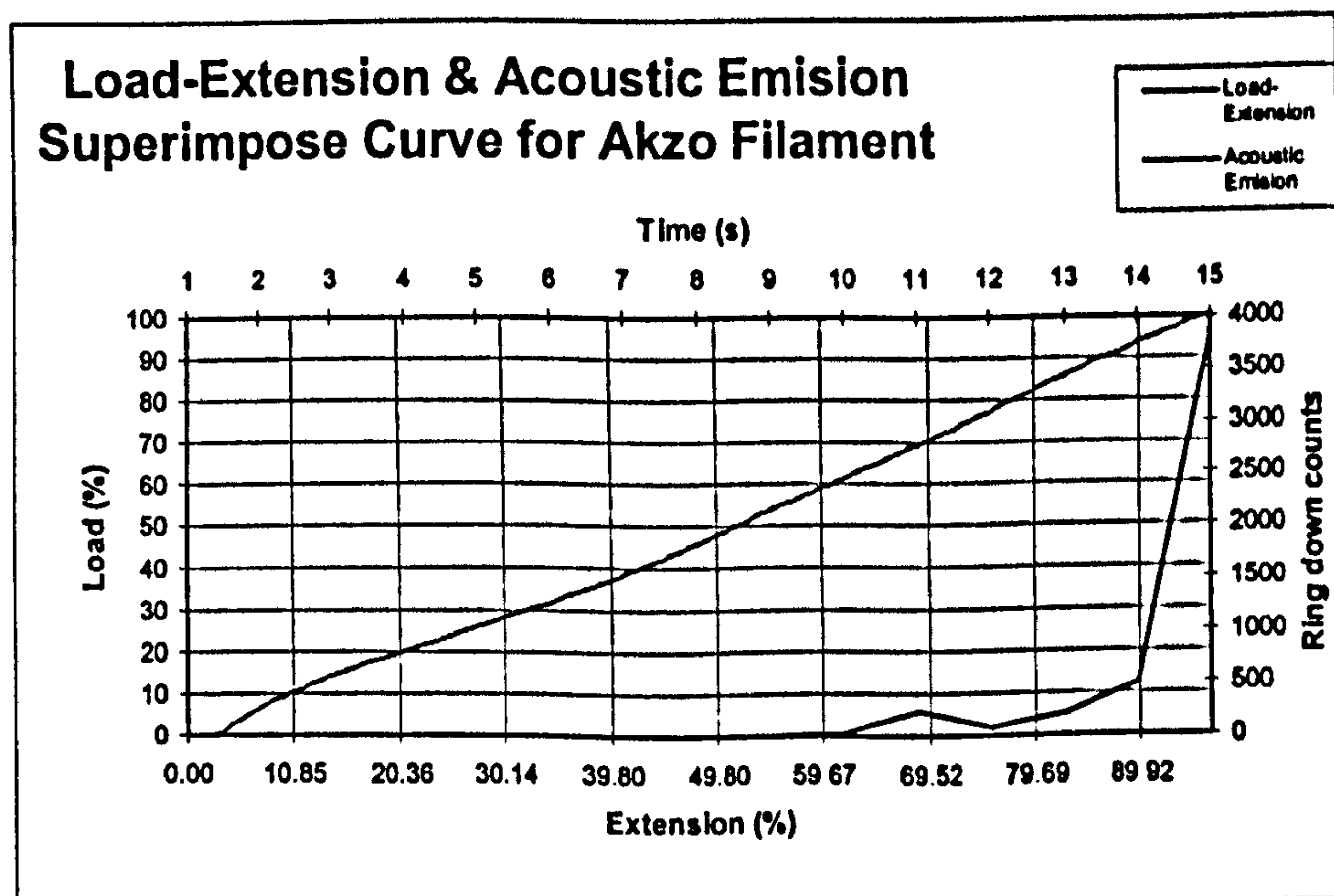


Figure 5.28: The Ring down counts start to change as result of fibre adjustment.

The ring-down value for some tests is very low and this could be as result for faults in sensor or its attachment to the machine. That's why the Ring down counts appeared to be low in the charts. Although some ideas about the failure starting time could be monitored by AE curves, to keep the consistency of results, it is preferred to ignore these cases.

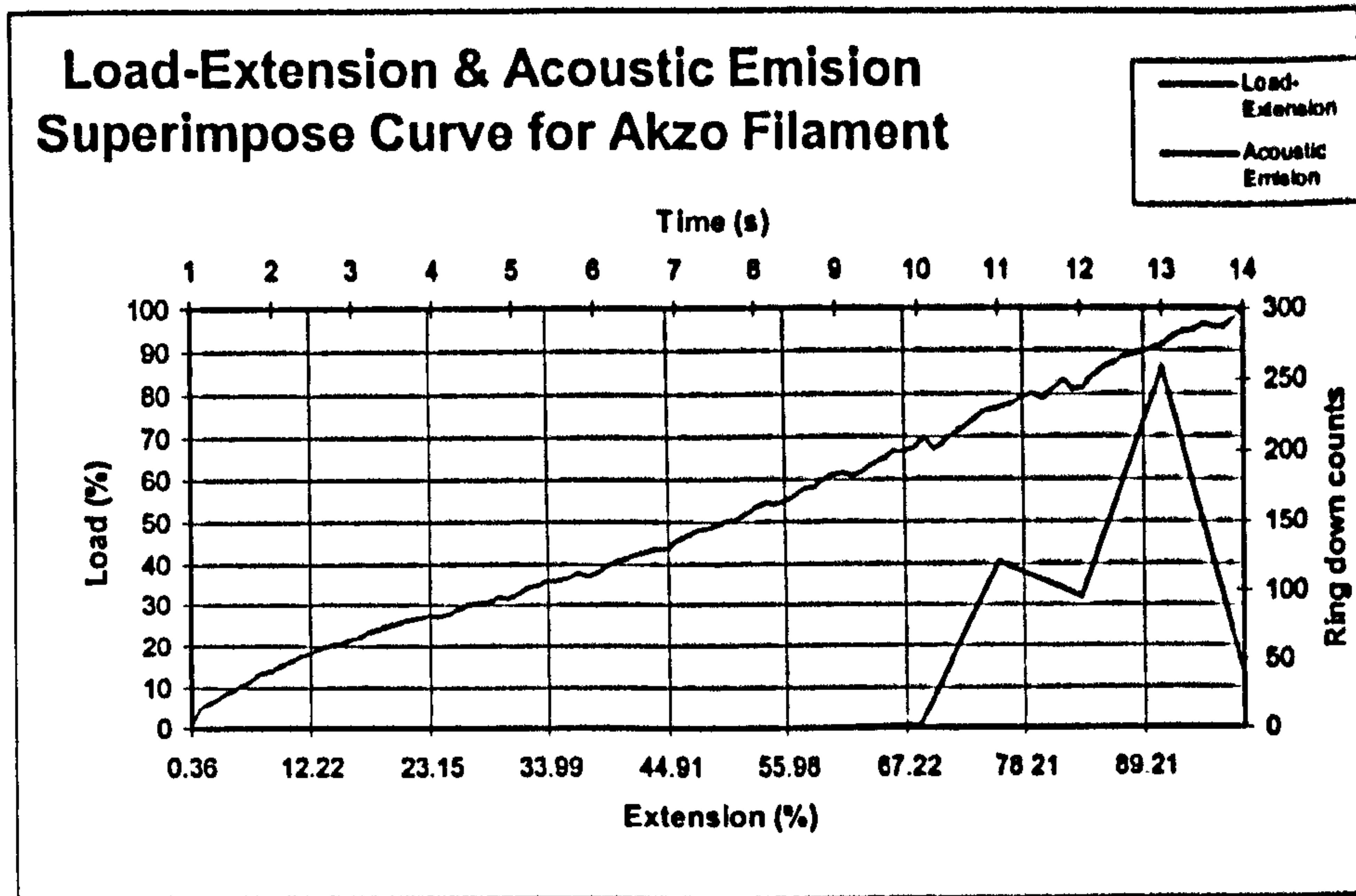


Figure 5.29: The Ring down counts are very low comparing to the other tests.

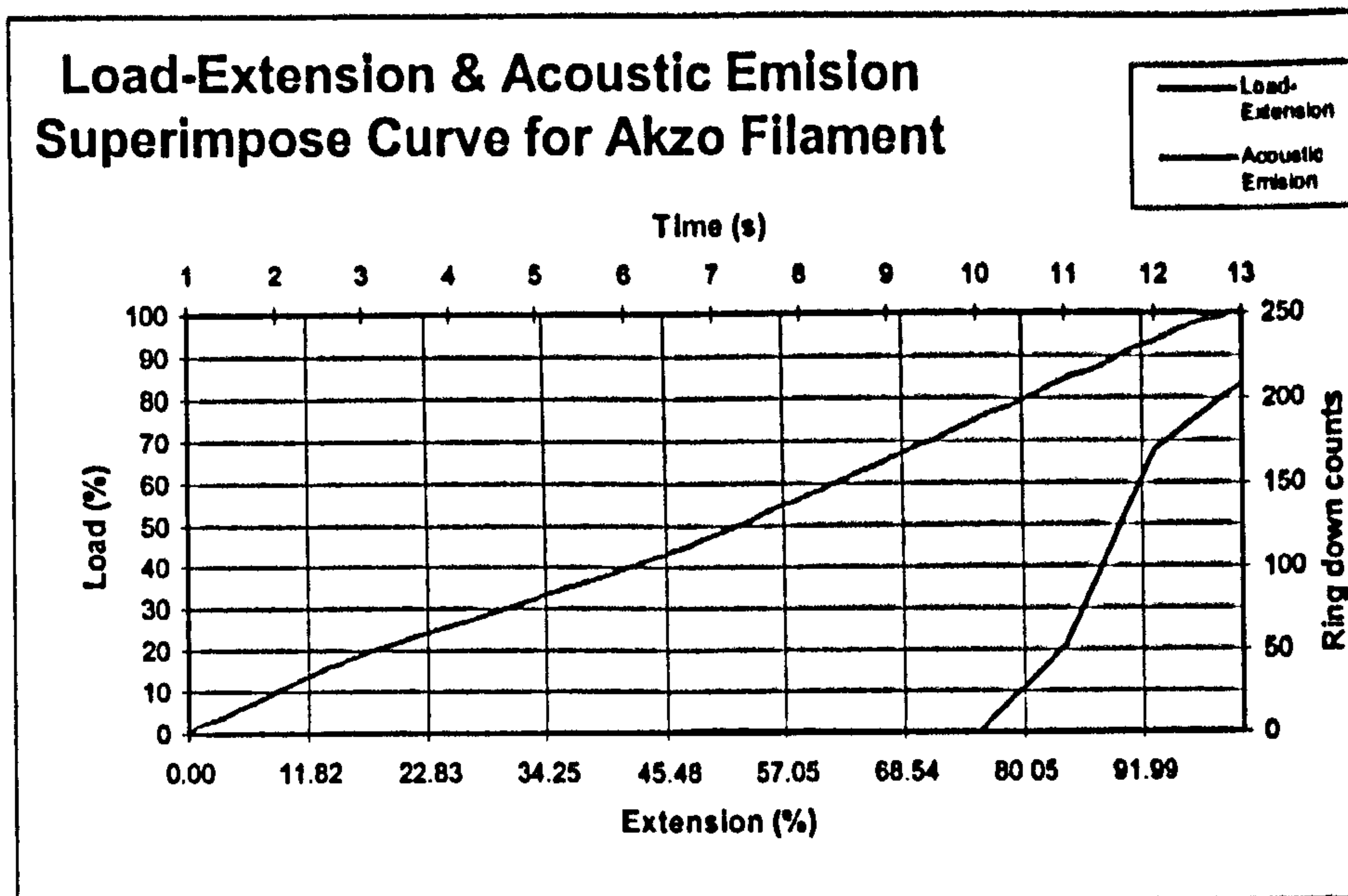


Figure 5.30: The Ring down counts are very low comparing to the other tests.

According to Vanderveldt & Tran (1971) significant increase in AE rate was found in 85% of failure for double braid rope. Egan (1972) collected AE data from double braided nylon rope tested in fresh water. He also observed an increase in AE activity prior to failure.

In this study, AE machine starts to detect from almost 55-65% of breaking failure of filaments.

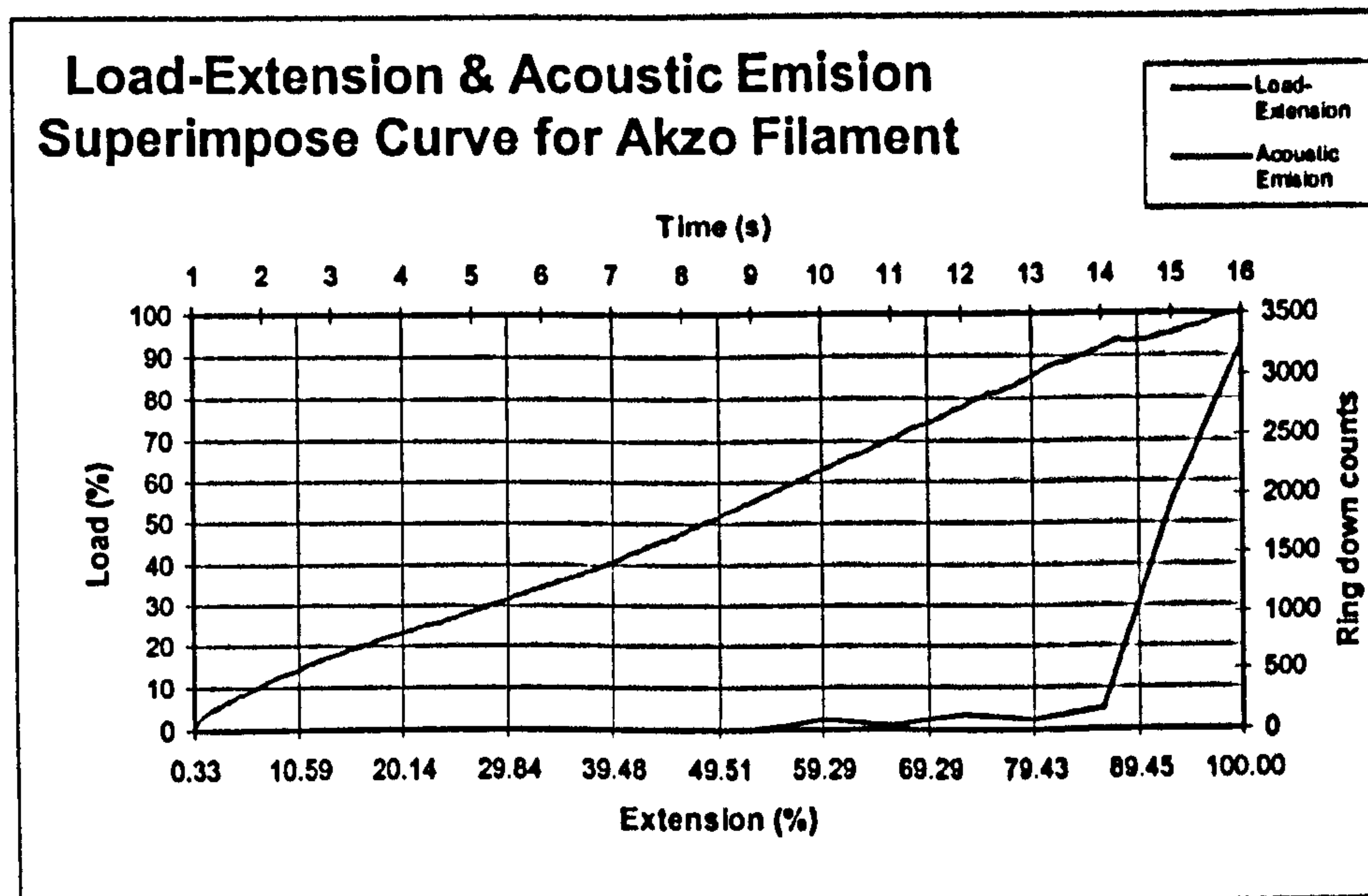


Figure 5.32: Ring down counts is detected from 55% load.

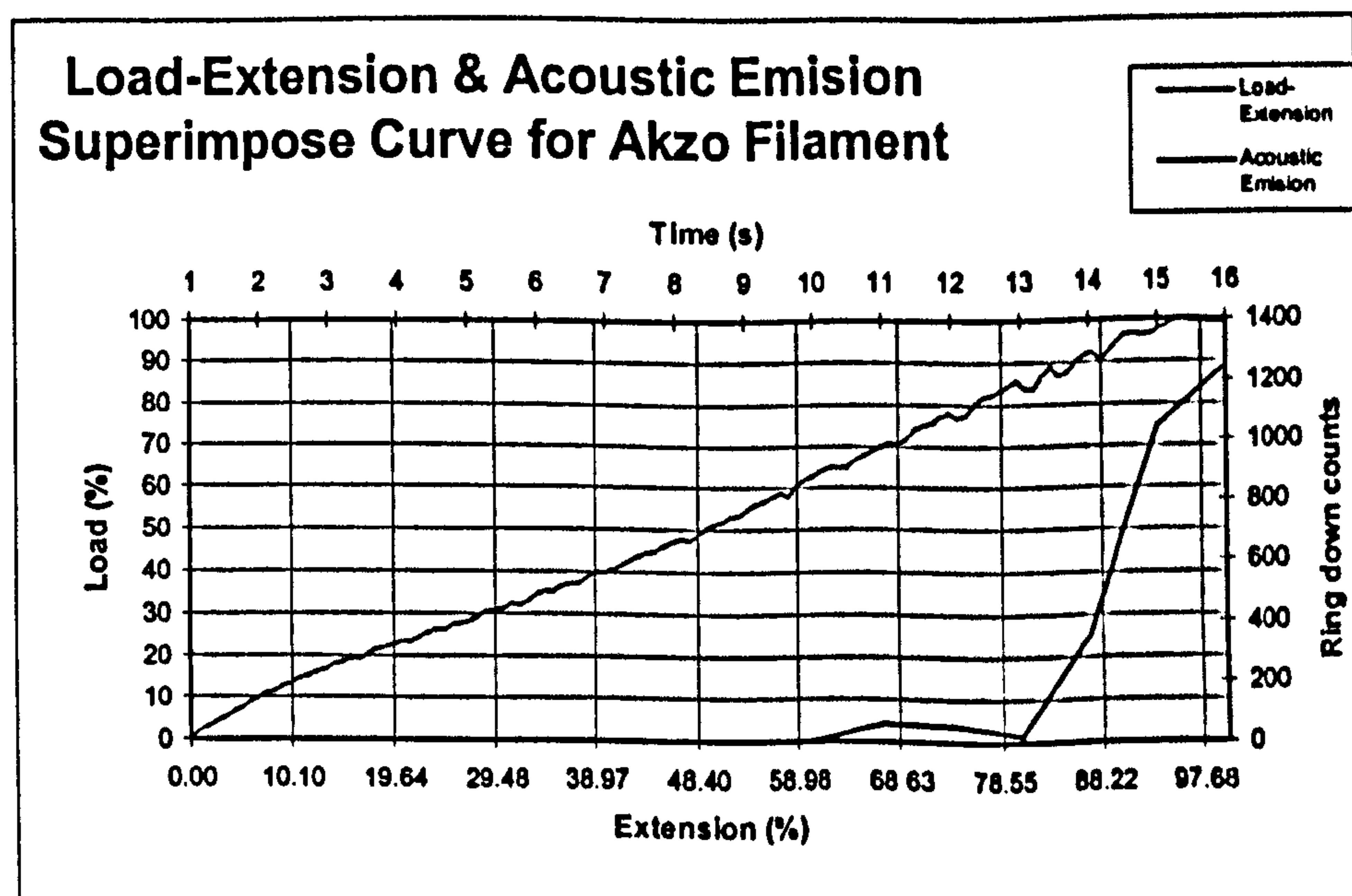


Figure 5.33: Ring down counts is detected from 65% load.

5.5.3 AE from Yarn

The average of breaking load in 30 tests is 3006.4 N. The minimum and maximum are 2803.0 N and 3141.0 N. It means that there is an improving effect by twisting the fibres in this construction because non of the fibre reach to the level of 100 N. The standard deviation is counted to be 89.2.

If a major crack happens in the bundle, the acoustic emission machine picks a high value. Fibre adjustment in the bundle and other small defects are not appeared to be detectable comparing to the high peaks.

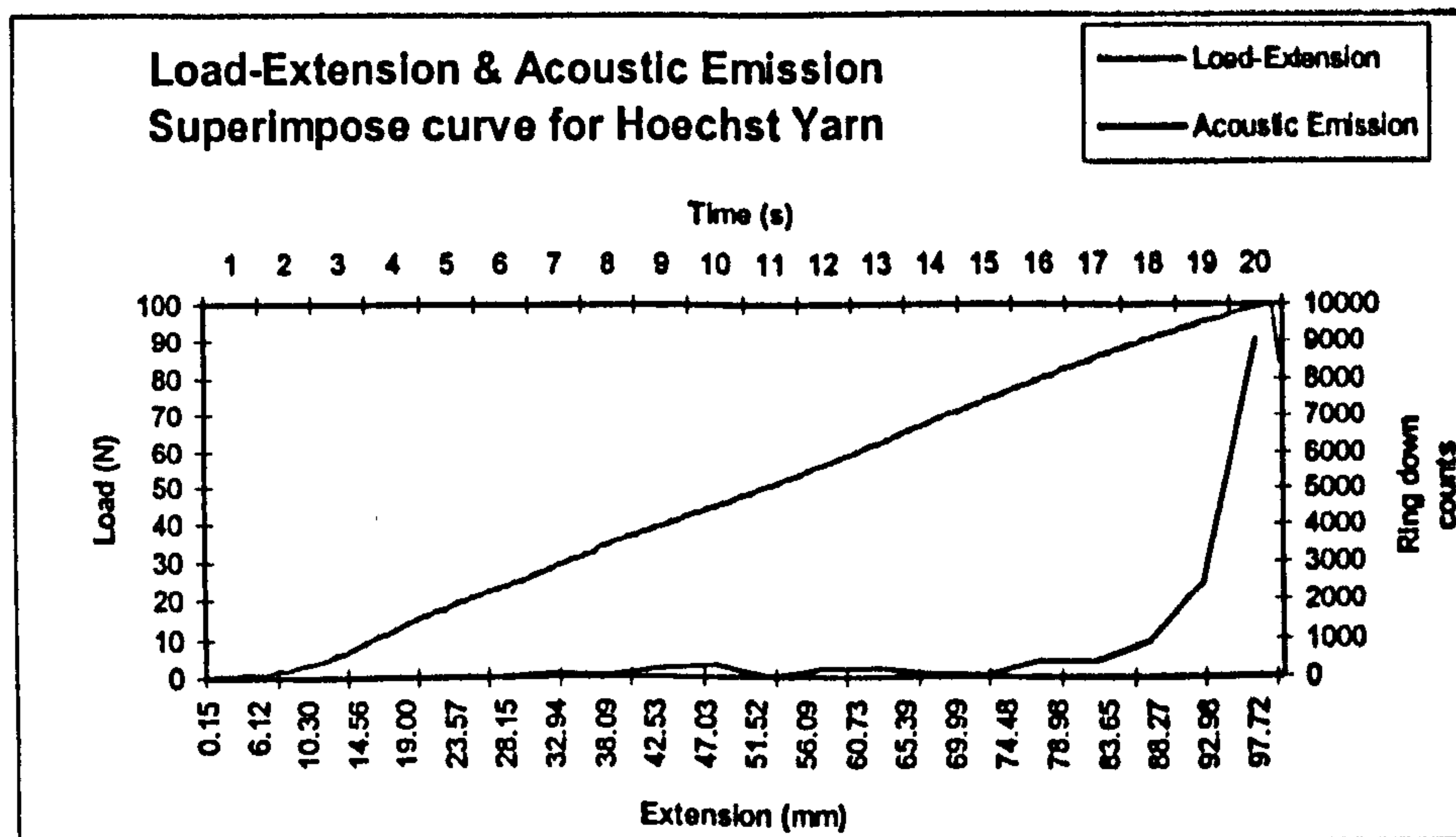


Figure 5.34: Small peaks are not visible comparing to the final failure. If the above curve is scaled up to 2000 for Ring down counts, the small defect in acoustic emission curve is visible.

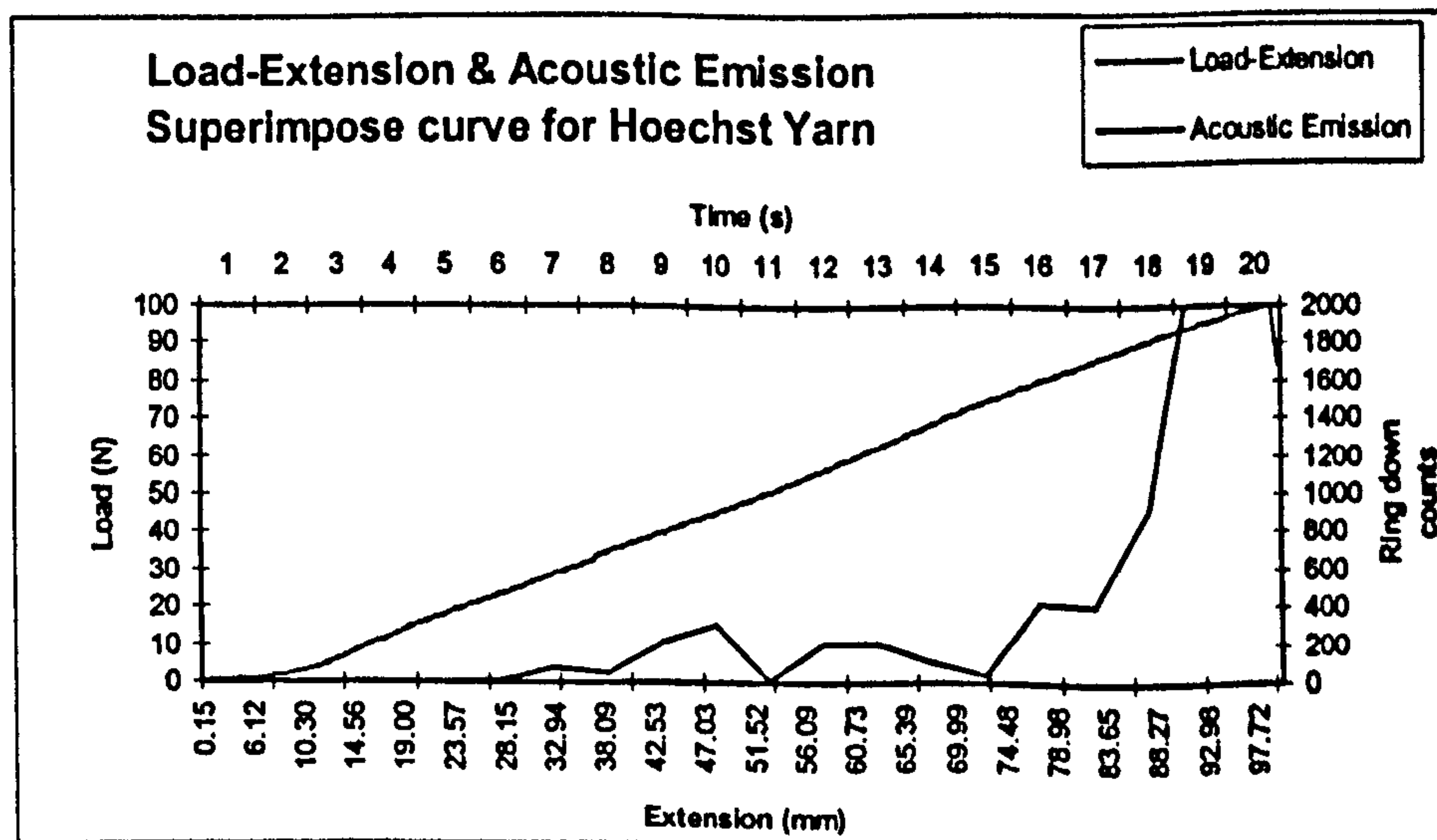


Figure 5.35: Magnification of figure 9 between 0-2000 Ring down counts.

Sometimes partial failure happens and causes low breaking strength and some of the fibres are still intact after the final failure these fibres could make some Ring down counts in lower resonance.

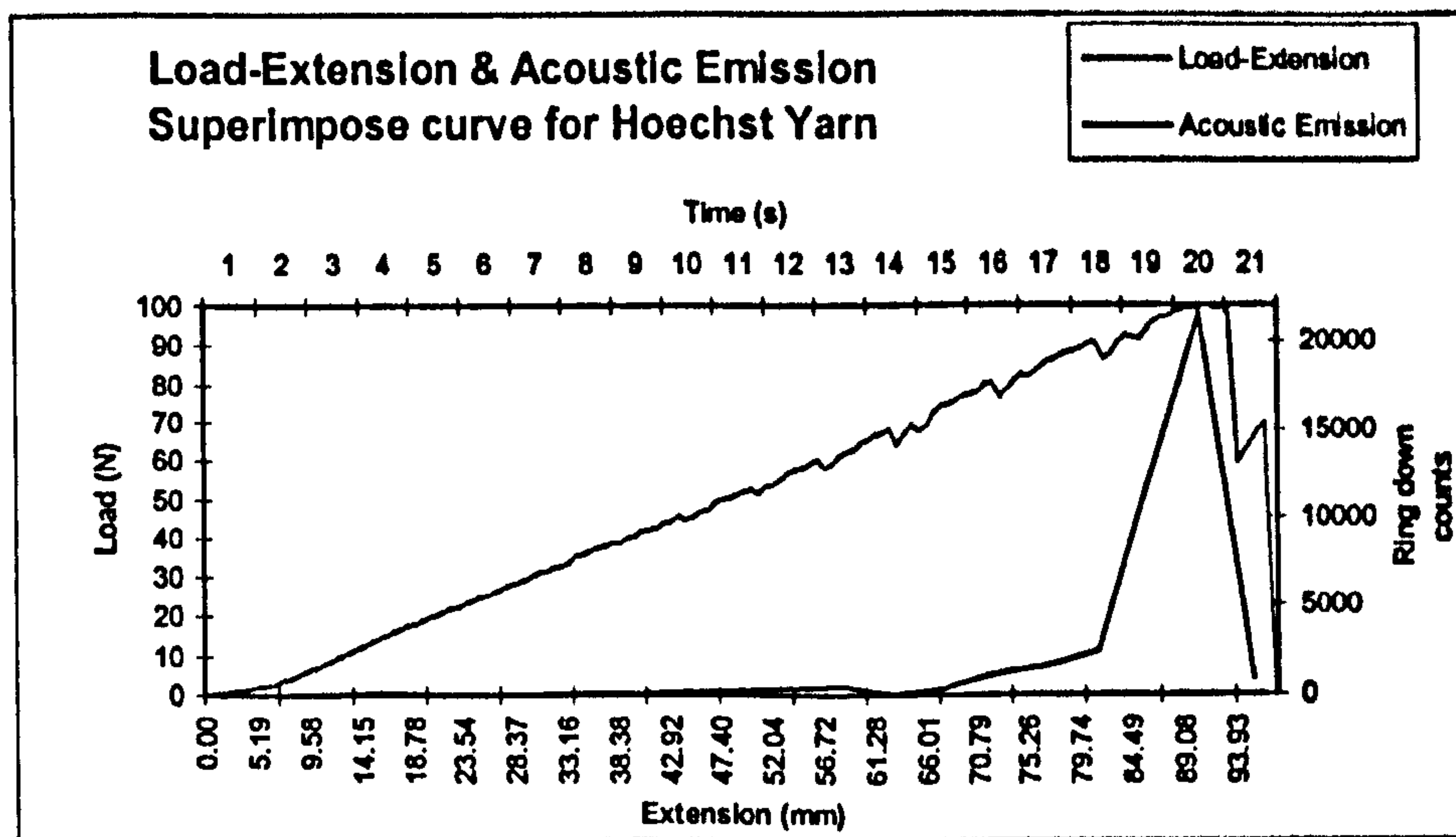


Figure 5.36: Detection of residual fibres after the final break.

It should be noted that primary and secondly X axis are not in the same scales and AE highest value belongs to highest load-extension peak although they are not in front of each others.

If the residual failure take a high load to break, the AE peak drops in between and increases again.

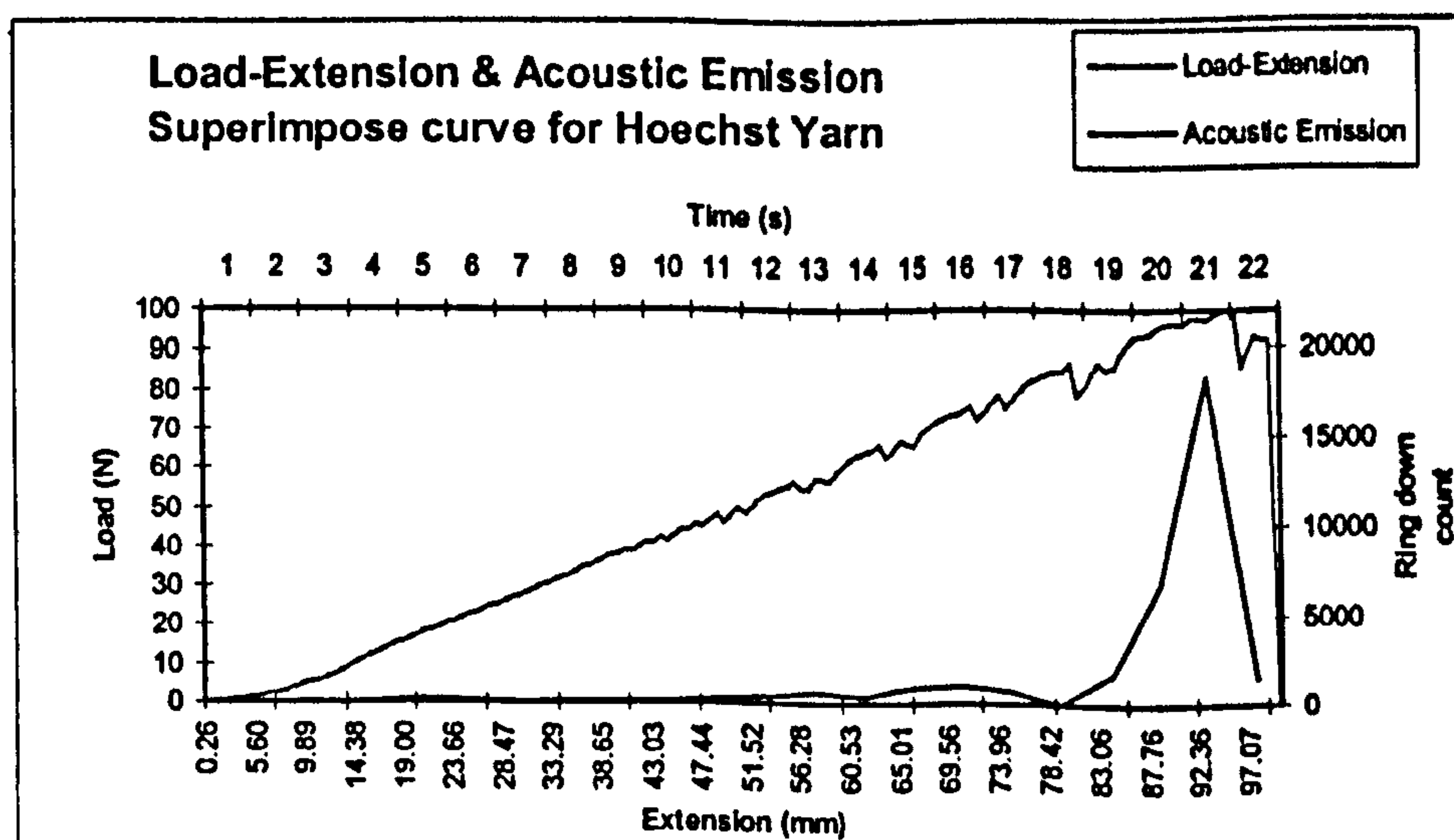


Figure 5.37: AE may detect different high peaks as a result of partial failure.

There could be a sharp increase in AE wave before the final peak. This indicates that the feature of partial failure is very close to final breaking of the rope.

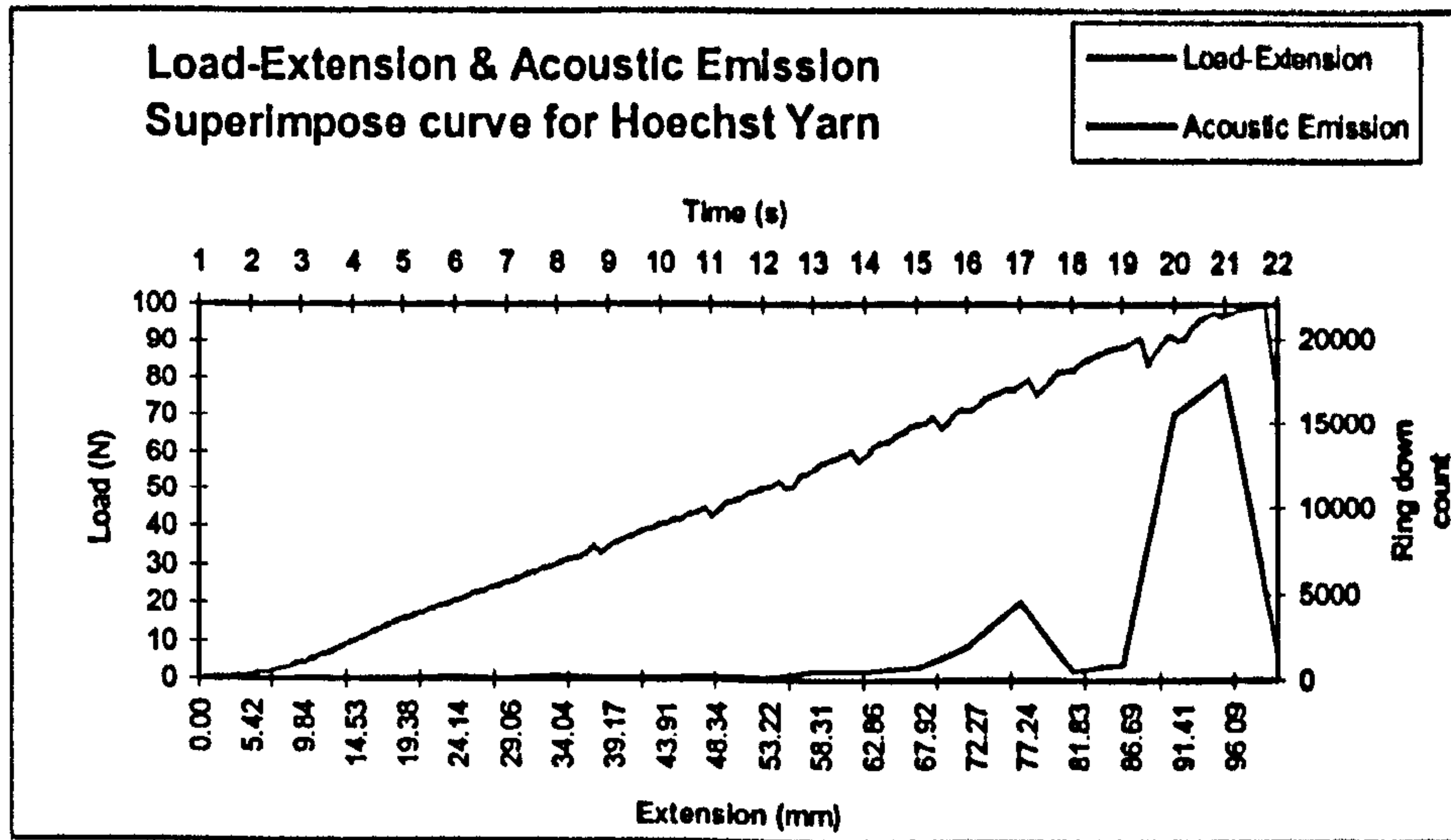


Figure 5.38: The sharp peak before the final break as a result of partial failure.

There are few cases that partial failure happens before the final break and after that in some residual fibres. In these cases, there are two sharp increases in the AE curve before and after final break. In load-extension curve the partial failure before the final break is not very clear although some drop could be seen in the graph but the partial failure after the break could clearly be seen in the graph.

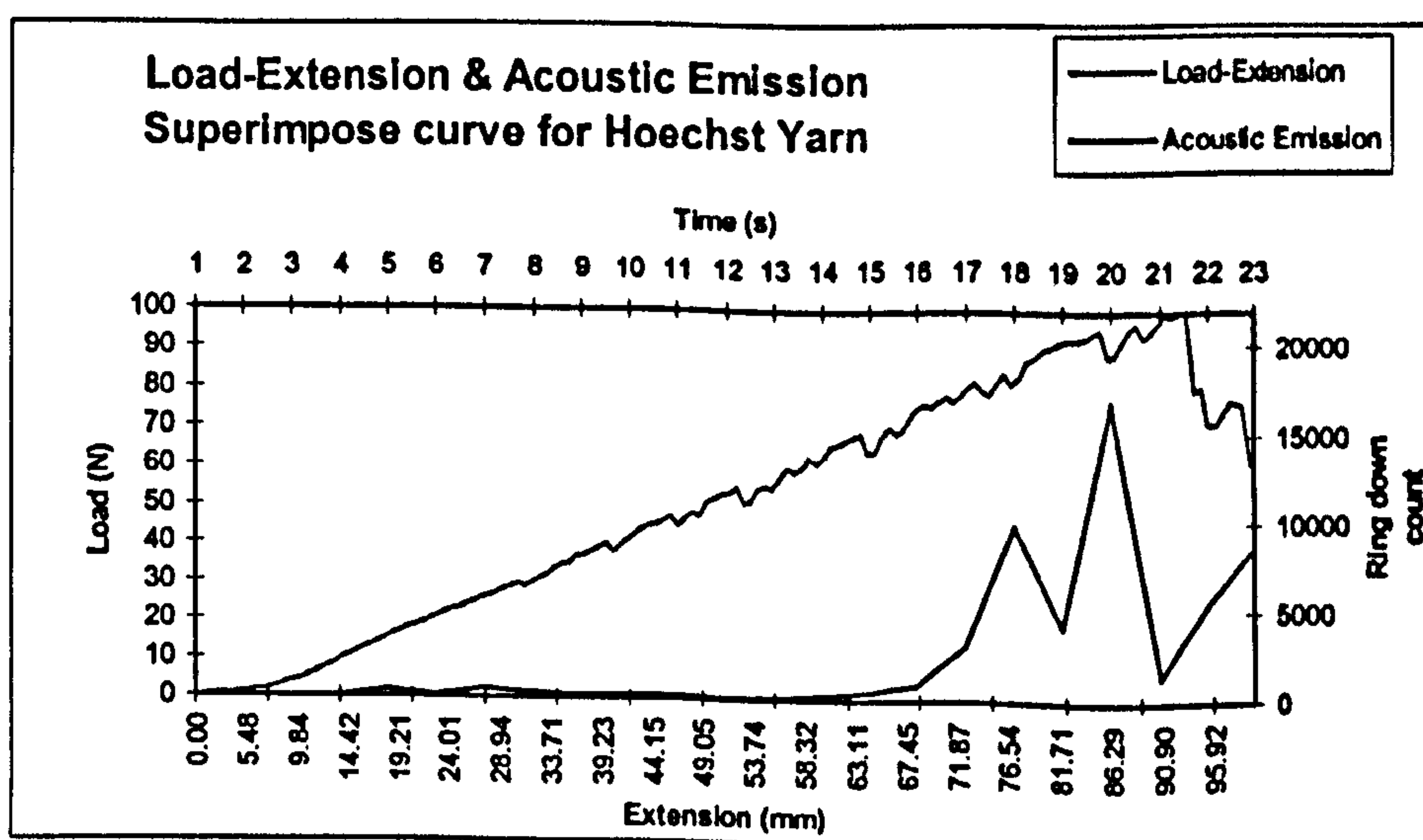


Figure 5.39: Partial failure before and after the final break.

Partial failure, in the rope, makes an unusual peak in AE curves in most cases and the sounds, that have been picked, may produce several high peaks apart from the highest one. This could be an indication of partial failure in the rope although post-mortem investigation on the rope could prove that. The advantage of AE method is to avoid partial failure in the rope before it happens. For example, in the following graph, if the test was stopped in the first AE peak, the final break could be avoided. This is a kind of indication for breaking of the rope.

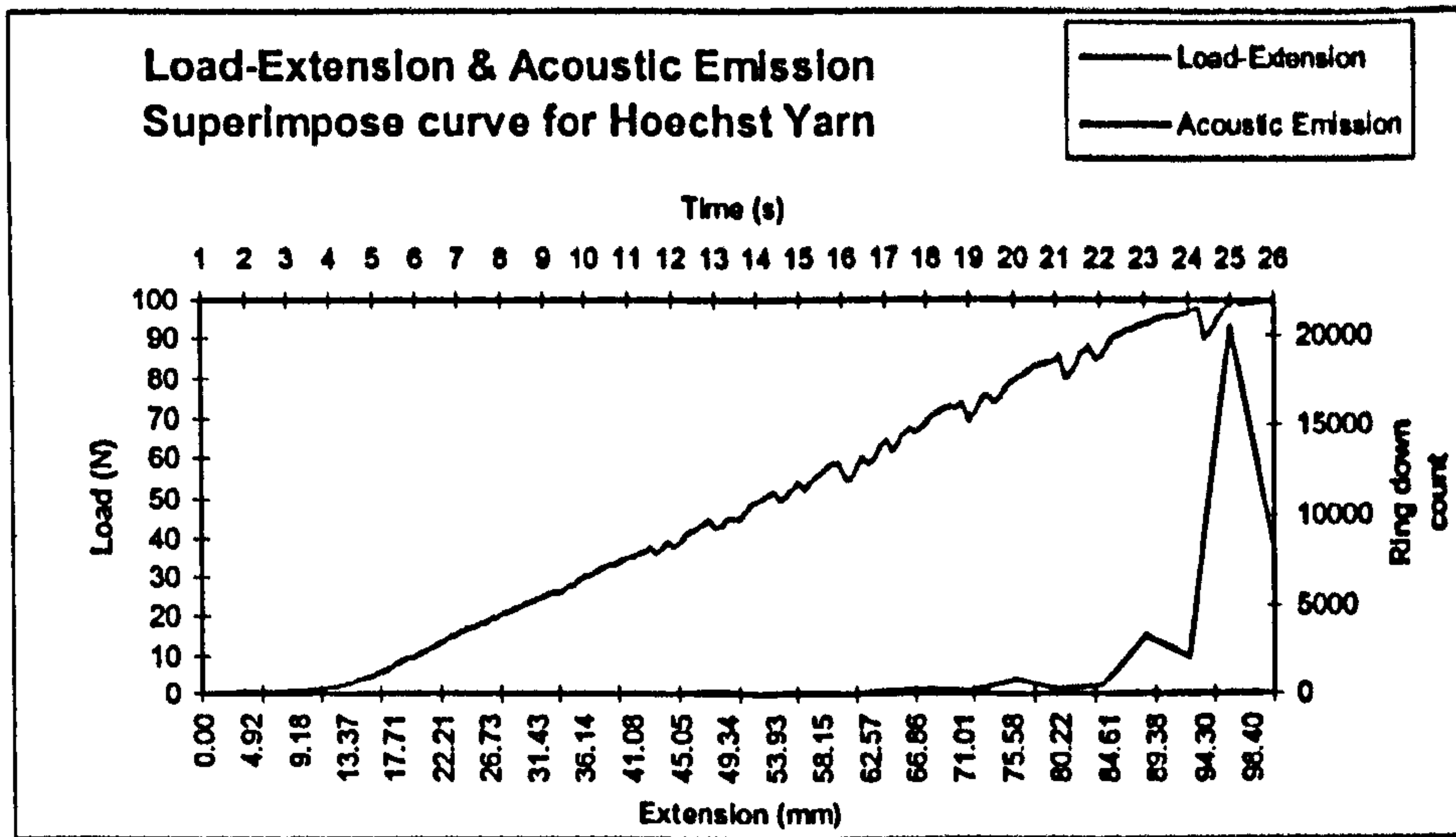


Figure 5.40: AE peaks as a result of fibres' failure.

To magnify the defect of fibre failure in the rope, Y axis in AE is changed:

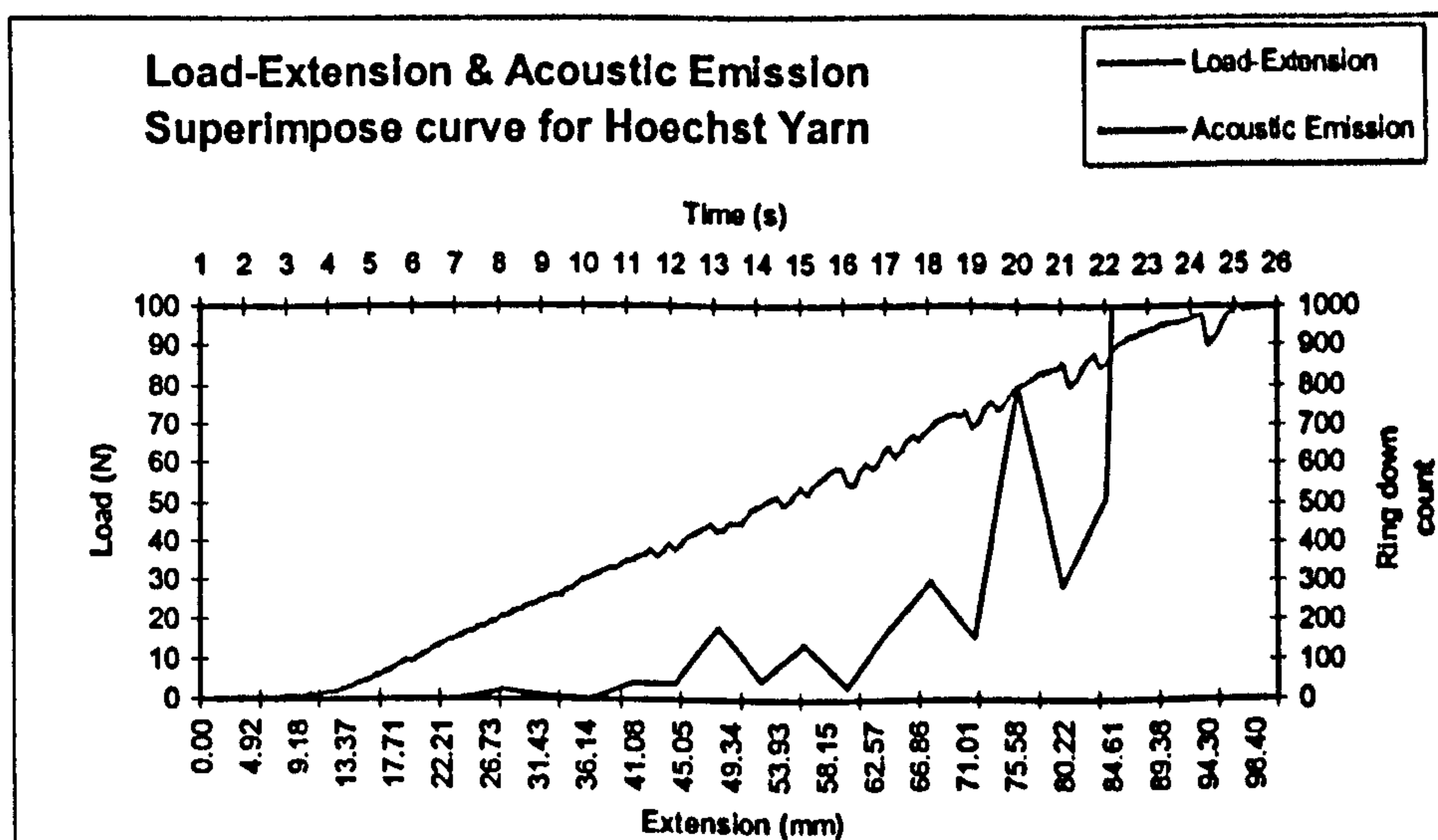


Figure 5.41: AE Magnification of previous graph in AE axis.

The relationship between the load-extension and AE curve in partial failure of rope is not fully established in these tests but almost in all cases, AE shows high pecks. This should be found out later.

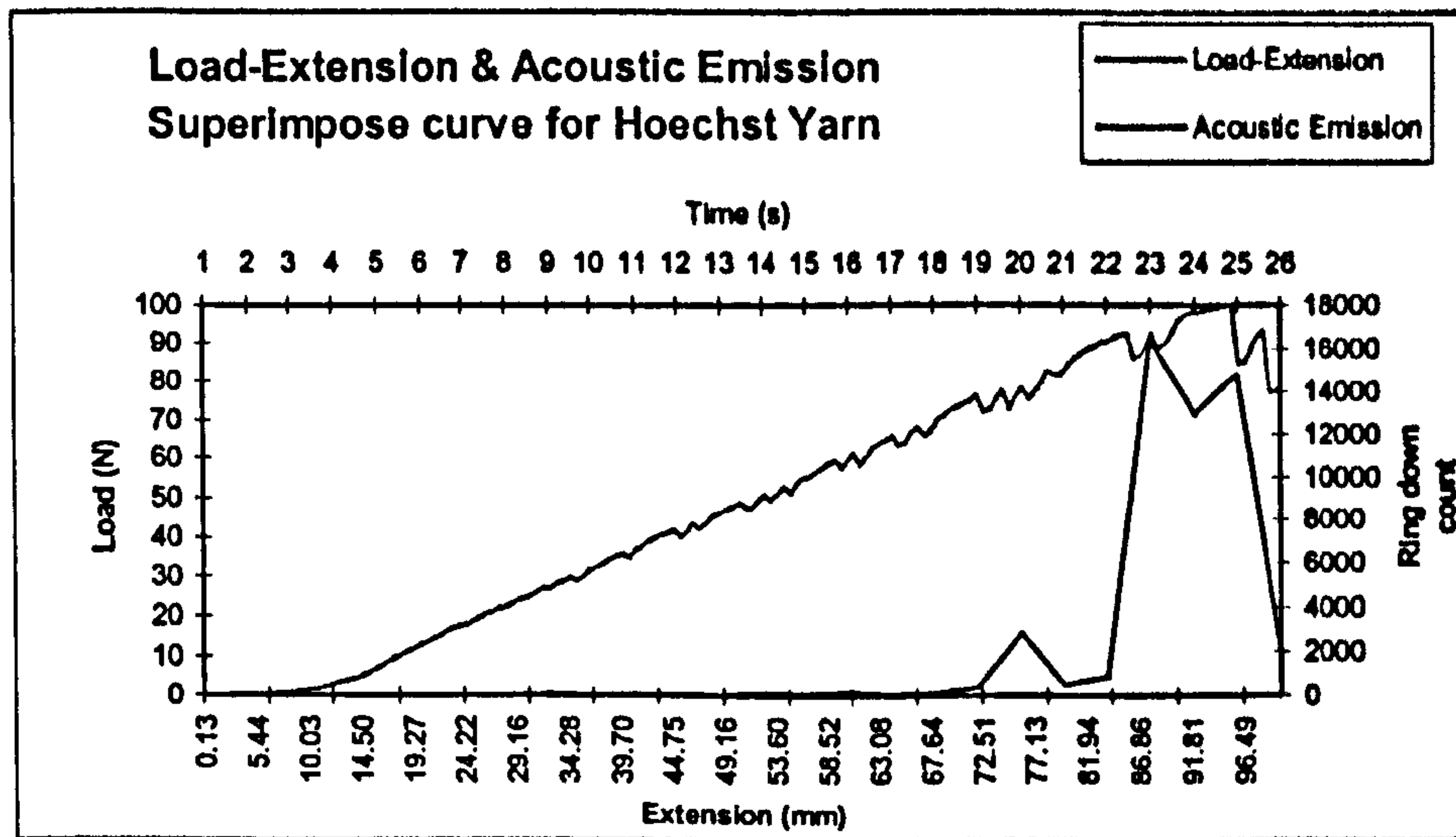


Figure 5.42: The relationship between the load-extension & AE emission.

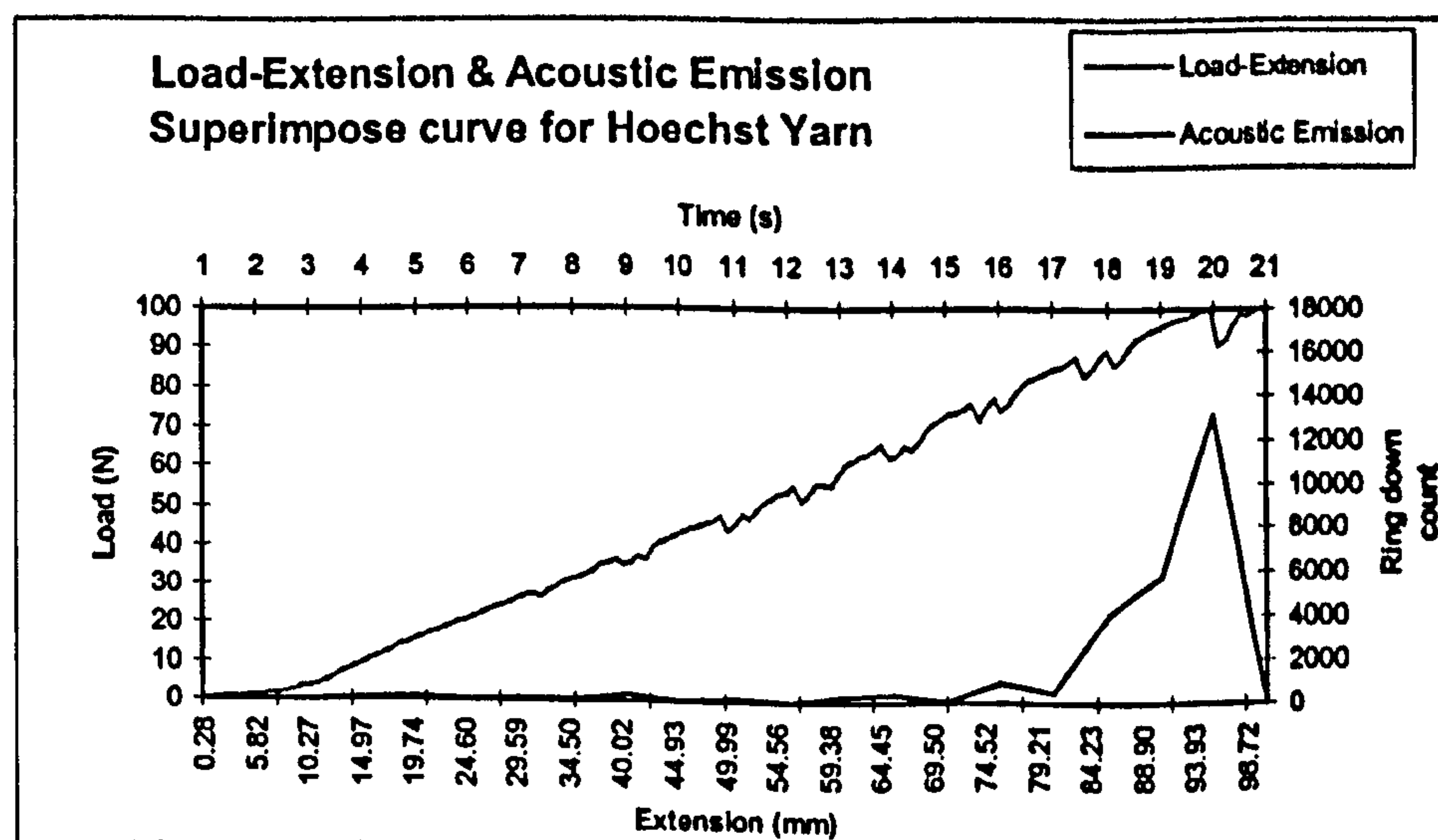


Figure 5.43: The relationship between the load-extension & AE emission.

5.5.4 AE from 18mm Sub-rope

The Parafil socket registered the highest ring-down counts in Akzo and it is 42% higher than splice and 4% higher than the Stress Relief Socket. However, the ring-down counts in the Stress Relief Socket have the highest value in Hoechst. It is 79% higher than the splice and 25% higher than the Parafil socket. The onset of AE is fairly similar in all samples.

The following points were observed from the above-mentioned results:

- 1- The onset of the AE signal is detected slightly later in the Parafil and the stress relief socket compared with the splice. Early detection of the AE signal in the splice termination, compared with others, indicated that some filaments in the splice termination failed before final break compared with the socket. Considering the termination types and the breaking features of the rope in different terminations, it is expected to have such behaviour because the partial failure is more likely to happen in the splice termination compared with others.
- 2- The onset of the AE signal is detected slightly later in Hoechst compared with Akzo.
- 3- More ring-down count was observed in the Parafil and the Stress Relief Socket compared with the splice. The splice termination inherently provides a more uniform load transfer than the socket termination. Also the partial failure of the splice would produce lower AE levels than the rope with socket termination.

5.5.5 AE from 44mm Viking7 rope

Typical results of ring down counts for the Akzo and Hoechst 44mm viking7 ropes in the Stress Relief terminations are graphically shown in Figures 5.44 - 5.45. In this section results of Akzo in the splice, normal and stress relief sockets and Hoechst in the stress relief socket are examined. Three Akzo samples in different terminations were compared and ring-down counts in the stress relief socket was 38% higher than the Parafil and 49% higher than the splice. The onset of AE was fairly similar for the three samples.

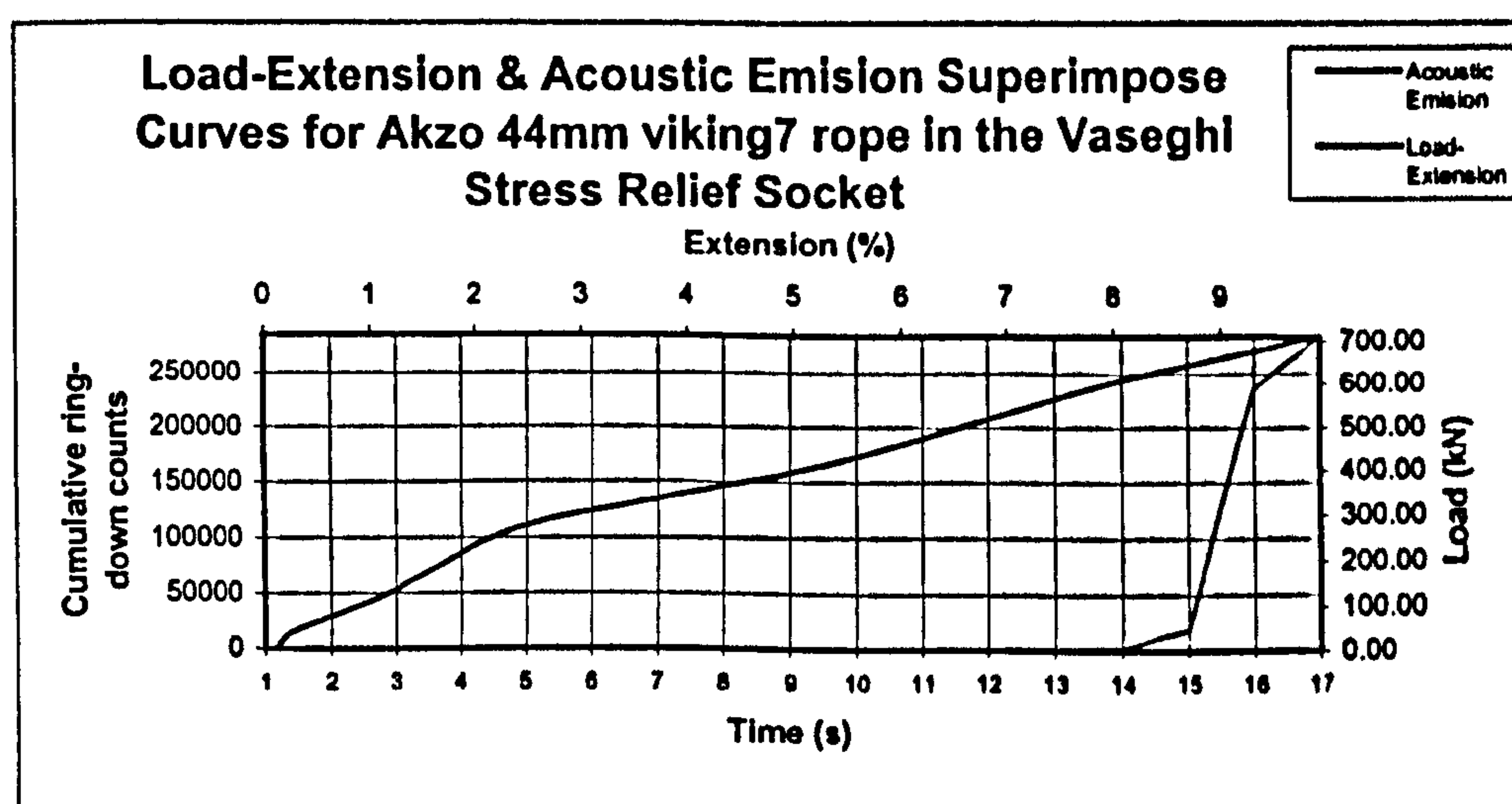


Figure 5.44: Load-Extension and Acoustic Emission superimpose curves for 44mm Akzo Viking7 rope tested in the Stress Relief Socket.

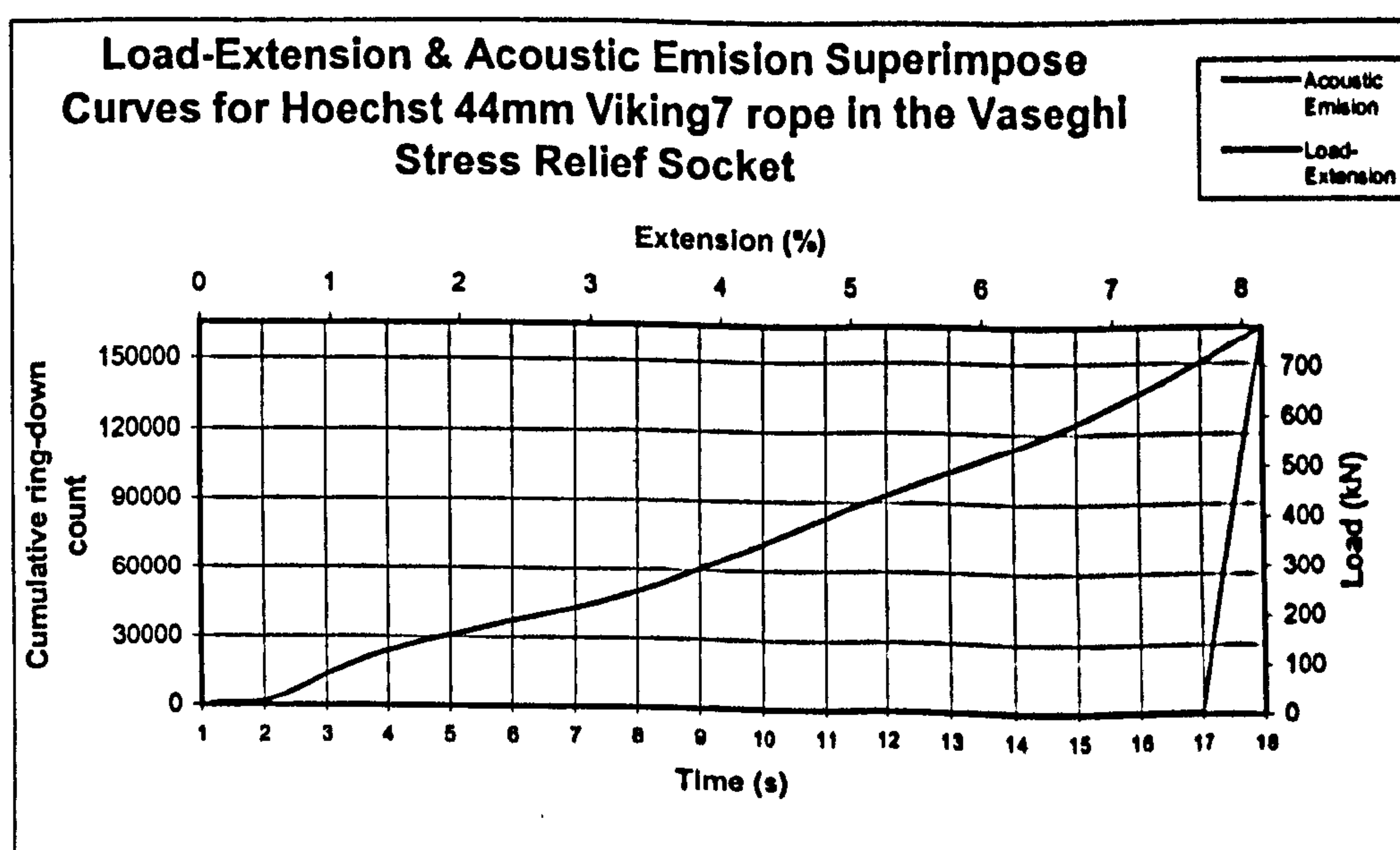


Figure 5.45: Load-Extension and Acoustic Emission superimpose curves for 44mm Hoechst Viking7 rope tested in the Stress Relief Socket.

The following comments are made on the basis of the above-mentioned results:

- 1- The highest value of ring-down counting appeared in the Hoechst material in the Stress Relief Socket. Higher breaking load could lead to higher AE ring down counting as observed in this test. However, this result was not repeated for the Hoechst material. Although the AE signal could be a good method to detect the rope behaviour under tensile load, but the results are not always correlated to the breaking load of the rope due to faults in sensors.
- 2- The onset of the AE graph for the spliced sample start from higher numbers compared with the normal and the stress relief sockets. It seems that some filaments started to break in the early stage of load application, and the number of these filaments is higher than those in the socket termination. This may be the reason for the high ring down counting in the early stage of load application in the splice.

5.5.6 Conclusion

It appears to be difficult to relate the AE signals to the terminations' type. Acoustic Emission gives some indication about breaking of the rope and the possibility of premature failure but it is not easy to evaluate termination performance for a rope using the AE signals. Koohgilani, 1998 proved that material type could not give an accurate difference in AE signals.

5.6 Finite element modelling process

Changes in geometry and extra material, used in the Stress Relief Socket, were based on some assumptions and practical experiences. Perhaps the amount of material used was the maximum in terms of safety and accuracy, but there was no optimum figure to be established, based on scientific data.

Finite element analysis was done to find stress concentration areas in the socket and if it was possible to optimise the amount of material to reach the maximum result. Also it was tried to establish a relationship between the experimental and the simulated results.

The initial objective was to find the stress concentration areas in the socket using the load applied to the socket by the rope. The stress concentration areas in the rope had to be studied in the following step.

Two methods were considered for the starting point of the work:

5.6.1 Three-dimensional socket

I) Solid Model

AutoCAD software was used to model the solid socket. A probe was inserted into the barrel or traversed around the spike, and touched against four points on the circumference; these coordinates were then used to calculate the centre of the circle and the radius. This was repeated at various sections along the length to build up the total geometry. The solid model was assembled in ANSYS (Figure 5.46) using the model made in AutoCAD. In order to achieve this, the cross section of socket in Z direction was rotated and then the extra volume and clevis pin, in the back, was subtracted.

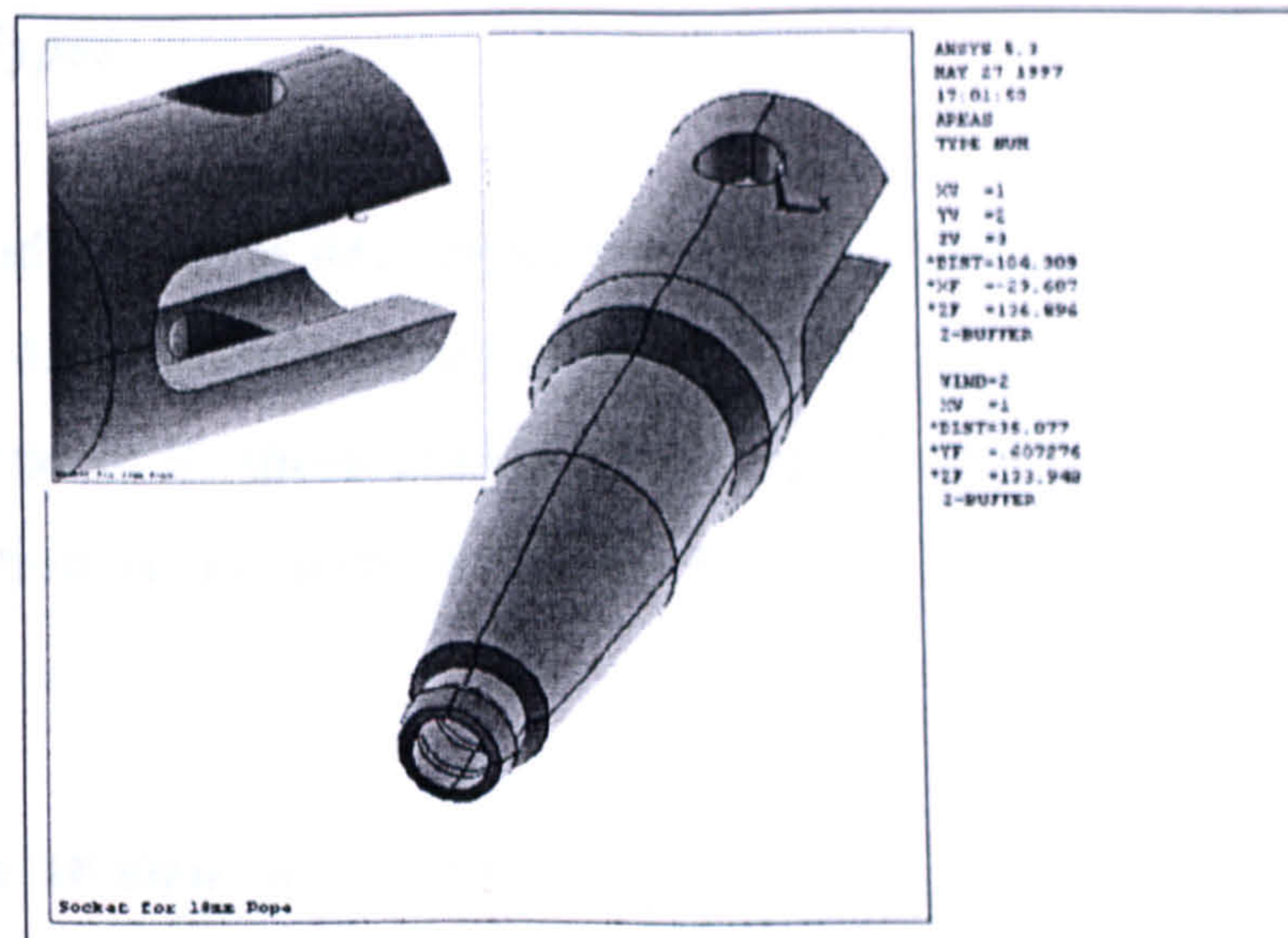


Figure 5.46: 100 kN Parafil socket modelled in ANSYS.

II) Approach

The basic concept was to replace a solid continuum with a mesh of small elements. The mesh was coarse at areas of low stress concentration to save on computation. This was refined to a fine mesh at areas of high stress concentration to facilitate convergence to the true stresses.

III) Meshing

Ansys software has two general options in meshing. 1. Mapped Meshing and 2. Free meshing. Mapped meshing was found to make the best fit regarding the shape of the model in the cylindrical parts. Mapped meshing was used for volumes that had either three or four sides. If a surface or section has more than three or four sides, you can use the Mapped Meshing Options form to create composite sides.

- A three-sided surface or section must have an equal number of elements on any two of the opposite sides.
- A four-sided surface or section must have an equal number of elements on one pair of opposite sides, but may have an equal or unequal number on the other pair of opposite sides.

IV) Mesh Types

- **Bricks - Solid elements 45:** Bricks element 45 and 95 were compared. Although bricks element 45 had less accuracy compared with 95 that has mid-side nodes, it was preferred because of its speed in solving the model (Figure 5.47). Furthermore if the meshing selection is not suitable for the model, it gives a warning to change the method.

- **Tetrahydran 10 elements:** Mapped meshing could not be applied to the back part of the socket because of its complex shape. The option was to find out some pre-defined element type and try to mesh the rest of the model. Tetrahydran-10-nodes with rotation was recognised to be suitable for the model. The way, of finding the best element type for the model, is by trial and error although previous experience could be very important. The software did not accept some of the element type because it could not be fitted to the model.

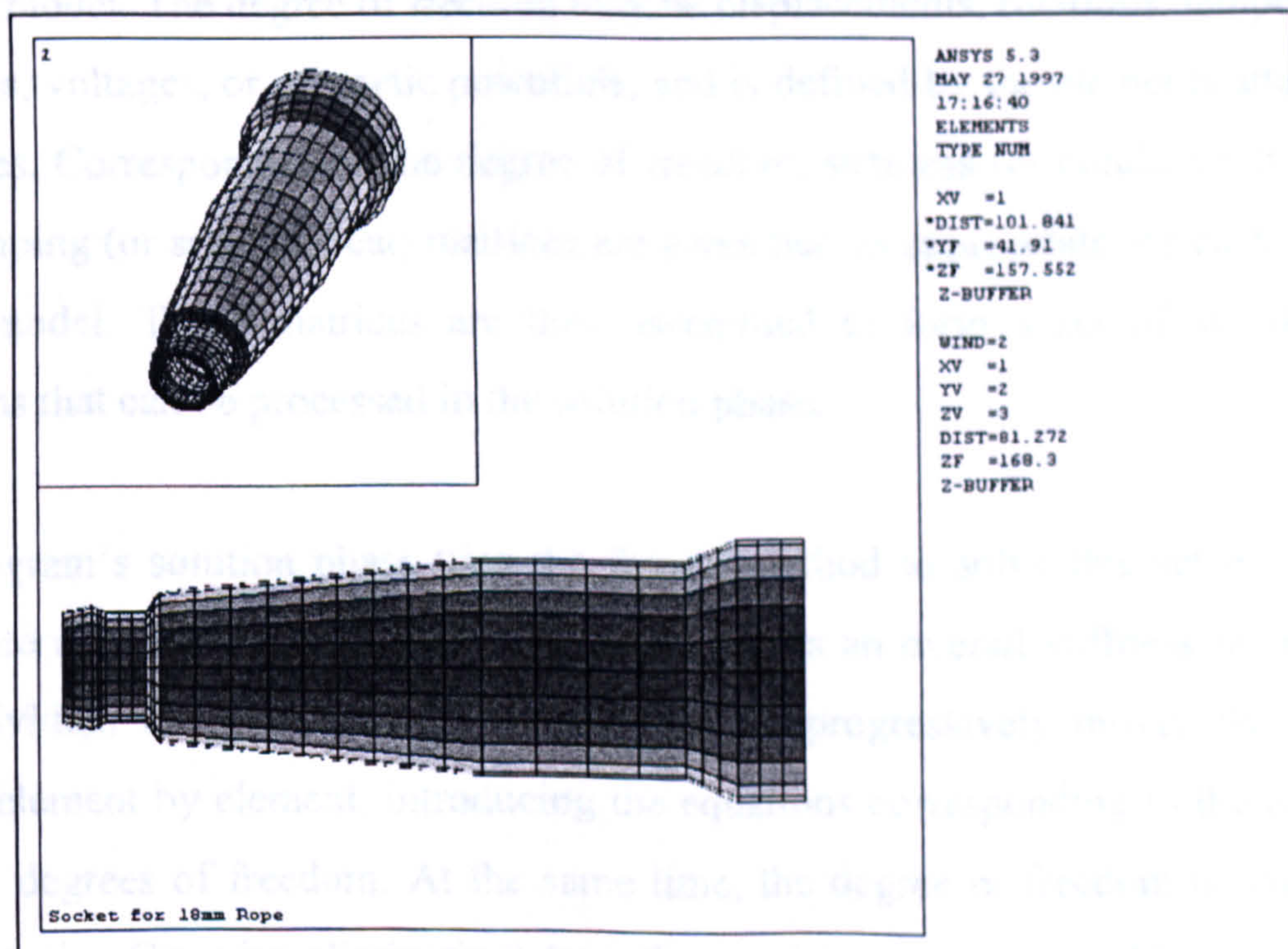


Figure 5.47: Solid element 45 - Bricks meshing for front part of socket in ANSYS.

V) Solution

The solution is the phase of analysis in which the computer takes over and solves the simultaneous equations generated by the finite element method. The results of the solution are: (a) nodal degree-of-freedom values, which form the primary solution, and (b) derived values, which form the element solution. The element solution is usually calculated at the elements' integration points.

All ANSYS analysis types are based on classical engineering concepts. Through proven numerical techniques, these concepts can be formulated into matrix equations that are suitable for analysis using the finite element method.

The system to be analysed is represented by a mathematical model consisting of discrete regions (elements) connected at a finite number of points (nodes). The primary unknowns in an analysis are the degree of freedom for each node in the finite element model. The degree of freedom may be displacements, rotations, temperatures, pressures, voltages, or magnetic potentials, and is defined by the elements attached to the nodes. Corresponding to the degree of freedom, stiffness (or conductivity), mass, and damping (or specific heat) matrices are generated as appropriate for each element in the model. These matrices are then assembled to form a set of simultaneous equations that can be processed in the solution phase.

The program's solution phase uses the frontal method to solve this set of equation procedure and simultaneously assembles and solves an overall stiffness matrix from the individual element matrices. This procedure progressively moves through the model, element by element, introducing the equations corresponding to the particular element degrees of freedom. At the same time, the degree of freedom is solved and deleted (using Gaussian elimination) from the matrix as soon as possible.

In the ANSYS program, the frontal solver is further improved by incorporation of Rank-n logic. Rank-n logic allows parallel processing to be used at the system level, since the degree of freedom is solved for in groups, rather than individually. By varying the size of the degree-of-freedom group, (the "n" in Rank-n), the ANSYS

program can be tuned by each hardware vendor for optimum performance on their machines.

The degree of freedom set present in the assembled matrix is known as the wavefront, which expands and contracts as degrees of freedom are introduced to and deleted from the matrix. After the wave-front has passed through all the elements and the response of each degree of freedom has been computed, post-processing functions can be used to display integrated results for the entire model.

Each analysis type in the ANSYS program is based on a governing equation constructed by using an appropriate mathematical relation of the stiffness, mass, and damping matrices.

VI) Loading Volume:

The word Load in ANSYS terminology includes boundary conditions and externally or internally applied forcing functions. Examples of load in structural disciplines, which is applied here, are as follow:

Displacement, forces, pressure, temperatures (for thermal energy), gravity

For this model, the contact area of the socket and the spike was considered to be the loading area. To find out the contact area, it was needed to calculate where the spike stopped inside the socket. It is valid to say that the spike stopped inside the socket when socket internal angle was the same as the spike back-end thickness. To measure the contact area, ANSYS needed to know Y_1 & Y_2 and Z_1 & Z_2 where Y & Z are displacements from the axis (Figure 5.48).

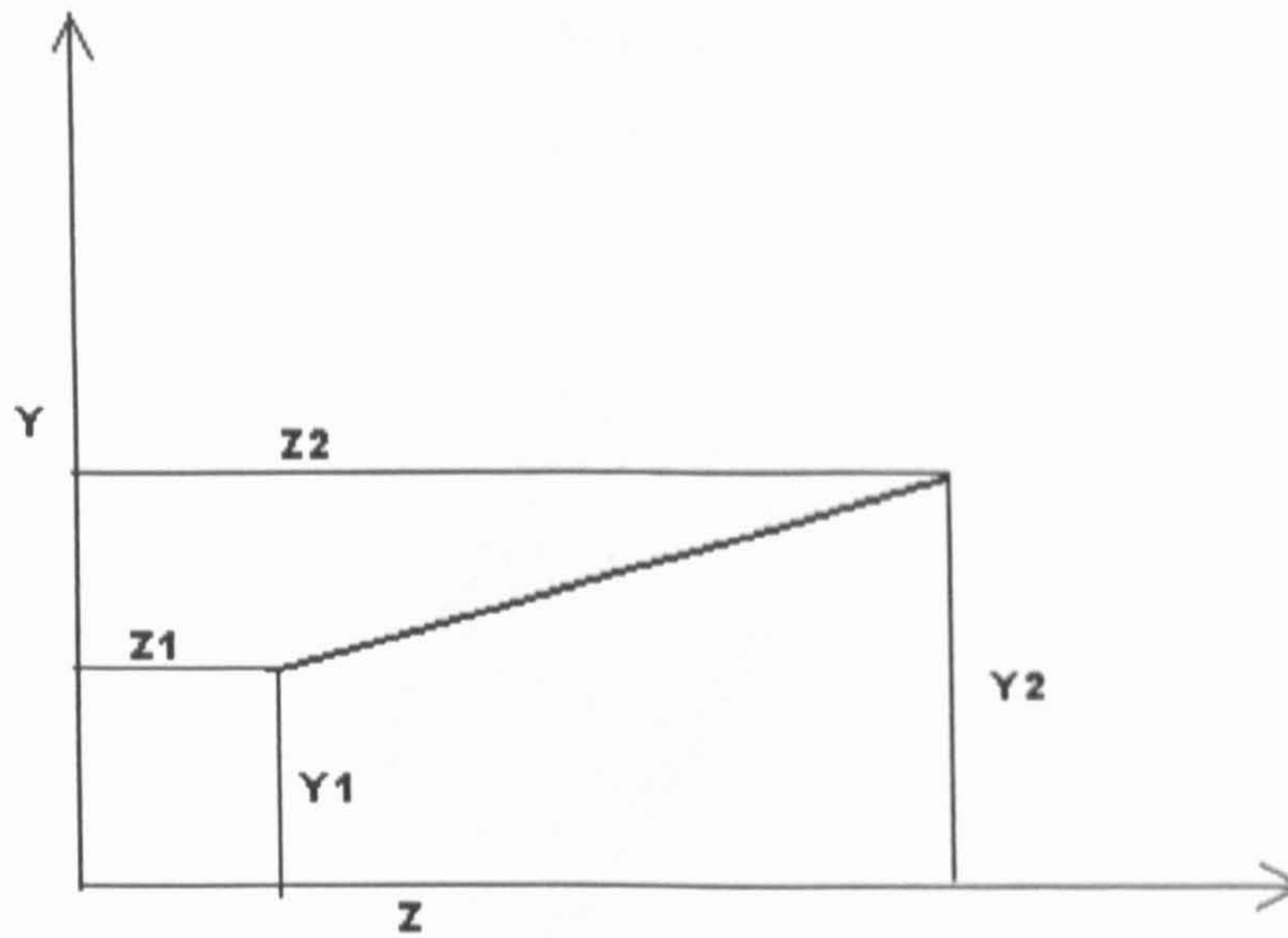


Figure 5.48: Measured dimensions to determine socket loading area in ANSYS .

$Z_1 = 126.17 \text{ mm}$ $Z_2 = 221.17$
 $Y_1 = 9.52 \text{ mm}$ – $Y_2 = 14.5 \text{ mm}$

Then contact area is being made by rotating the loading line around the X axis (Figure 5.49).

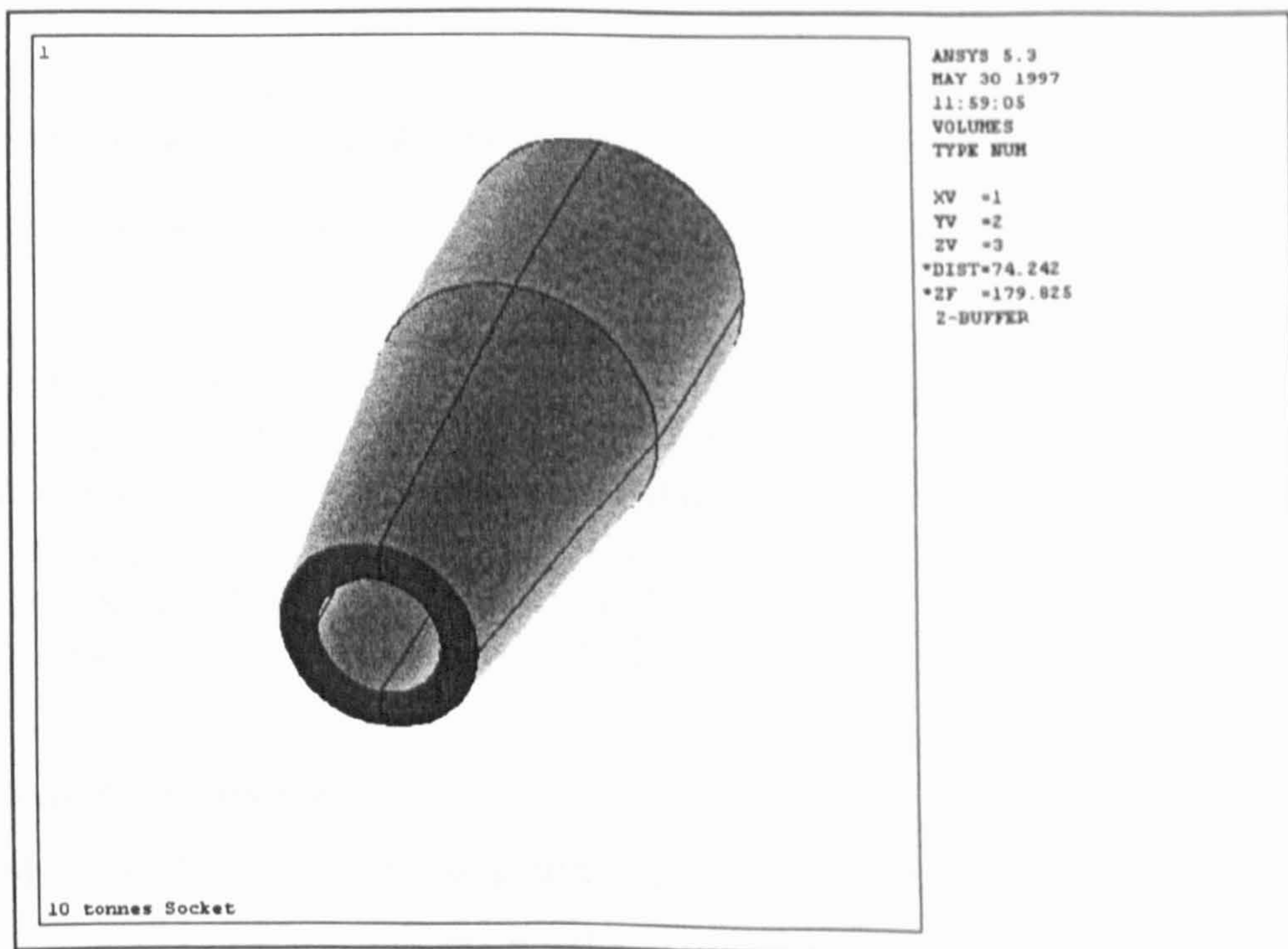


Figure 5.49: Loading volume made by ANSYS using rotation of loading line (Figure 5.31) around x axis.

Calculation of the loading node was done using the bricks meshing of the loading volume. The loading area was meshed to 1080 bricks elements and the internal surface had 336 nodes in contact with the load (Figure 5.50).

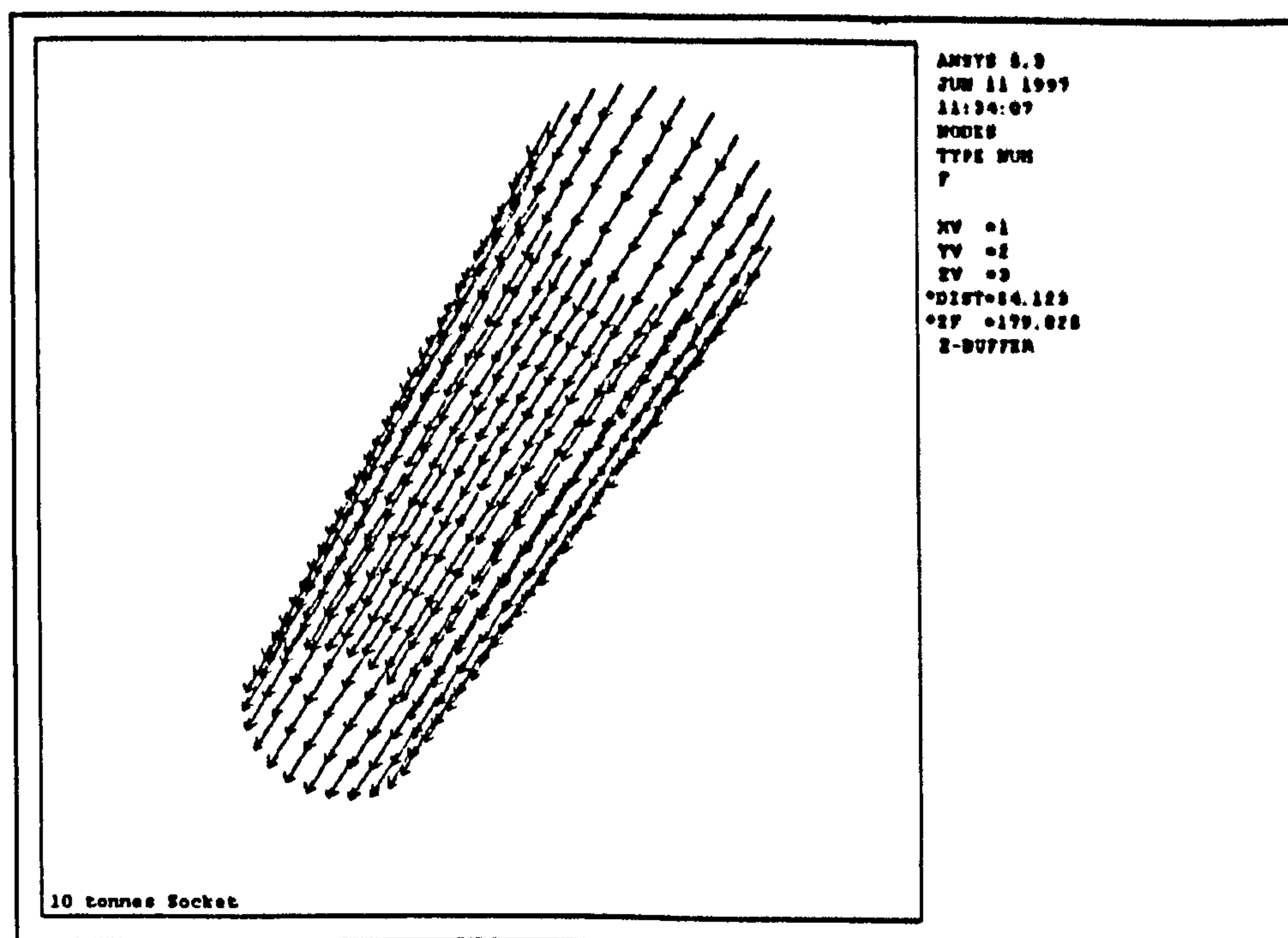


Figure 5.50: Load diagram applied to internal nodes of loading volume in socket model in ANSYS.

To solve the model, the material specification has to be applied. The following specification was known to be the best fit for the socket and tube material "steel":

Young Modulus (EX)	= 19300000000 N/m ²
Shear Modulus (EX)	= 72375 N/m ²
Density (DENS)	= 8030 Kg/m ³
Poisson's ratio (NUXY)	= 0.29
Thermal conductivity (KXX)	= 16.3
Specific heat (c)	= 502

VII) Boundary Conditions

Zero displacement was chosen as a boundary condition to solve the model. This was because the socket was fixed in the tensile machine in the pin area.

VIII) Solution (Contour Plots of Stress)

ANSYS takes the boundary condition and material characteristic to solve the model (Figure 5.51).

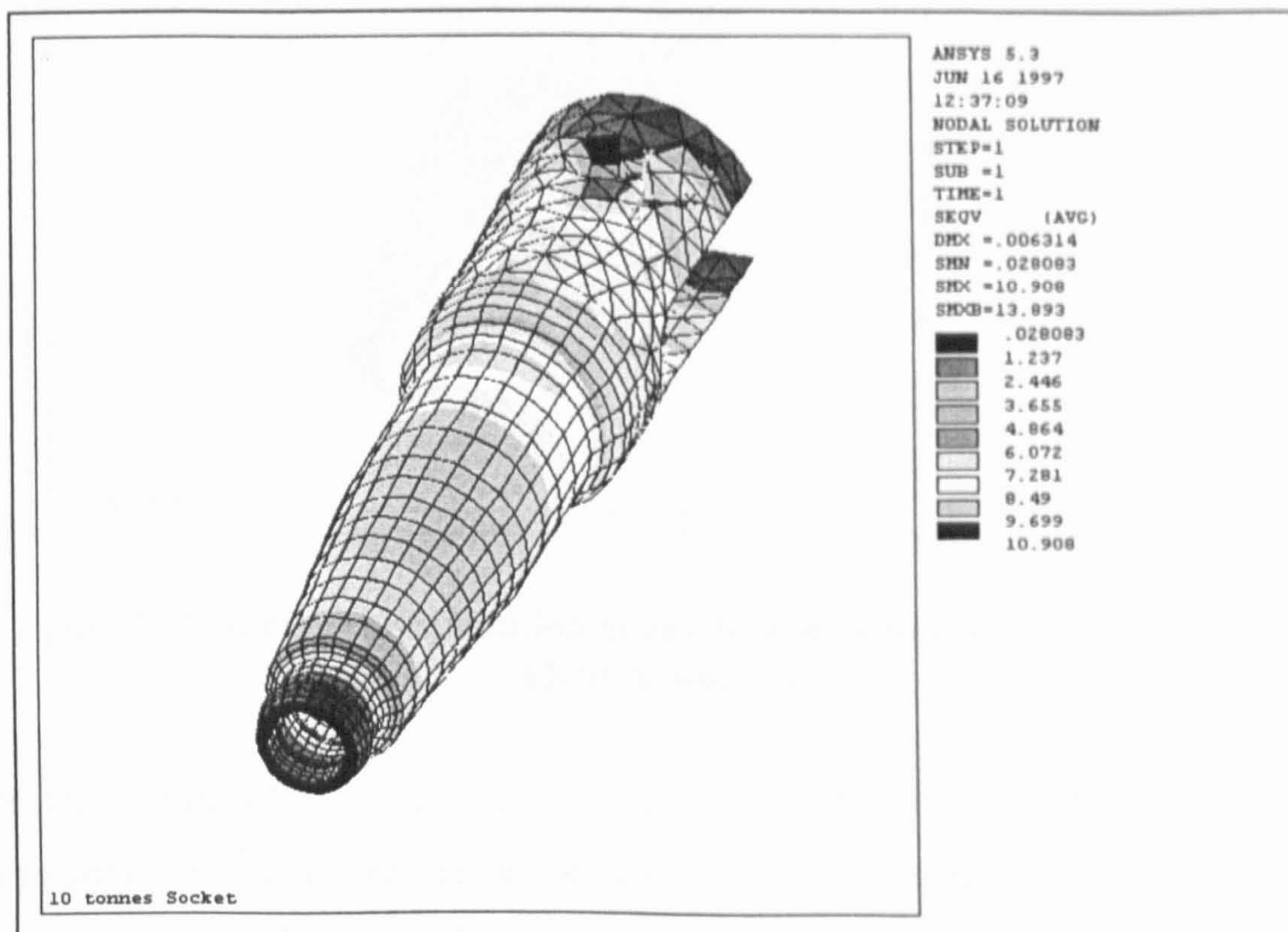


Figure 5.51: Solution on the basis of three-dimension socket.

On loading to failure, maximum tension was present in the contact area of the termination with the clevis pin. Maximum compression appeared to be on the back end and also nose to the socket (Figure 5.51). It is clear when the load was applied to the rope, socket is pulled forward. The clevis pin prevents the socket to move. Therefore contact points between socket and pin is compressed. Another area that has compression force is the nose of the socket. The load applied to the rope is transferred to the spike and the spike is trying to pull out and compress the socket nose.

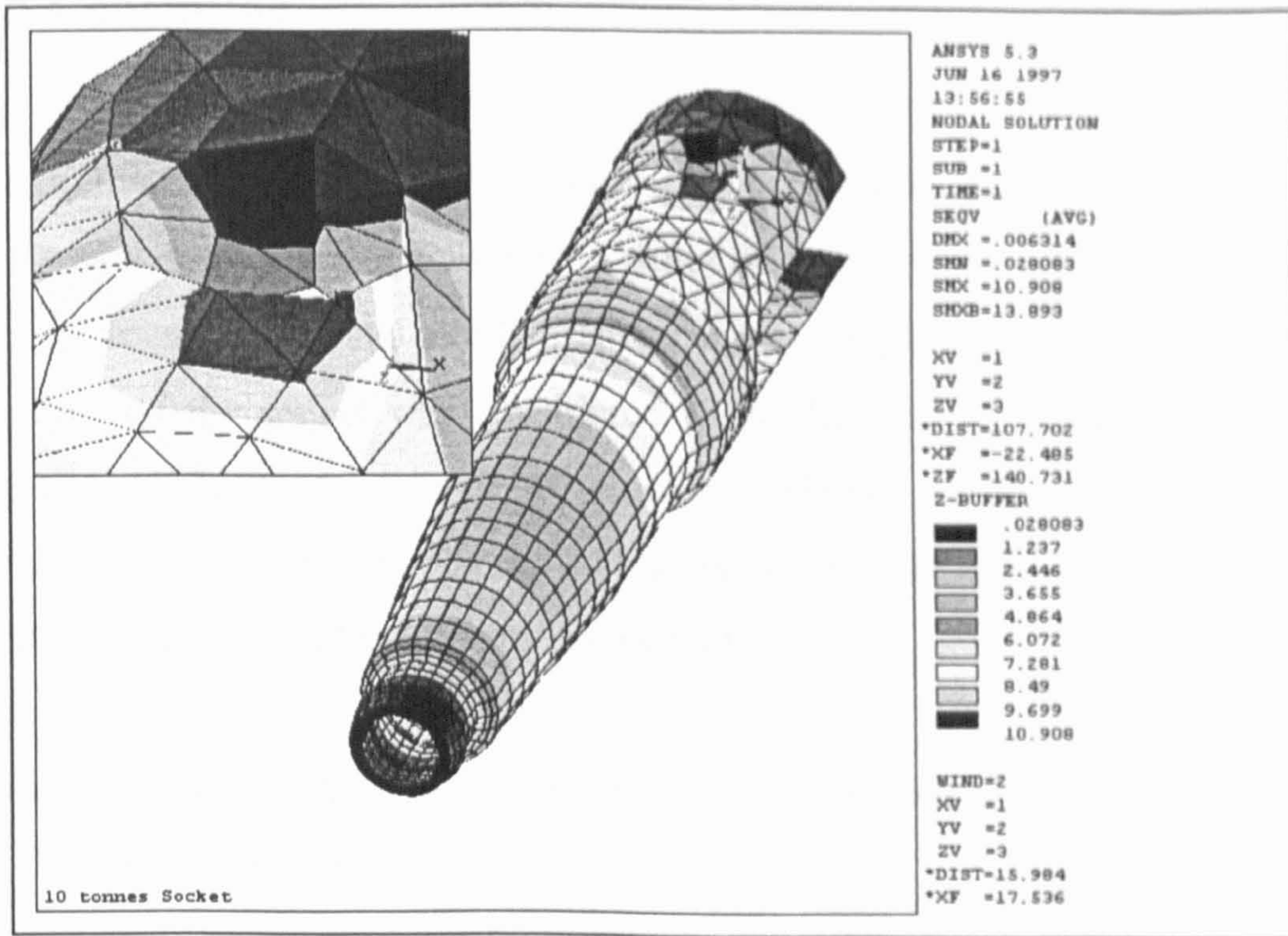


Figure 5.52: Stress concentration areas demonstrated around clevis pin in ANSYS solution.

To test the results of the finite element solution, the following operations were done: The relative stress between the yellow and orange area in figure 5.52 was counted to be 8.49 N/mm² in the finite element solution. This area was made of two radii r_0 , r_i which are $r_0 = 15.5\text{mm}$, $r_i = 25.0\text{mm}$. Then the area was calculated $A = \pi (r_0 + r_i)(r_0 - r_i) = 1208.7 \text{ mm}^2$

The relative stress in this area considering the 10000 N force applied was counted:

$$\sigma = F/A = 10000/1208.7 = 8.27 \text{ N/mm}^2$$

This simple calculation showed that the result from the finite element solution was comparable with what was counted manually.

5.6.2 Conclusion

Based on the three-dimensional socket, the model was developed. In the first part the socket was modelled using drawings in AutoCAD. Then the socket was meshed using bricks for regular parts and tetrahedran for more complex areas. The contact area of the spike and the socket was considered to be the loading surface. Minimum and maximum loads (rope breaking) were considered to represent the boundary conditions. The nodal solution gave reasonable results compared with what was predicted on the basis of the theoretical concepts.

The finite element method on a joint structure of the socket and the rope could give the following useful information:

- 1- The high stress concentration areas are predictable and improvement could be concentrated on those areas.
- 2- The critical amount of extra material could be predicted by stress values from finite element results.
- 3- Critical areas in the socket could be identified.

Chapter 6: Summary and recommendations

Traditional methods of rope termination for heavy-duty ropes in marine environments lead to premature failure due to high stress concentration areas around the termination. This always restricts the rope breaking load and leads to early failure.

A new method of termination, the “Stress Relief Socket”, is introduced to improve high stress concentration areas inside the termination, so as to increase the tensile strength of the rope. The Stress Relief Socket improved rope performance up to 13% compared with the traditional methods.

The Stress Relief Socket is based on reinforcing the rope inside the termination using extra material. Inserting extra material inside the rope caused great improvement in tensile properties and moved the breaking point along the rope. Previously, ropes mostly broke inside or near the termination. Having a clear break along the rope supports the idea of maximum breaking load using the Stress Relief Socket. It is believed that a rope will reach its maximum tensile capacity if load is separated equally between all sub-ropes. If all sub-ropes break simultaneously, the rope has achieved its best loading strength.

To support the findings of the tensile tests, two methods of cycling test were performed on samples terminated by the Stress Relief Socket. It was proved that termination had no adverse effect to cycling performance of the rope, and the residual strength was the same as what was achieved in tensile tests.

The acoustic emission was performed to investigate the relationship of rope termination and AE signals. It was found that very little links could be found between AE signals in rope tensile tests using different terminations.

The finite element modelling was done to find out the high stress concentration areas in the Stress Relief Socket. Result showed socket need to be reinforced around clevis pin. Basically the most concentrated load areas are around connection point with tensile machine or in general where socket is tied with any other external body.

The Stress Relief Socket proved a novel method for a new generation of socket termination for heavy duty ropes in marine environments. Although the new method proved superior in terms of tensile and cycling performance, theoretical and scientific background of this method should be further investigated to be an acceptable method of termination for high duty ropes in marine environments, specially mooring systems.

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Chapter 8: Appendixes

- 1- Registered patent specification UK 2 313 853
- 2- Registered patent specification US 5,904,438
- 3- Detailed designed resulting from above mentioned patents.



(12) UK Patent (19) GB (11) 2 313 853 (13) B

(54) Title of Invention

A method of terminating a fibre rope

(51) INT CL⁷; F16G 11/05

(21) Application No
9711830.1

(22) Date of filing
06.06.1997

(30) Priority Data

(31) 9611976.3

(32) 07.06.1996

(33) GB

(43) Application published
10.12.1997

(45) Patent published
20.12.2000

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(52) Domestic classification
(Edition R)
D1T T3B2

(56) Documents cited
GB2281318 A
GB2279972 A
US4760991 A
US4184784 A

(58) Field of search

As for published application
2313853 A viz:
UK CL(Edition O) D1T
INT CL⁷ F16G
Online: WPI
updated as appropriate

1/3

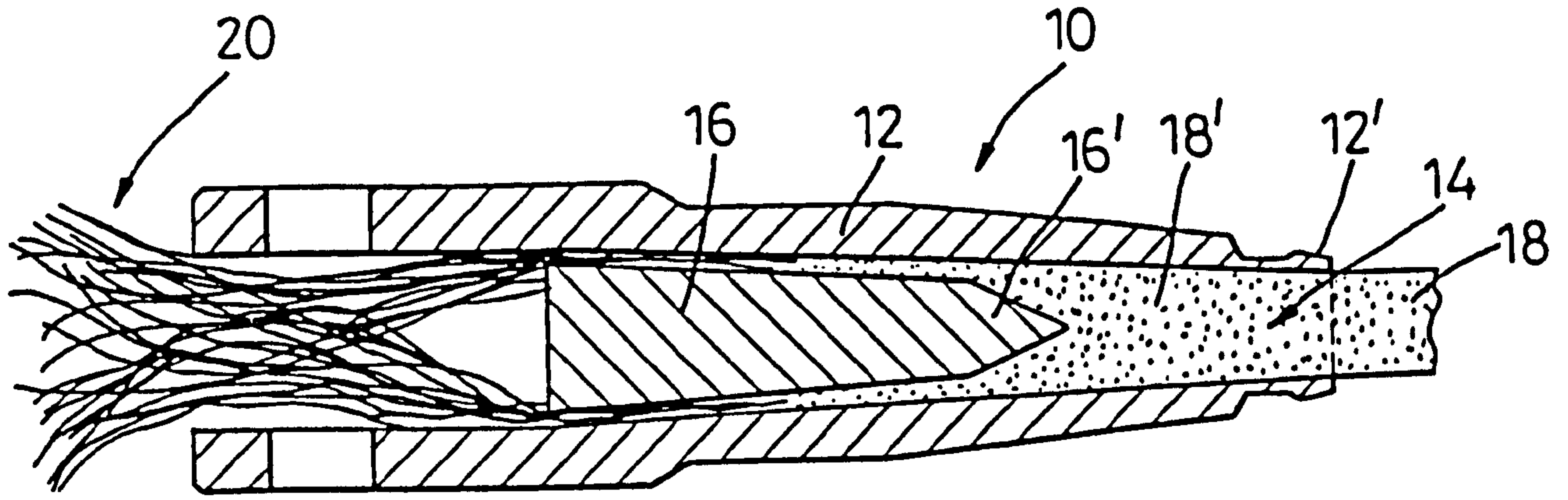


Fig. 1

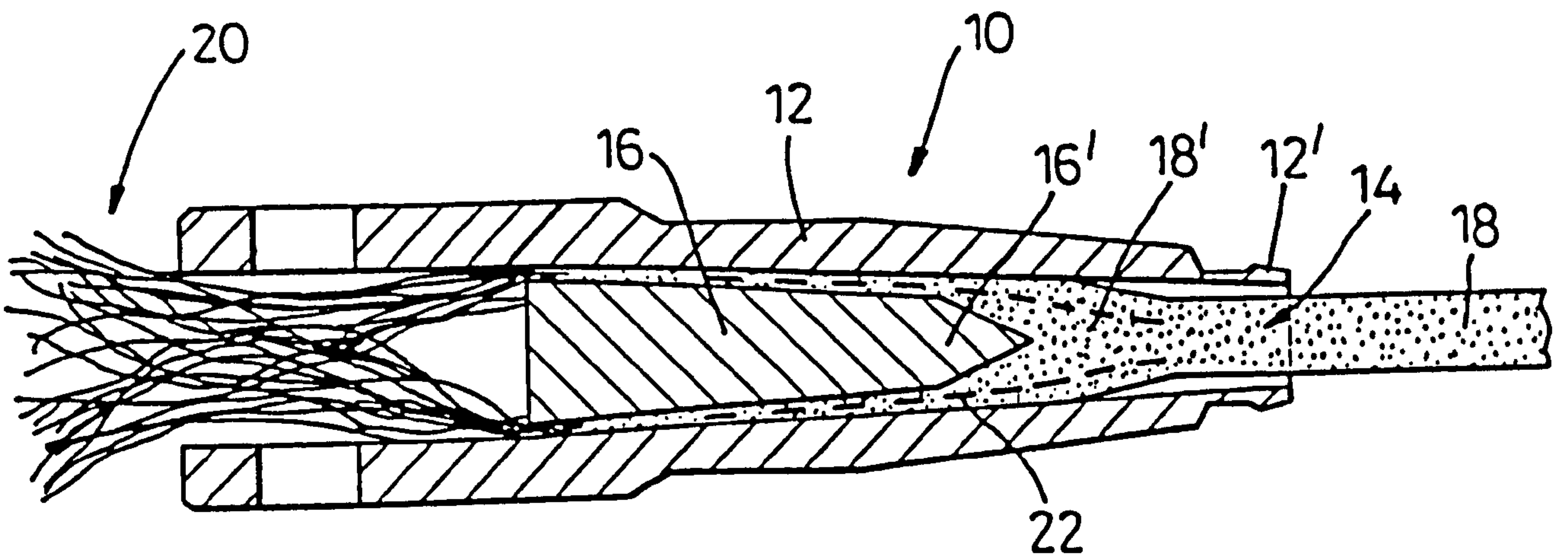


Fig. 2a

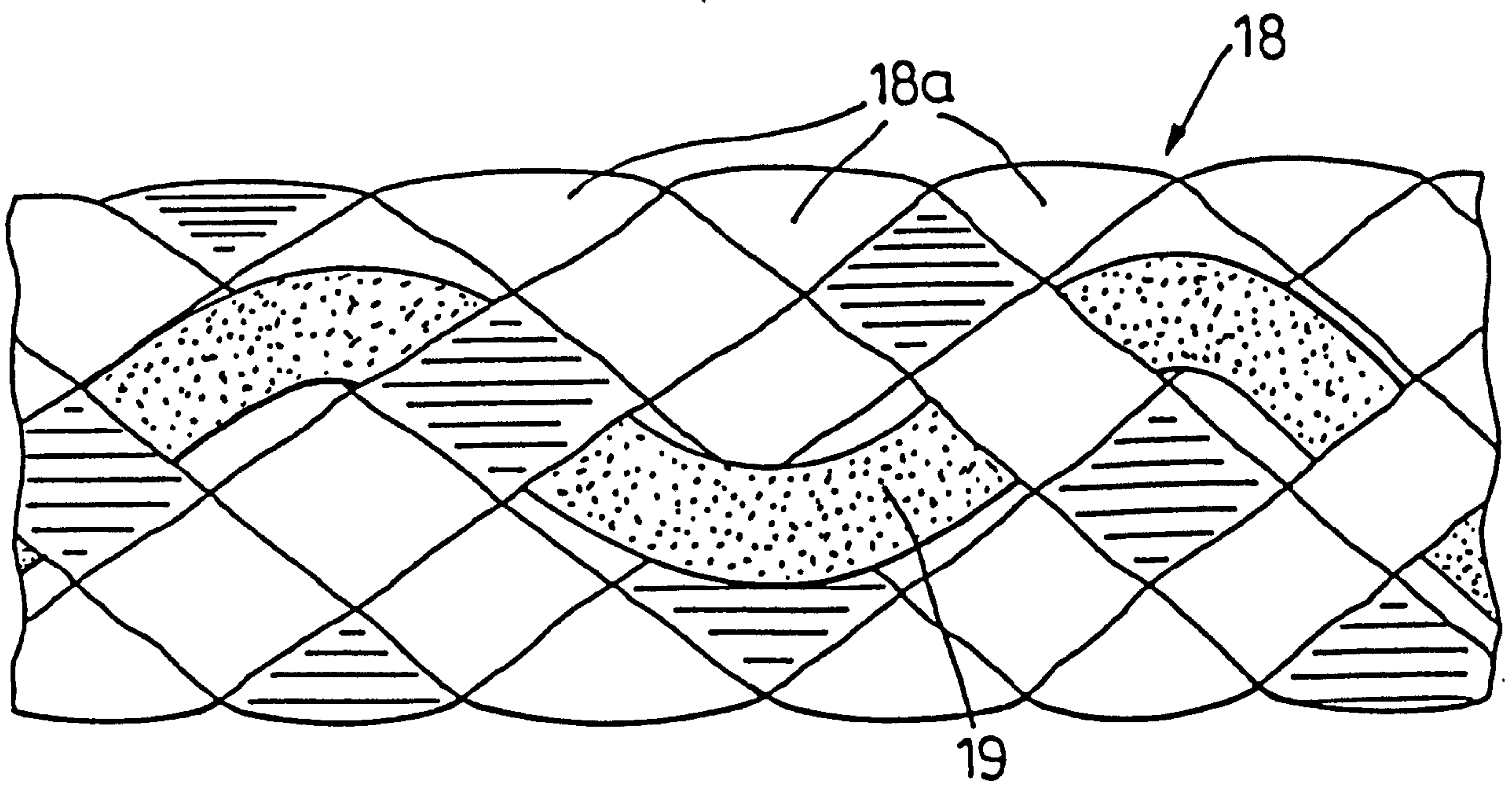


Fig. 2b

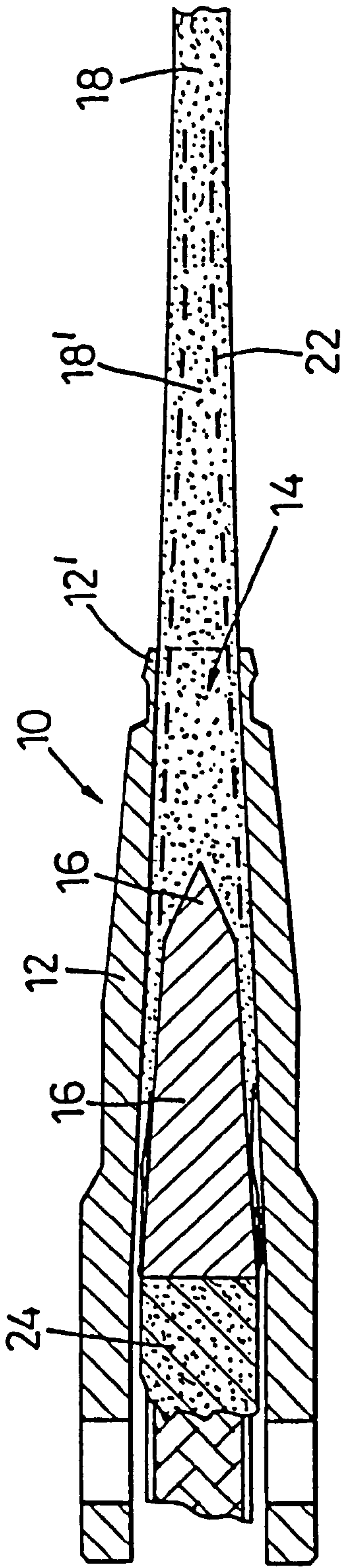


Fig. 3

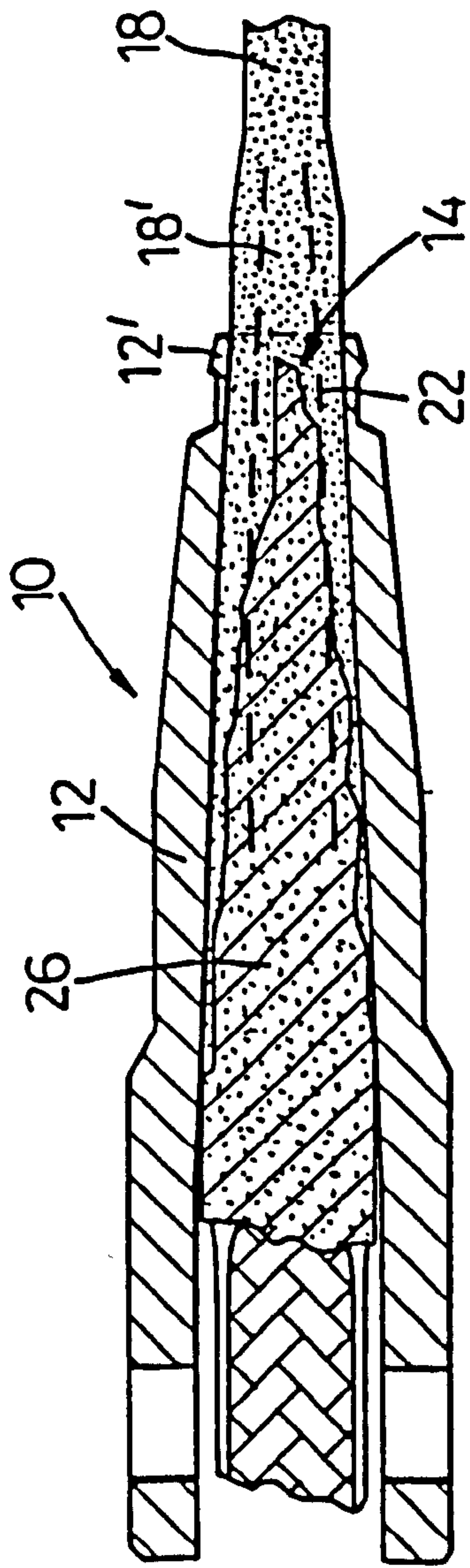


Fig. 4

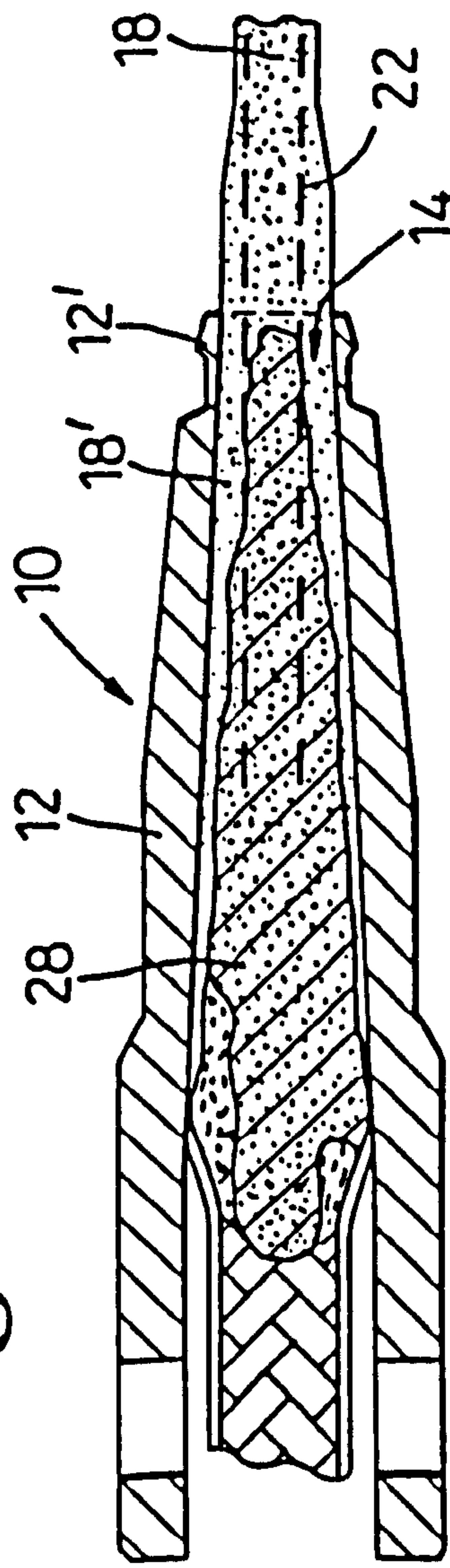


Fig. 5

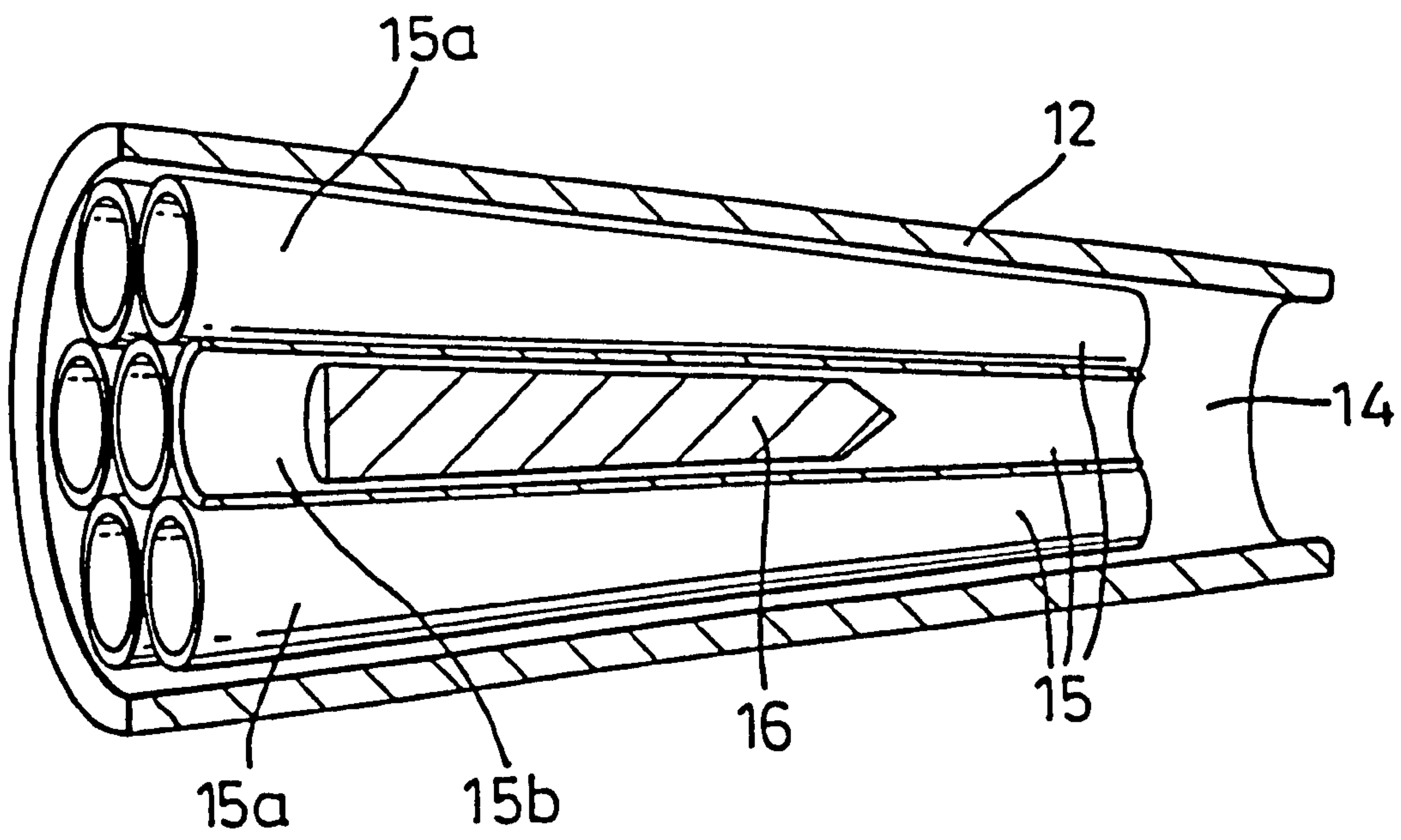


Fig. 6

2313853

1

A METHOD OF TERMINATING A FIBRE ROPE

The present invention relates to a method of terminating a fibre rope utilising a device of the type comprising a housing member having a generally frusto-
5 conical bore in which an end portion of the rope can be wedgedly retained.

It is known from GB 1 341 013 to terminate a fibre rope using a device of the abovementioned type. A conically shaped wedge member locates within the frusto-conical bore
10 of the housing member to wedgedly trap fibres of the end portion of the rope within the bore of the housing member thus terminating the rope. The housing member includes means for attaching it to an anchorage, for example.

It has been found with this method of terminating a
15 rope that there is a tendency for the fibres of the rope end portion to abrade. Abrasion of the fibres occurs mainly in the region where the fibres contact an apex part of the conically shaped wedge member, although abrasion may also occur at a narrow mouth part of the housing member
20 through which the terminated rope extends. The abrasion of the rope fibres substantially reduces the breaking strength of the rope.

A method of overcoming this problem is suggested in GB
2 236 546 in which the fibres of the rope end portion are
25 treated with a resin composition. The resin composition is employed to provide a lubricating effect on the fibres to reduce abrasion thereof around the apex part of the conically shaped wedge member. Despite this, the combination of tensile load exerted on the rope and the

stress induced in the constituent fibres of the rope end portion by the crushing action of the wedge member results in tensile failure of the rope at a point generally in a region extending from around the apex part of the wedge member to the narrow mouth part of the housing member.

US-A-4 184 784 discloses a method of terminating a braided fibre rope of small diameter. The rope has a diameter of approximately $1/10^{\text{th}}$ inches (0.25cm) and is combined with a plurality of parallel sections of such rope to be terminated in a single collar having a tapered interior channel. The collar is passed over the ends of the plurality of rope and each rope has a short tapered section of rope of the same material inserted in its braided core as a means of thickening its end. The thickened ends of the plurality of parallel rope sections are separated ("fuzzed") into their individual fibres and a tube having a tapered outer surface is located therebetween. The tube is drawn into the collar by a centering tool and tightly wedges the "fuzzed" parts plus a significant part of the braided lengths of the ropes between the tube and collar. This method is applied to the termination of bundles of very small diameter braided fibre ropes in a single termination device, said terminated bundles of ropes being employed to keep tensile loads from conductors in underwater cables. This method is not suitable for terminating layer diameter fibre ropes because their structures are more resistant to the compression necessary to secure the rope ends between the collar and tube. It will be appreciated from the disclosure of US-A-4

184 784 that the amount of surface contact between each rope end and the surfaces of the channel and tube is restricted.

5 It is an object of the present invention to obviate or mitigate the aforesaid problems associated with the prior art methods of terminating a fibre rope.

10 It is a further object of the present invention to provide a method of terminating a fibre rope having a diameter in the order of 1 inch (2.5cm) or larger fibre ropes of this and much larger diameters are employed in marine applications when light weight but high tensile strength is required.

15 According to a first aspect of the present invention there is provided a method of terminating a fibre rope, comprising the steps of:- introducing into or incorporating in an end portion of the rope a reinforcing portion of fibre rope; locating said reinforced rope end portion in a generally frusto-conical bore of a housing member; and
20 securing said reinforced rope end portion in said housing member bore, wherein the method includes introducing or incorporating the reinforcing portion of fibre rope into less than the entire length of said rope by splicing a number of the strands of the portion of the reinforcing rope with a number of strands comprising the rope end
25 portion so as to increase a tension load capacity of said rope end portion.

According to a second aspect of the present invention there is provided a rope terminated using a device comprising a housing
30 member having a generally frusto-conical bore by a method in accordance with the first aspect of the invention.

Advantageously, the method in accordance with the first aspect of the invention also comprises of the following: - passing said rope end portion through the bore of the housing member prior to introducing
5 into or incorporating in it the reinforcing means; and drawing said rope end portion back towards the housing member bore to locate it therein.

Further features of the present invention are set out in the
10 appended claims.

The foregoing and further features on the present invention will be more readily understood from the following description of preferred embodiments, by way of

example thereof, with reference to the accompanying drawings, of which:-

Figure 1 is a cross-sectional side view of a rope and a rope end termination device illustrating a prior art method of terminating a rope;

Figure 2a is a cross-sectional side view of a rope and a rope end termination device illustrating a first method of terminating a rope in accordance with the present invention;

10 Figure 2b is an enlarged view of a portion of braided layer of a fibre rope reinforced in accordance with the first method of the invention;

Figure 3 is a cross-sectional side view of a rope and a rope end termination device illustrating a second method of terminating a rope in accordance with the present invention;

Figure 4 is a cross-sectional side view of a rope and a rope end termination device illustrating a third method of terminating a rope in accordance with the present invention;

Figure 5 is a cross-sectional side view of a rope and a rope end termination device illustrating a fourth method of terminating a rope in accordance with the present invention;

25 Figure 6 is a cross-sectional side view of a rope end termination device illustrating a fifth method of terminating a rope in accordance with the present invention.



Referring to figure 1, this illustrates a prior art method of terminating a rope using a rope end termination device 10 of the type comprising a housing member 12 having a generally frusto-conical bore 14 in which a conically shaped wedge member 16 locates to wedgedly retain an end portion 18' of the rope 18 by trapping the fibres 20 comprising said rope end portion 18'. The prior art method comprises passing the rope end portion 18' through the bore 14 of the housing member 12, splaying the fibres 20 of the rope end portion 18' and inserting, apex first, the wedge member 16 generally in the centre of the splayed fibres 20 before drawing the rope end portion 18' back into the housing member 12 such that the wedge member 16 locates within the bore 14 of the housing member 12 trapping the fibres 20 therein. Further tensile load exerted on the rope 18 will cause the rope end portion 18' to become more securely retained within the housing member 12, but the wedge member 16 will exert a greater crushing force on the trapped fibres 20 of the rope end portion 18' which can result in their being damaged. A further problem with this method of terminating a rope is that the fibres 20 of the rope end portion 18' in a region surrounding an apex part 16' of the wedge member 16 tend to become abraded thus substantially reducing the breaking strength of the rope 18. The rope fibres 20 may be treated with a resin to lubricate them and reduce abrasion thereof in and around the apex part 16' of the wedge member 16. However, the fibres 20 of the rope 18 may also become abraded in a region surrounding a mouth part 12' of the housing member

12 and experience has shown that this is the most likely point of tensile failure of the rope 18.

Figure 2a illustrates a method of terminating a rope end portion in accordance with a first method of the present invention. The device for terminating the rope has a similar structure to that utilised in the prior art method and therefore like numerals will be used to denote like parts.

The first method of the invention comprises introducing into or incorporating in the rope end portion 18' means to reinforce it such that the breaking strength of the rope end portion 18' in the region surrounding the apex part 16' of the wedge member 16 is increased. In the preferred form of the first method, the reinforcing means comprises a portion 22 of a fibre rope of similar structure to that of the rope 18 to be terminated and this is incorporated in the rope end portion 18' by splicing. A tensile load exerted on the rope 18 causes it to constrict such that load on the rope 18 transfers through friction to the fibres of the reinforcing rope portion 22 thus transferrring part of the tensile load in the rope fibres away from the apex part 16' of the wedge member 16. In a further preferred form of the first method, the rope 18 to be terminated comprises a braided rope having a hollow construction and the reinforcing fibre rope portion 22 is spliced with the strands comprising said rope 18. Constriction of the rope 18 under tensile load causes part of the load to be exerted on the reinforcing fibre rope

extends beyond the mouth part 12' of the housing member 12. In this way, a tensile load exerted on the rope 18 is transferred away from both the region surrounding the apex part 16' of the wedge member 16 and also the mouth part 12' of the housing member 12.

It has been found that by incorporating a reinforcing fibre rope portion 22 of a structure similar to that of the rope 18 to be terminated, it is possible to transfer up to half the tensile load exerted on the rope away from the housing member 12 and thus the breaking strength of the rope is substantially increased. The failure point of the rope 18 will therefore be transferred some distance away from the mouth part 12' of the housing member 12. The reinforced rope end portion 18' may be reinforced over a length which is several times the length of the bore 14 of the housing member 12 thus transferring a portion of the tensile load exerted on the rope 18 a substantial distance away from the housing member 12.

The reinforcing fibre rope portion 22 is preferably formed to have a decreasing number of filaments or fibres along its length such that, when it is introduced into or incorporated in the rope end portion 18', it results in a generally continuous or incremental increase in the number of fibres comprising the reinforced rope end portion 18' in a direction towards a free end of the rope end portion 18'. This contrasts with the rather abrupt increase in rope diameter at a point distant from the housing member 12 which would be the case if the reinforcing fibre rope portion 22 were not formed with a tapered structure.

Tapering the reinforcing fibre rope portion 22 has the advantage of transferring a portion of the tensile load exerted on the rope 18 away from the housing member 12 but avoiding an abrupt change in the number of fibres on which
5 said tensile load is exerted at a distance away from the housing member 12. It has been found that with this arrangement, the breaking strength of the rope is increased further since there is a gentle transition between the number of fibres comprising the reinforced rope end portion
10 18' and the lesser number of fibres comprising the main or standing part of the terminated rope 18.

The fibres of the reinforced rope end portion 18' may be treated with a resin composition of the type disclosed in UK 2 236 546.

15 The method may include placing a further resin composition 24 in an end portion of the housing member bore 14 behind the wedge member 16 to bind the loose fibres 20 of the rope end portion 18' at the rear end of the housing member 12.

20 Figure 4 illustrates a third method of terminating a rope in accordance with the present invention. This method involves reinforcing the rope end portion 18' in a manner similar to either of the methods described respectively with reference to figures 2 and 3, but a wedge member is
25 not required to secure the rope end portion 18' in the housing member 12. In this method, the reinforced rope end portion 18' is secured by locating it in the bore 14 of the housing member 12 and by pouring a resin composition 26 into the bore 14 of the housing to adhere the fibres 20

comprising the reinforced rope end portion 18' into a conical shape defined by the frusto-conical bore 14 of the housing member 12. Once the resin has set, a tensile load applied to the rope 18 will cause the resin cone 26 formed by the above method to become wedgedly secured in the bore 14 of the housing member 12. Transfer of tensile load exerted on the rope 18 occurs by the same mechanism as in the methods described with reference to figures 2 and 3 respectively.

Figure 5 illustrates a fourth method in accordance with the present invention. This method is similar to that described with respect to figure 3, but differs in that the reinforcing fibre rope portion 22 is preformed with a resin cone 28 at an end thereof and the combined rope portion 22 and resin cone 28 is inserted into the rope end portion 18'. The rope end portion 18' is then drawn into the bore 14 of the housing member 12 where the resin cone 28 wedgedly retains the rope end portion 18' in the housing member 12 and the rope portion 22 reinforces the rope end portion 18'. This method has the advantage of reducing the number of components to be combined when terminating the rope 18.

A further example of the fourth method in accordance with the present invention introduces the resin composition into the housing member 12 such that the resin cone 28 so formed extends outwardly from the mouth part of the housing member.

Figure 6 illustrates a fifth method of reinforcing a fibre rope in accordance with a fifth method of the present invention. This method is particularly applicable to terminating fibre ropes of relatively large diameter, i.e. having a diameter in the order of 4 inches (10cm) or greater.

This method employs a housing member 12 having a frusto-conical bore 14. A plurality of hollow members 15 located, in use, within said housing member bore 14 in side by side relationship. Each hollow member 15 has a frusto-
5 conical outer surface and a frusto-conical chamber for wedgedly retaining an end of one of a multiplicity of strands comprising a rope. Each rope end strand can be retained in its respective hollow member in accordance with any of the first to fourth methods of the invention.

10 This method of the invention can also be used to terminate a bundle of fibre ropes comprising a plurality of parallel lengths of fibre rope of similar construction for use to heavy duty marine application.

The methods of the present invention make use of load
15 transference by means of introducing into or incorporating in an end portion of a rope to be terminated a material or means which increases the load bearing characteristics of the rope end portion such that a portion of the tensile load exerted on the rope transfers down the rope away from
20 the reinforced end portion.

Whilst the various methods of the present invention have been described generally with reference to terminating a fibre rope having a braided construction using a reinforcing fibre rope portion also of a braided
25 construction, it will be appreciated that the method can be applied to any fibre rope which is capable of exerting a transverse compressive load when subjected to an axial force (tensile load).

CLAIMS

1. A method of terminating a fibre rope, comprising the steps of:-introducing into or incorporating in an end portion of the rope a reinforcing portion of fibre rope; 5 locating said reinforced rope end portion in a generally frusto-conical bore of a housing member; and securing said reinforced rope end portion in said housing member bore, wherein the method includes introducing or incorporating the reinforcing portion of fibre rope into less than the entire 10 length of said rope by splicing a number of the strands of the portion of the reinforcing rope with a number of the strands comprising the rope end portion so as to increase a tension load capacity of said rope end portion.

2. A method as claimed in claim 1, wherein it includes 15 the steps of:- passing said rope end portion through the bore of the housing member prior to introducing into or incorporating in it the reinforcing means; and drawing said rope end portion back towards the housing member bore to locate it therein.

20 3. A method as claimed in any preceding claim, wherein it includes using a reinforcing fibre rope portion generally having the same structure as the rope to be terminated.

.. 4. A method as claimed in any preceding claim, wherein it includes reinforcing said rope end portion over a length 25 which is several times the length of the housing member bore.

5. A method as claimed in any preceding claim, wherein it includes using a reinforcing fibre rope portion having a decreasing number of filaments or fibres along its length and where said reinforcing fibre rope portion is introduced into 30 or incorporated in the rope end portion with an end thereof

having the greater number of filaments or fibres being located nearest the end of the rope to be terminated.

6. A method as claimed in any preceding claim, wherein it includes locating the reinforced rope end portion in the housing member bore such that it extends outwardly beyond a narrow mouth part of the housing member.

7. A method as claimed in claim 6, wherein it includes locating the reinforced rope end portion in the housing member bore such that a longer part of the reinforced rope end portion extends outwardly beyond the mouth part of the housing member.

8. A method as claimed in any preceding claim, wherein it includes securing the reinforced rope end portion in the housing member bore by means of a conically shaped wedge member, a resin composition or a combination thereof.

9. A method as claimed in claim 8, wherein where the reinforced rope end portion is secured in the housing member by means of a resin composition only, the method includes introducing the resin composition into the housing member such that the resin composition combined with fibres of the reinforced rope end portion forms a wedge means for retaining the reinforced rope end portion in the housing member.

10. A method as claimed in claim 9, wherein it includes introducing the resin composition into the housing member such that the wedge means so formed extends outwardly from the mouth part of the housing member.

11. A method as claimed in any preceding claim, wherein the housing member has a plurality of generally frusto-conical members having generally frusto-conical hollow chambers, wherein, in use, each rope strand of the reinforced rope end portion comprising multiple rope strands is passed through a respective one of said hollow chamber and secured

therein and the frusto-conical members are arranged in juxtaposed relationship within the bore of the housing member such that each of said members contacts at least one adjacent member and such that a load applied to the rope end portion acts through the multiple rope strands in a direction towards a narrower end of the housing member.

12. A combination of a rope terminated with a device comprising a housing member having a generally frusto-conical bore and by a method in accordance with any one of claims 1 to 11.

13. A method substantially as hereinbefore described with reference to figure 2 of the drawings.

14. A method substantially as hereinbefore described with reference to figure 3 of the drawings.

15. A method substantially as hereinbefore described with reference to figure 4 of the drawings.

16. A method substantially as hereinbefore described with reference to figure 5 of the drawings.

17. A method substantially as hereinbefore described with reference to figure 6 of the drawings.

18. A rope terminated in accordance with a method substantially as hereinbefore described with reference to figure 2 of the drawings.

19. A rope terminated in accordance with a method substantially as hereinbefore described with reference to figure 3 of the drawings.

20. A rope terminated in accordance with a method substantially as hereinbefore described with reference to figure 4 of the drawings.

21. A rope terminated in accordance with a method substantially as hereinbefore described with reference to figure 5 of the drawings.

22. A rope terminated in accordance with a method substantially as hereinbefore described with reference to figure 6 of the drawings.



US005904438A

United States Patent [19]

[11] Patent Number: 5,904,438

Vaseghi et al.

[45] Date of Patent: May 18, 1999

[54] METHOD OF TERMINATING A FIBER ROPE

3,660,887	5/1972	Davis	403/267 X
3,739,457	6/1973	Davis	403/281 X
4,184,784	1/1980	Killian	403/267
4,755,076	7/1988	Salama et al.	403/275
4,760,991	8/1988	Asai	254/134.3
5,699,657	12/1997	Paulson	87/13 X
5,735,628	4/1998	Short	403/218

[75] Inventors: Rahim Vaseghi, Bournemouth; John Kenneth Yeardley, London, both of United Kingdom

[73] Assignee: Bridon PLC, South Yorkshire, United Kingdom

[21] Appl. No.: 08/870,884

[22] Filed: Jun. 6, 1997

[30] Foreign Application Priority Data

Jun. 7, 1996 [GB] United Kingdom 96 11 976

[51] Int. Cl.⁶ B23P 3/00

[52] U.S. Cl. 403/268; 403/404; 29/460; 87/3; 87/5

[58] Field of Search 403/268, 267, 403/275, 277, 248, 334, 404, 374, 218; 29/461; 87/1, 3, 7, 8, 13, 9, 5

[56] References Cited

U.S. PATENT DOCUMENTS

2,803,486	11/1957	Larson et al.	403/268 X
3,030,851	2/1962	Meyer	87/5 X
3,036,490	9/1962	Muller et al.	87/5 X
3,507,949	4/1970	Campbell	403/267 X

FOREIGN PATENT DOCUMENTS

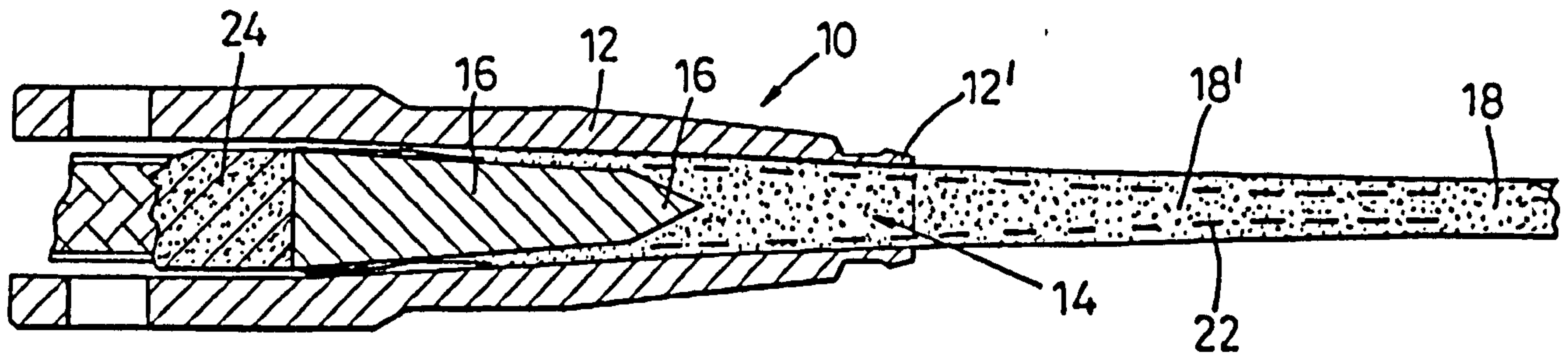
1341013	12/1973	United Kingdom .
2236546	4/1991	United Kingdom .
2279972	1/1995	United Kingdom .

Primary Examiner—Harry C. Kim
Assistant Examiner—John R. Cottingham
Attorney, Agent, or Firm—Nilles & Nilles SC

[57] ABSTRACT

A method of terminating a fiber rope utilizing a device of the type which has a housing member having a frusto-conical bore in which an end portion of the rope can be wedgedly retained. The end portion of the rope has a reinforcing device incorporated therein in order to increase the tensile load capacity of the rope end portion. The reinforcing device may include a fiber type material, a length of fiber rope or a resinous compound applied to the fibers of the rope end portion.

17 Claims, 3 Drawing Sheets



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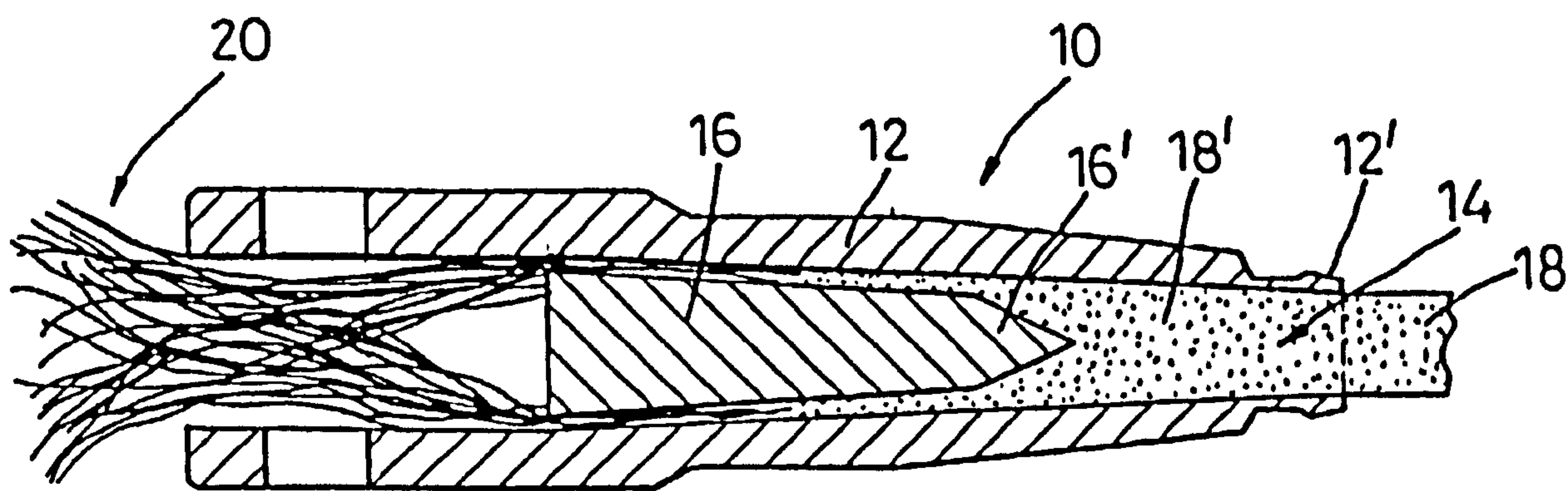


Fig. 1
Prior Art

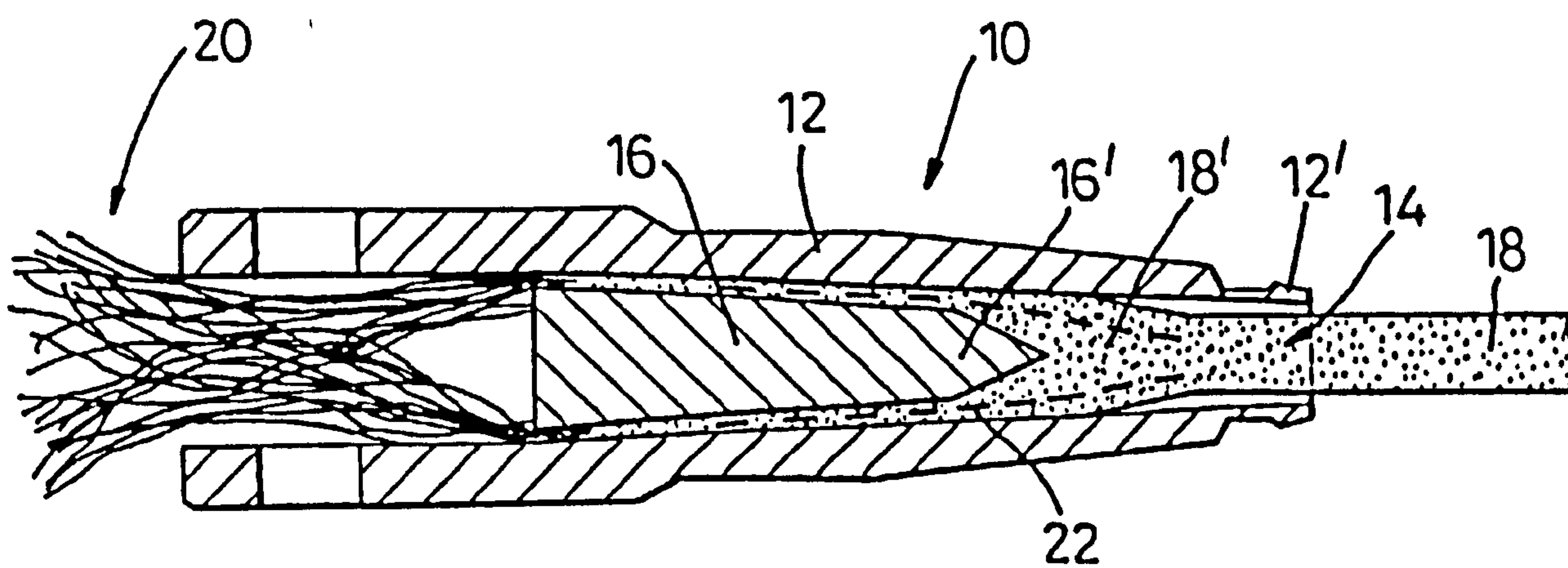


Fig. 2a

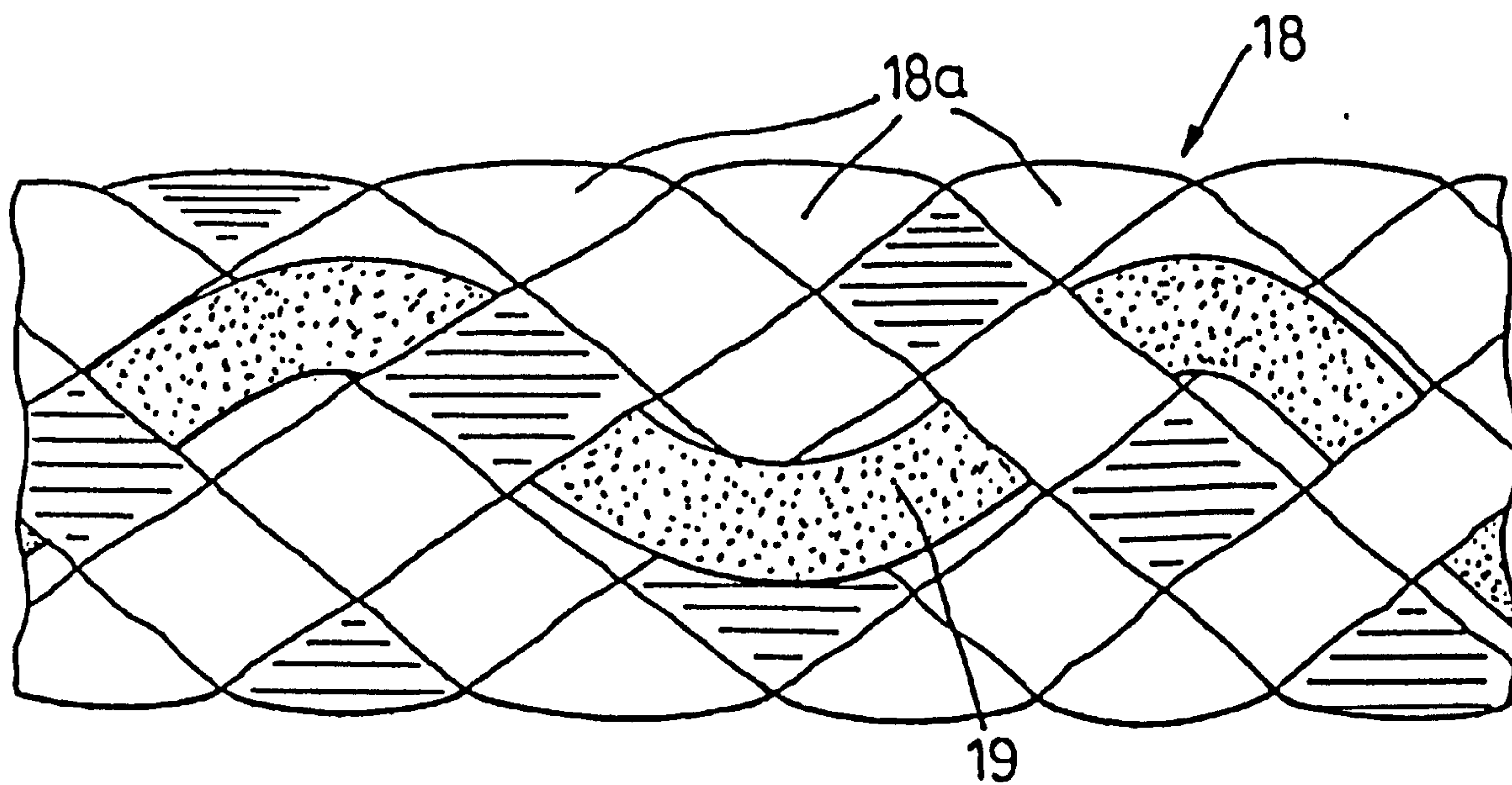


Fig. 2b

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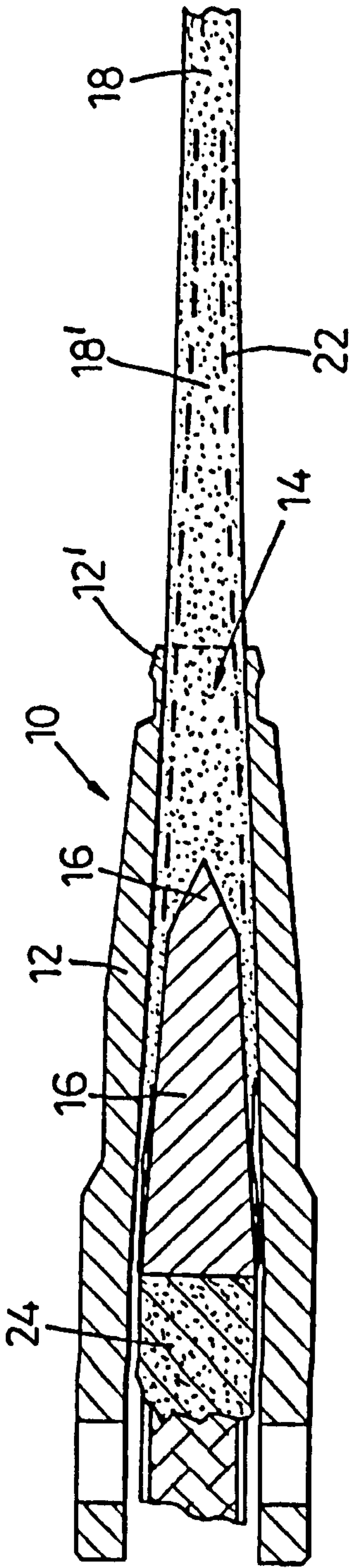


Fig. 3

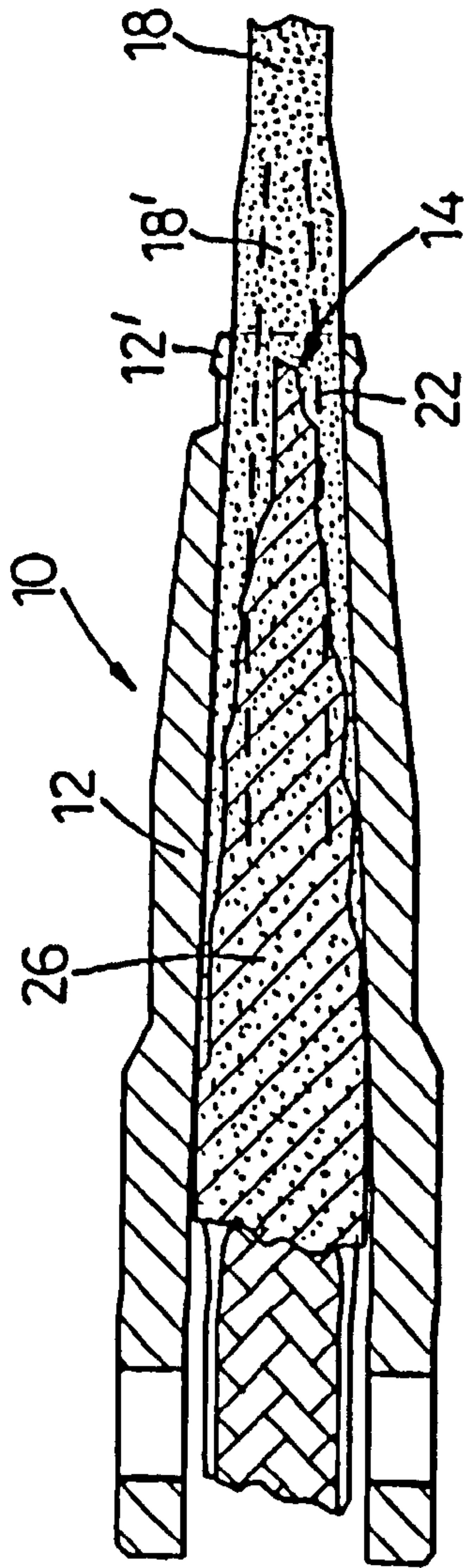


Fig. 4

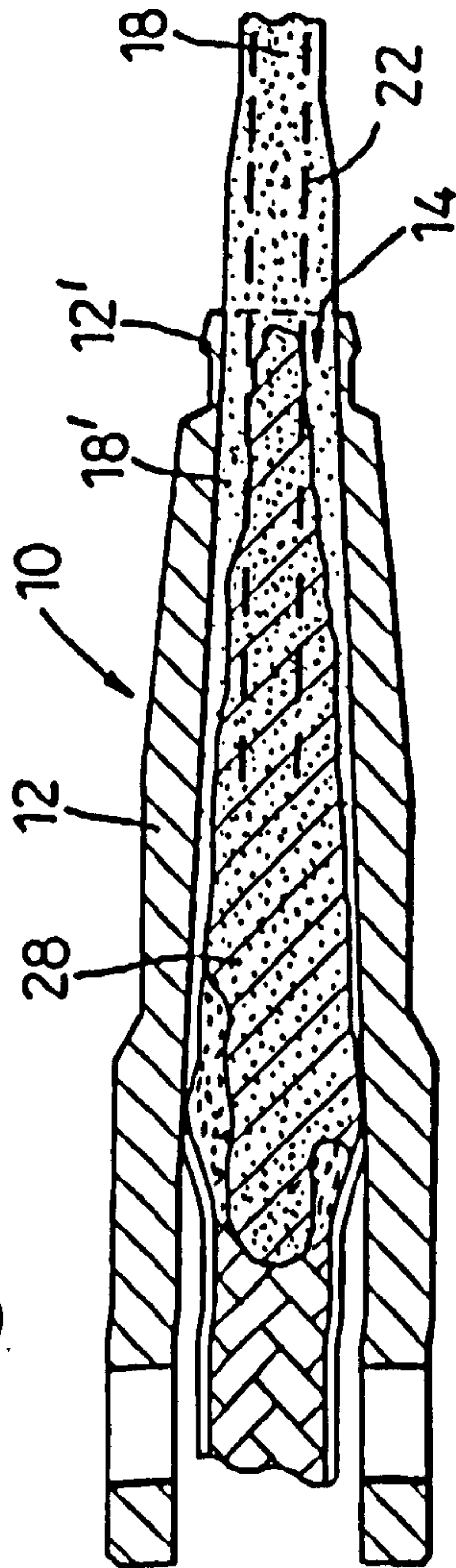


Fig. 5

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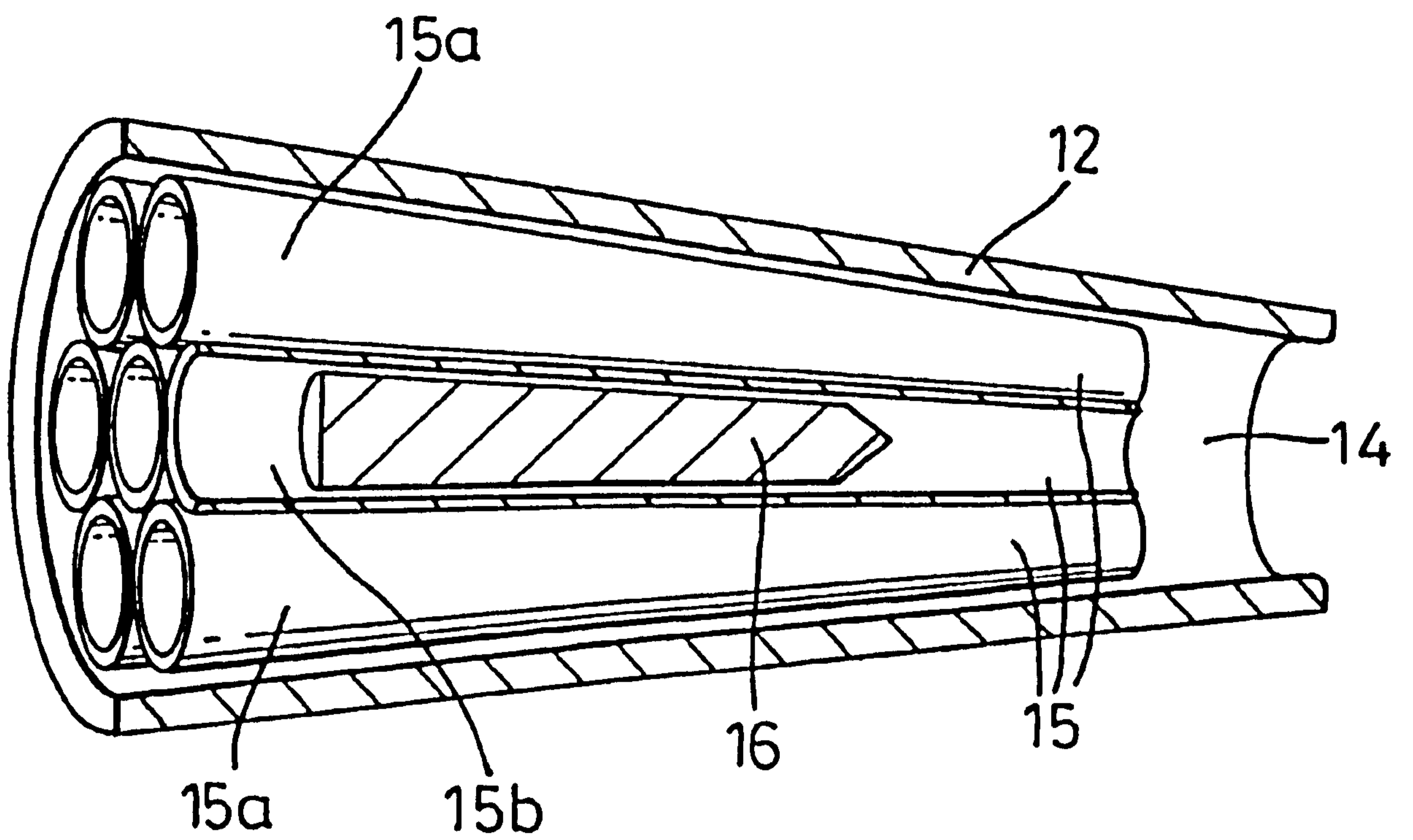


Fig. 6

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METHOD OF TERMINATING A FIBER ROPE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method of terminating a fiber rope utilising a device of the type comprising a housing member having a generally frusto-conical bore in which an end portion of the rope can be wedgedly retained.

2. Description of the Related Art

It is known from GB 1 341 013 to terminate a fiber rope using a device of the abovementioned type. A conically shaped wedge member locates within the frusto-conical bore of the housing member to wedgedly trap fibers of the end portion of the rope within the bore of the housing member thus terminating the rope. The housing member includes a device for attaching it to an anchorage, for example.

It has been that with this method of terminating a rope, that there is a tendency for the fibers of the rope end portion to abrade. Abrasion of the fibers occurs mainly in the region where the fibers contact an apex part of the conically shaped wedge member, although abrasion may also occur at a narrow mouth part of the housing member through which the terminated rope extends. The abrasion of the rope fibers substantially reduces the breaking strength of the rope.

A method of overcoming this problem is suggested in GB 2 236 546 in which the fibers of the rope end portion are treated with a resin composition. The resin composition is employed to provide a lubricating effect on the fibers to reduce abrasion thereof around the apex part of the conically shaped wedge member. Despite this, the combination of tensile load exerted on the rope and the stress induced in the constituent fibers of the rope end portion by the crushing action of the wedge member results in tensile failure of the rope at a point generally in a region extending from around the apex part of the wedge member to the narrow mouth part of the housing member.

U.S. Pat. No. 4,184,784 discloses a method of terminating a raided fiber rope of small diameter. The rope has a diameter of approximately $\frac{1}{16}$ inch (0.25 cm) and is combined with a plurality of parallel sections of such rope to be terminated in a single collar having a tapered interior channel. The collar is passed over the ends of the plurality of ropes, and each rope has a short tapered section of rope of the same material inserted in its braided core as a device of thickening its end. The thickened ends of the plurality of parallel rope sections are separated ("fuzzed") into their individual fibers and a tube having a tapered outer surface is located therebetween. The tube is drawn into the collar by a centering tool and tightly wedges the "fuzzed" parts, plus a significant part of the braided lengths of the ropes, between the tube and collar.

This method is applied to the termination of bundles of very small diameter braided fiber ropes in a single termination device, said terminated bundles of ropes being employed to keep tensile loads from conductors in underwater cables. This method is not suitable for terminating larger diameter fiber ropes because their structures are more resistant to the compression necessary to secure the rope ends between the collar and tube. It will be appreciated from the disclosure of U.S. Pat. No. 4,184,784 that the amount of surface contact between each rope end and the respective surfaces of the channel and tube is restricted.

OBJECTS AND SUMMARY OF THE INVENTION

It is an object of the present invention to obviate or mitigate the aforesaid problems associated with the prior art methods of terminating a fiber rope.

It is a further object of the present invention to provide a method of terminating a fiber rope having a diameter in the order of 1 inch (2.5 cm) or larger. Fibre ropes of this and much larger diameters are employed in marine applications when light weight but high tensile strength are required.

According to a first aspect of the present invention, there is provided a method of terminating a fiber rope, comprising the steps of: introducing into or incorporating in an end portion of the rope for reinforcing said rope end portion; locating said reinforced rope end portion in a generally frusto-conical bore of a housing member; and securing said rope end portion in said housing member bore.

According to a second aspect of the present invention, there is provided a rope terminated using a device comprising a housing member having a generally frusto-conical bore by a method in accordance with the first aspect of the invention.

Further features of the present invention are set out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and further features of the present invention will be more readily understood from the following description of preferred embodiments, by way of example thereof, with reference to the accompanying drawings, of which:

FIG. 1 is a cross-sectional side view of a rope and a rope end termination device illustrating a prior art method of terminating a rope;

FIG. 2a is a cross-sectional side view of a rope and a rope end termination device illustrating a first method of terminating a rope in accordance with the present invention;

FIG. 2b is an enlarged view of a portion of a braided layer of a fiber rope reinforced in accordance with the first method of the invention;

FIG. 3 is a cross-sectional side view of a rope and a rope end termination device illustrating a second method of terminating a rope in accordance with the present invention;

FIG. 4 is a cross-sectional side view of a rope and a rope end termination device illustrating a third method of terminating a rope in accordance with the present invention;

FIG. 5 is a cross-sectional side view of a rope and a rope end termination device illustrating a fourth method of terminating a rope in accordance with the present invention; and

FIG. 6 is a cross-sectional side view of a rope end termination device illustrating a fifth method of terminating a rope in accordance with the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, this illustrates a prior art method of terminating a rope using a rope end termination device 10 of the type comprising a housing member 12 having a generally frusto-conical bore 14 in which a conically shaped wedge member 16 locates to wedgedly retain an end portion 18' of the rope 18 by trapping the fiber 20 comprising the rope end portion 18'. The prior art method comprises passing the rope end portion 18' through the bore 14 of the housing member 12, splaying the fiber 20 of the rope end portion 18' and inserting, apex first, the wedge member 16 generally in the centre of the splayed fibers 20 before drawing the rope end portion 18' back into the housing member 12 such that the wedge member 16 locates within the bore 14 of the

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housing member 12, trapping the fiber 20 therein. Further tensile load exerted on the rope 18 will cause the rope end portion 18' to become more securely retained within the housing member 12, but the wedge member 16 will exert a greater crushing force on the trapped fiber 20 of the rope end portion 18' which can result in their being damaged. A further problem with this method of terminating a rope is that the fiber 20 of the rope end portion 18' in a region surrounding an apex part 16' of the wedge member 16 tend to become abraded thus substantially reducing the breaking strength of the rope 18. The rope fiber 20 may be treated with a resin to lubricate them and reduce abrasion thereof in and around the apex part 16' of the wedge member 16. However, the fiber 20 of the rope 18 may also become abraded in a region surrounding a mouth part 12' of the housing member 12 and experience has shown that this is the most likely point of tensile failure of the rope 18.

FIG. 2a illustrates a method of terminating a rope end portion in accordance with a first method of the present invention. The device for terminating the rope has a similar structure to that utilised in the prior art method and therefore like numerals will be used to denote like parts.

The first method of the invention comprises introducing into or incorporating in the rope end portion 18' measure to reinforce it such that the breaking strength of the rope end portion 18' in the region surrounding the apex part 16' of the wedge member 16 is increased. In the preferred form of the first method, the reinforcing structure comprises a portion 22 of a fibers rope of similar structure to that of the rope 18 to be terminated, and this is preferably incorporated in the rope end portion 18' by splicing. A tensile load exerted on the rope 18 causes it to constrict such that load on the rope 18 transfers through friction to the fibers of the reinforcing rope portion 22, thus transferring part of the tensile load in the rope fibers 20 away from the apex part 16' of the wedge member 16. In a further preferred form of the first method, the rope 18 to be terminated comprises a braided rope having a hollow construction, and the reinforcing fiber rope portion 22 is located in the hollow part of the rope 18 or is preferably spliced with the strands comprising the rope 18. Constriction of the rope 18 under tensile load causes part of the load to be exerted on the reinforcing fiber rope portion 22, thus substantially increasing the breaking strength of the reinforced rope end portion 18'. The rope end portion 18' may be reinforced such that a reinforced part thereof extends over at least the apex part 16' of the wedge member 16. Whilst the diameter of the mouth part 12' of the housing member is shown as being larger than the diameter of the rope 18, it will be appreciated that, in practice, this need not be so.

FIG. 2b shows an enlarged view of a braided layer of a fiber rope 18, reinforced over a part of its length by splicing strands 19 of a reinforcing section of rope of the same structure with strands 18a of the fiber rope 18. For convenience, only one strand 19 of the reinforcing rope is shown in the figure. It will be appreciated that splicing strands (18a and 19) as aforesaid is impracticable with fiber ropes of relatively small diameter. However, for ropes having a diameter of greater than 1 inch (2.5 cm), the strands comprising the rope are of a size which allows splicing to be relatively easily achieved.

The splicing of the reinforcing strands 19 with the strands 18a of the rope 18 greatly increases tensile load transference within the structure of the reinforced rope end when compared to a rope end reinforced with a reinforcing rope section merely inserted within the core of a braided fiber rope.

FIG. 3 illustrates a second method in accordance with the invention. This method is similar to that of the first method.

However, it differs in that a longer length end portion 18' of the rope 18 is reinforced with a fiber rope portion 22 such that the reinforced rope end portion 18' extends beyond the mouth part 12' of the housing member 12. In this way, a tensile load exerted on the rope 18 is transferred away from both the region surrounding the apex part 16' of the wedge member 16 and also the mouth part 12' of the housing member 12.

It has been found that by incorporating a reinforcing fiber rope portion 22 of a structure similar to that of the rope 18 to be terminated, it is possible to transfer up to half the tensile load exerted on the rope away from the housing member 12 and thus the breaking strength of the rope is substantially increased. The failure point of the rope 18 will therefore be transferred some distance away from the mouth part 12' of the housing member 12. The reinforced rope end portion 18' may be reinforced over a length which is several times the length of the bore 14 of the housing member 12 thus transferring a portion of the tensile load exerted on the rope 18 a substantial distance away from the housing member 12.

The reinforcing fiber rope portion 22 is preferably formed to have a decreasing number of filaments or fibers along its length such that, when it is introduced into or incorporated in the rope end portion 18', it results in a generally continuous or incremental increase in the number of fibers comprising the reinforced rope end portion 18' in a direction towards a free end of the rope end portion 18'. This contrasts with the rather abrupt increase in rope diameter at a point distant from the housing member 12 which would be the case if the reinforcing fiber rope portion 22 were not formed with a tapered structure. Tapering the reinforcing fiber rope portion 22 has the advantage of transferring a portion of the tensile load exerted on the rope 18 away from the housing member 12 but avoiding an abrupt change in the number of fibers on which the tensile load is exerted at a distance away from the housing member 12. It has been found that, with this arrangement, the breaking strength of the rope is increased further since there is a gentle transition between the number of fibers comprising the reinforced rope end portion 18' and the lesser number of fibers comprising the main or standing part of the terminated rope 18.

The fibers of the reinforced rope end portion 18' may be treated with a resin composition of the type disclosed in UK 2 236 546.

The method may include placing a further resin composition 24 in an end portion of the housing member bore 14 behind the wedge member 16 to bind the loose fibers 20 of the rope end portion 18' at the rear end of the housing member 12.

FIG. 4 illustrates a third method of terminating a rope in accordance with the present invention. This method involves reinforcing the rope end portion 18' in a manner similar to either of the methods described respectively with reference to FIGS. 2 and 3, but a wedge member is not required to secure the rope end portion 18' in the housing member 12. In this method, the reinforced rope end portion 18' is secured by locating it in the bore 14 of the housing member 12 and by pouring a resin composition 26 into the bore 14 of the housing to adhere the fibers 20 comprising the reinforced rope end portion 18' into a conical shape defined by the frusto-conical bore 14 of the housing member 12. Once the resin has set, a tensile load applied to the rope 18 will cause the resin cone 26 formed by the above method to become wedgedly secured in the bore 14 of the housing member 12. Transfer of tensile load exerted on the rope 18 occurs by the

same mechanism as in the methods described with reference to FIGS. 2 and 3, respectively.

FIG. 5 illustrates a fourth method in accordance with the present invention. This method is similar to that described with respect to FIG. 3, but differs in that the reinforcing fiber rope portion 22 is preformed with a resin cone 28 at an end thereof and the combined rope portion 22 and resin cone 28 is inserted into the rope end portion 18'. The rope end portion 18' is then drawn into the bore 14 of the housing member 12 where the resin cone 28 wedgedly retains the rope end portion 18' in the housing member 12 and the rope portion 22 reinforces the rope end portion 18'. This method has the advantage of reducing the number of components to be combined when terminating the rope 18.

FIG. 6 illustrates a fifth method of reinforcing a fiber rope in accordance with a fifth method of the present invention. This method is particularly applicable to terminating fiber ropes of relatively large diameter, ie having a diameter in the order of 4 inches (10 cm) or greater.

This method employs a housing member 12 having a frusto-conical bore 14. A plurality of hollow members 15 locate, in use, within the housing member bore 14 in side by side relationship. Each hollow member 15 has a frusto-conical outer surface 15a and a frusto-conical chamber 15b for wedgedly retaining an end of one of a multiplicity of strands comprising a rope (not shown). Each rope end strand can be retained in its respective hollow member 15 in accordance with any one of the first to fourth methods of the invention or any combination thereof, although for purposes of illustration, a frusto-conical wedge member 16 is shown located in a center one of the hollow members 15.

This method of the invention can also be used to terminate a bundle of fiber ropes comprising a plurality of parallel lengths of fiber rope of similar construction for use in heavy duty marine applications.

The methods of the present invention make use of load transference by means of introducing into or incorporating in an end portion of a rope to be terminated a material or process which increases the load bearing characteristics of the rope end portion such that a portion of the tensile load exerted on the rope transfers down the rope away from the reinforced end portion.

Whilst the various methods of the present invention have been described generally with reference to terminating a fiber rope having a braided construction using a reinforcing fiber rope portion also of a braided construction, it will be appreciated that the method can be applied to any fiber rope which is capable of exerting a transverse compressive load when subjected to an axial force (tensile load).

We claim:

1. A method of terminating a fiber rope, comprising the steps of: introducing into or incorporating in an end portion of the rope a reinforcing portion of fiber rope so as to increase a tension load capacity of said rope end portion; locating said reinforced rope end portion in a generally frusto-conical bore of a housing member; and securing said reinforced rope end portion in said housing member bore, wherein the method includes introducing or incorporating the reinforcing portion of fiber rope into less than the entire length of said rope.

2. A method of terminating a fiber rope, comprising the steps of:

introducing into or incorporating in an end portion of the rope a reinforcing portion of fiber rope so as to increase a tension load capacity of said rope end portion; locating said reinforced rope end portion in a generally

frusto-conical bore of a housing member; and securing said reinforced rope end portion in said housing member bore, wherein the method includes the steps of: passing said rope end portion through the bore of the housing member prior to introducing into or incorporating in it the reinforcing portion of fiber rope; and drawing said rope end portion back towards the housing member bore to locate it therein.

3. A method as claimed in claim 1, wherein the reinforcing portion of fiber rope comprises a plurality of filaments or fibers.

4. A method as claimed in claim 3, wherein the method includes reinforcing said rope end portion by splicing some of said fibers or filaments with some of the strands comprising the rope end portion.

5. A method of terminating a fiber rope, comprising the steps of:

introducing into or incorporating in an end portion of the rope a reinforcing portion of fiber rope so as to increase a tension load capacity of said rope end portion; locating said reinforced rope end portion in a generally frusto-conical bore of a housing member; and securing said reinforced rope end portion in said housing member bore, wherein the reinforcing portion of fiber rope has generally the same structure as the rope to be terminated.

6. A method as claimed in claim 1, wherein the method includes reinforcing said rope end portion over a length which is several times the length of the housing member bore.

7. A method of terminating a fiber rope, comprising the steps of:

introducing into or incorporating in an end portion of the rope a reinforcing portion of fiber rope so as to increase a tension load capacity of said rope end portion; locating said reinforced rope end portion in a generally frusto-conical bore of a housing member; and securing said reinforced rope end portion in said housing member bore, wherein the reinforcing fiber rope portion has a decreasing number of filaments or fibers along its length, and wherein said reinforcing portion of fiber rope is introduced into or incorporated in the rope end portion with an end thereof having the greater number of filaments or fibers being located nearest the end of the rope to be terminated.

8. A method as claimed in claim 1, wherein the method includes splicing a number of the strands of the reinforcing portion of fiber rope with a number of the strands comprising the rope end portion.

9. A method as claimed in claim 1, wherein the method includes locating the reinforced rope end portion in the housing member bore such that the reinforced end portion extends outwardly beyond a narrow mouth part of the housing member.

10. A method as claimed in claim 9, wherein the method includes locating the reinforced rope end portion in the housing member bore such that a larger part of the reinforced rope end portion extends outwardly beyond the mouth part of the housing member.

11. A method as claimed claim 9, wherein the method includes securing the reinforced rope end portion in the housing member bore by way of a conically shaped wedge member, a resin composition or a combination thereof.

12. A method as claimed in claim 11, wherein where the reinforced rope end portion is secured in the housing member by way of a resin composition only, the method includes introducing the resin composition into the housing member

such that the resin composition combined with fibers of the reinforced rope end portion forms wedge means for retaining the reinforced rope end portion in the housing member.

13. A method as claimed in claim 12, wherein the resin composition is introduced into the housing member such that the wedge means so formed extends outwardly from the mouth part of the housing member. 5

14. A method as claimed in claim 1, wherein the housing member has a plurality of generally frusto-conical members having generally frusto-conical hollow chambers, wherein, in use, 1) each rope strand of the rope end portion comprising multiple rope strands is passed through a respective one of said hollow chambers and 2) secured therein and the frusto-conical members are arranged in juxtaposed relationship within the bore of the housing member such that each of said frusto-conical members contacts at least one adjacent frusto-conical member and such that a load applied to the rope end portion acts through the multiple rope strands in a direction towards a narrower end of the housing member. 10 15

15. A combination of a rope terminated with a device comprising a housing member having a generally frusto-conical bore and by a method in accordance with claim 1. 20

16. A method of terminating a fiber rope, comprising the steps of:

- providing a fiber rope having an end portion; 25
- introducing or incorporating a reinforcing portion of fiber rope into said end portion of said rope so as to increase the tensile load capacity of said end portion of said

rope, thereby reinforcing said end portion of said rope relative to another portion of said rope;

locating part of said reinforced end portion of said rope in a generally frusto-conical bore of a housing member such that said reinforcing portion of fiber rope extends beyond said housing member but extends less than the entire length of said rope; and

securing said reinforced end portion of said rope in said bore.

17. In combination:

a fiber rope comprising a reinforced end portion, said reinforced end portion being reinforced with a reinforcing portion of fiber rope that is incorporated or introduced into said reinforced end portion of said rope so as to increase a tensile load capacity of said reinforced end portion of said rope relative to another portion of said rope; and

a housing member having a generally frusto-conical bore formed therein, wherein part of said reinforced end portion of said rope is disposed within said bore of said housing member, wherein

said reinforced end portion of said rope is secured to said housing member, and wherein

said reinforcing portion of fiber rope extends beyond said housing member but does not extend the entire length of said rope.

* * * * *

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VIA FACSIMILE (0181 305 1603) TOTAL PAGES : 15

OUR REF 61/45651GB

YOUR REF JKY/PS

DATE 7 June 1996

Dear Mr Yeardley,

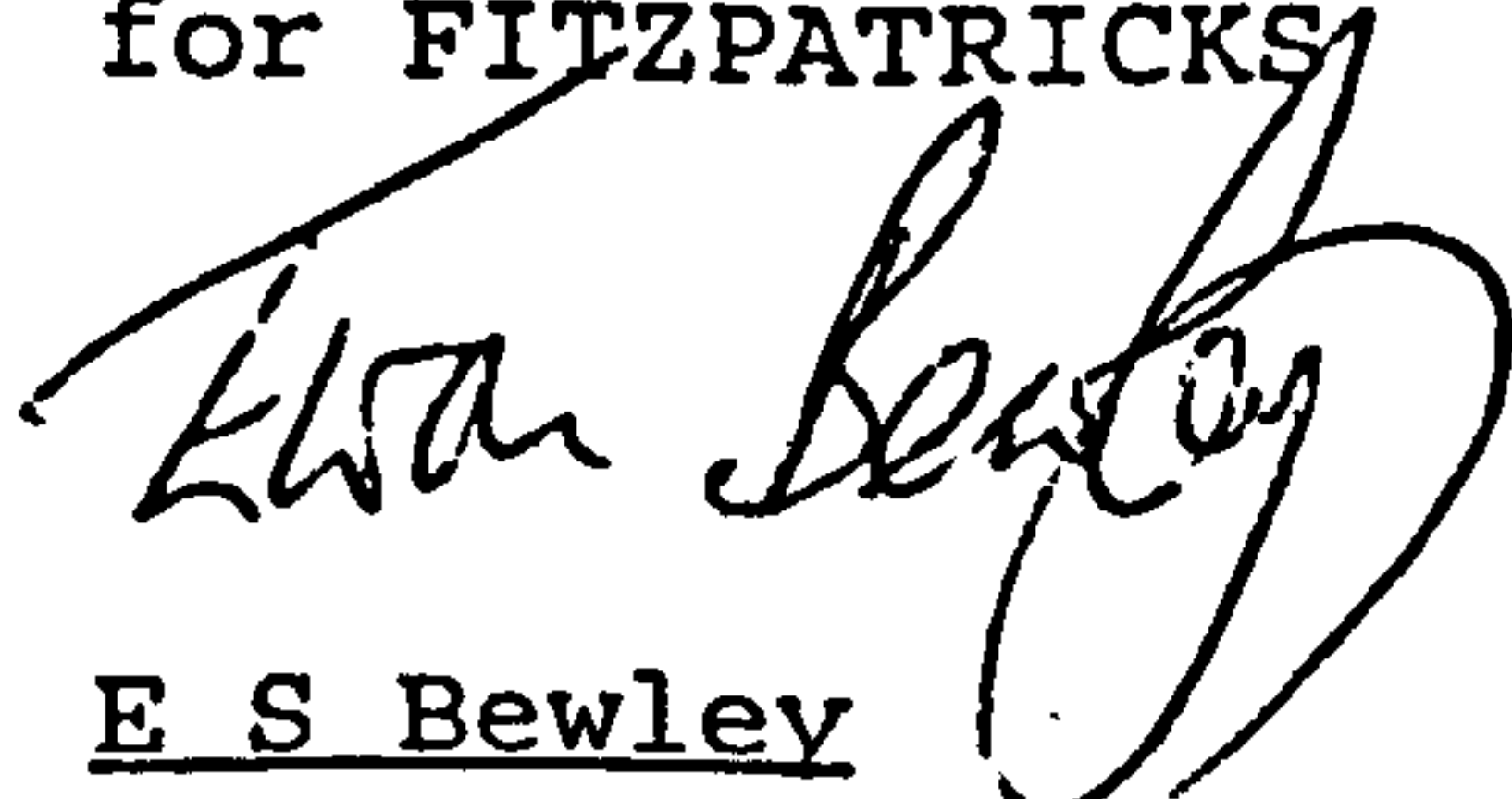
PROPOSED NEW UNITED KINGDOM PATENT APPLICATION
"A METHOD OF TERMINATING A FIBRE ROPE"

Further to our telephone discussion yesterday afternoon, I have pleasure in enclosing herewith a draft patent specification for your consideration.

I should be grateful if you would consider the draft specification with a view to confirming that it is technically correct. Upon receipt of your comments/approval of the draft specification, we can prepare application documents for lodging with the UK Patent Office. If you are able to provide me with your comments/approval before 2 pm today, we will be able to prepare and hand-file the application documents to obtain today as the official filing date for the new application. Please note that in the draft specification, I have amended some of the drawings provided by you to provide a comparison between the different methods of terminating a rope in accordance with the present invention. I am sure you will appreciate that this is necessary to support a broad patent claim.

I note that the new application is to be filed in the name of Bridon Plc and should name yourself with Mr Vesaghi as joint inventors. In this regard, please find enclosed an assignment document and please ensure that this is signed by at least Mr Vesaghi before the new application is filed. Please provide me with a copy of the assignment document, once executed. I will provide an application agreement for execution by you in due course.

Yours sincerely
for FITZPATRICKS



E S Bewley

encs

THIS ASSIGNMENT is made with effect from 15 May 1995 between (one) inventor Rahim VESAGHI, of 178A Woolwich Road, Charlton, London, SE7 7RA (hereinafter call "the Inventor" which expression shall include where the context so requires his administrators, executors and assigns) and (two) BRIDON PLC, a company incorporated in the United Kingdom of Carr Hill, Doncaster, South Yorkshire, DN4 8DG, United Kingdom (hereinafter called "the Assignee") which expression shall include where the context so requires its successors and assigns).

WHEREAS

(1) The Inventor in one of two joint inventors of an invention entitled "A Method Of Terminating A Fibre Rope" ("the Invention") which is to be the subject of a United Kingdom Patent Application and is to be filed in the name of the Assignee.

(2) The Inventor has agreed to assign all his rights in and to the Invention to the Assignee.

NOW IT IS HEREBY AGREED and declared between the parties as follows:-

In consideration of the sum of ten pounds (GB £10.00) paid by the Assignee to the Inventor (receipt of which is hereby acknowledged):-

1. The Inventor agrees to assign to the Assignee the full and exclusive benefit thereof including the right to apply for and obtain in the Assignee's own name Letters Patent and the like protection for the Invention in all territories and the full right to file continuation or divisional application or applications in respect of any part or parts of the subject matter of the Invention in all territories to hold the same unto the Assignee absolutely.

2. The Inventor hereby covenants and agrees with the Assignee that he will at the request of the Assignee (but at the expense of the Assignee) sign and execute all such documents and do all such things as may be necessary or expedient for the Assignee to enjoy the full benefits of the rights hereby assigned and to apply for and obtain Letters Patent or like protection for the *Invention in all territories and to vest the same* in the Assignee or its nominees when obtained.

3. IT IS HEREBY CERTIFIED that this transaction does not form part of a larger transaction or a series of transactions, in respect of which the aggregate value of the transaction or series of transactions exceeds sixty thousand (60,000) pounds sterling.

IN WITNESS WHEREOF these presents have been entered into on the date and year first above written.

Rahim Vesaghi

1ST witness

2ND witness

Signed

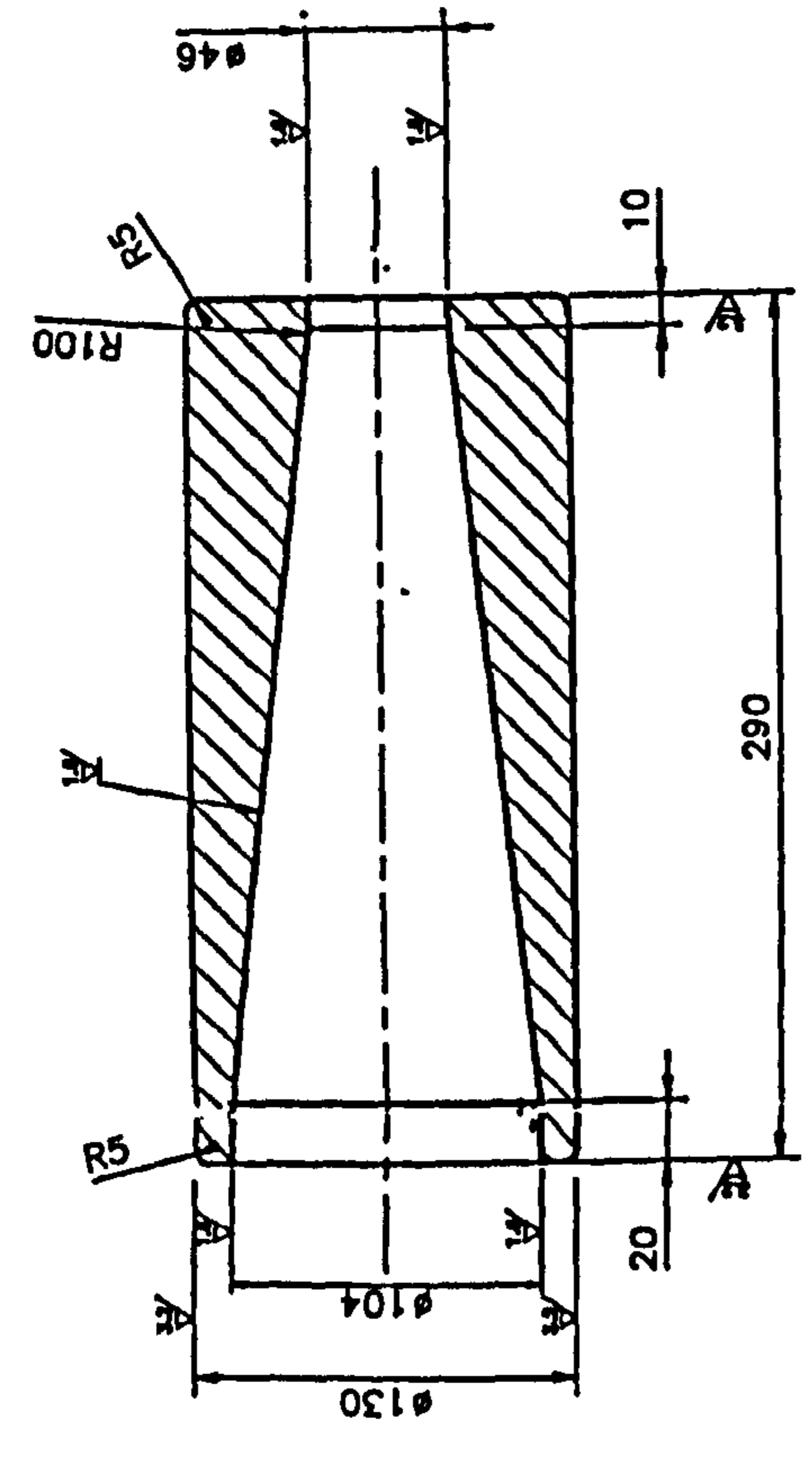
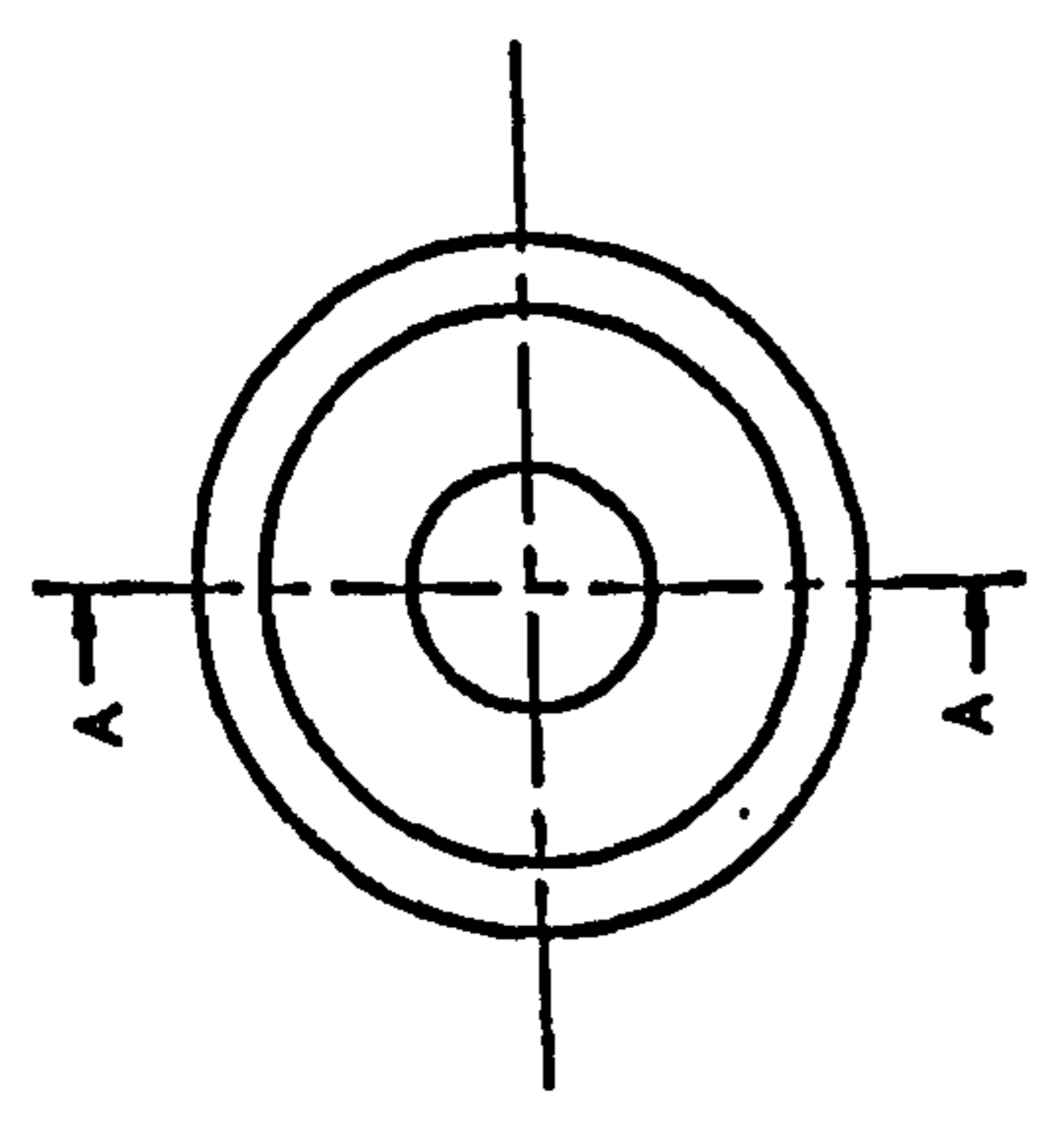
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For and on behalf of
the Assignee

BEST COPY

AVAILABLE

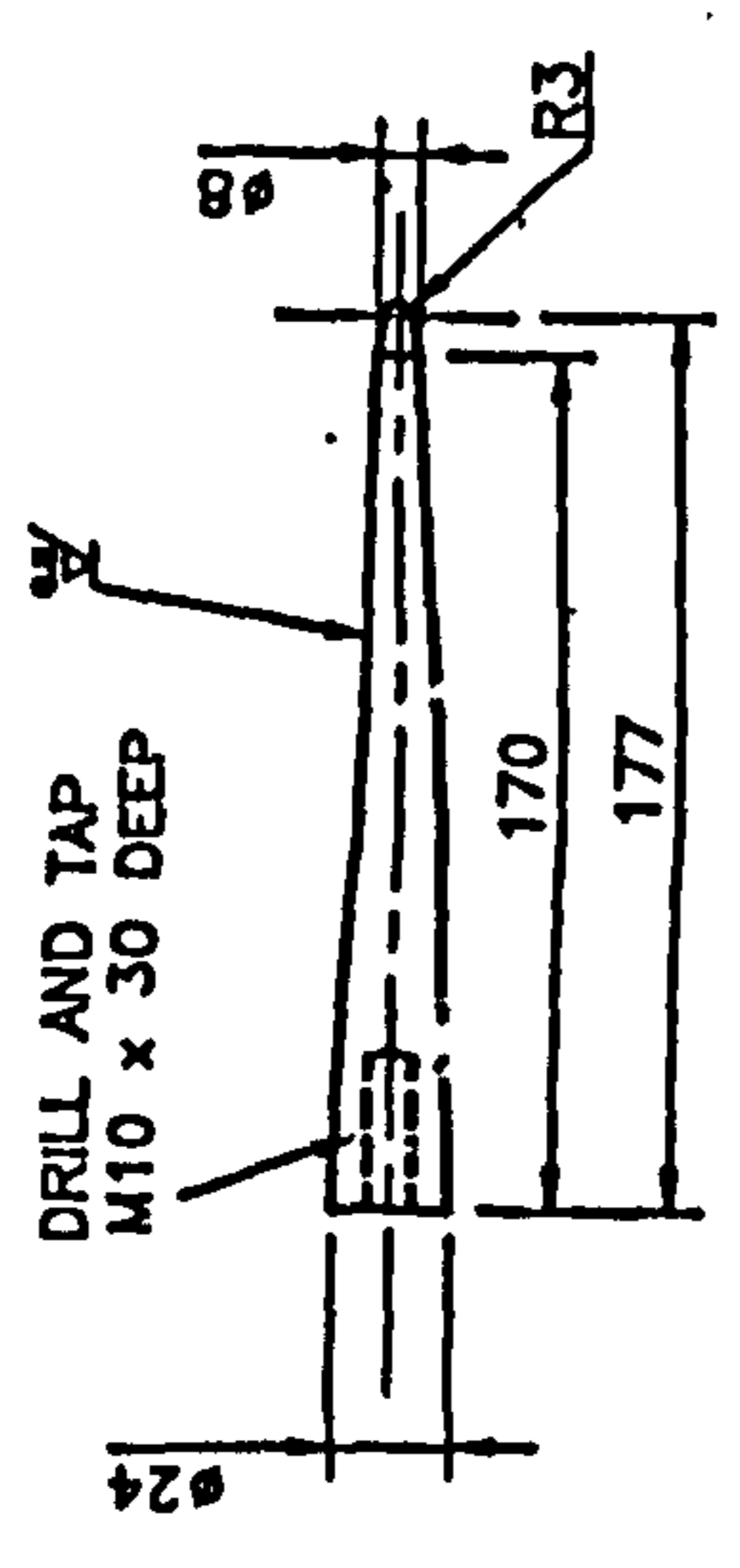
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SECTION A-A

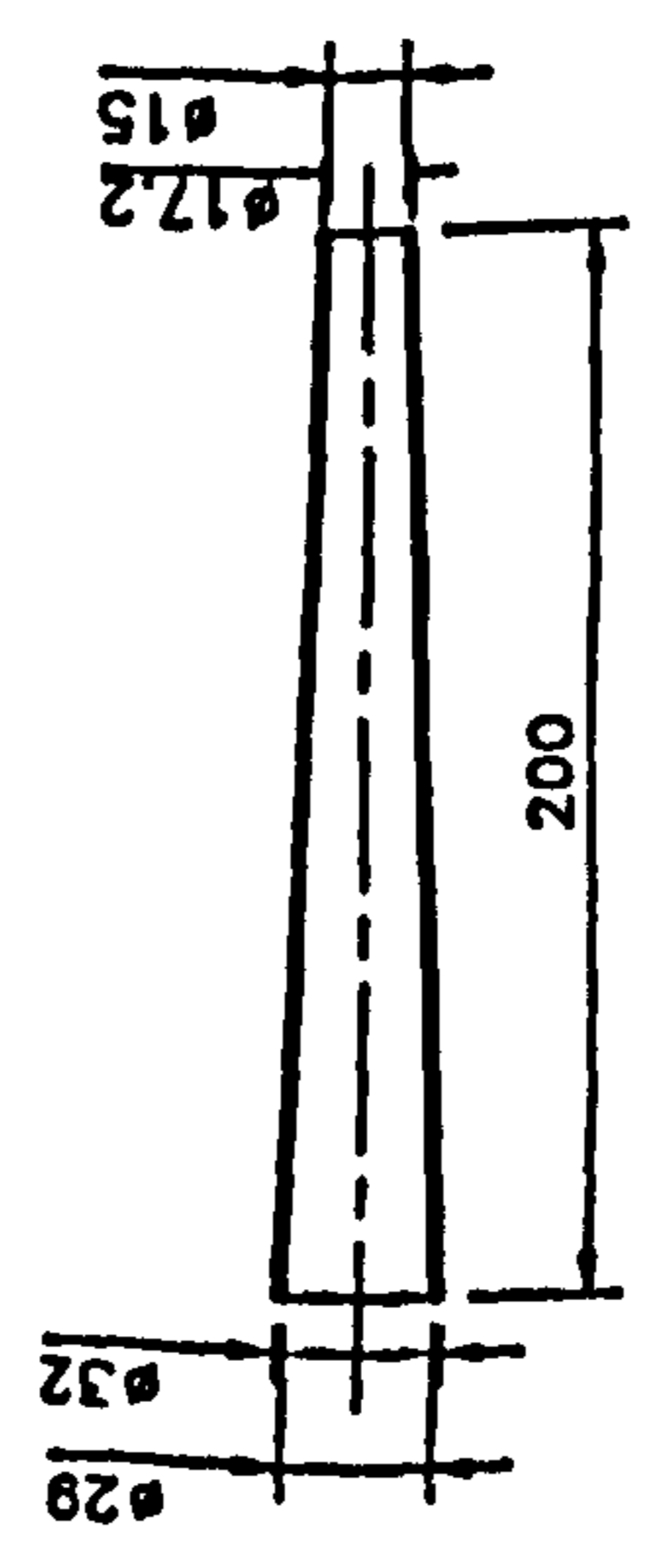
ITEM 1 - VIKING 7' 44MM TEST SOCKET

- MATERIAL - DURALUMIN BAR H30 (DESIGNATION 6082) CONDITION TF
- ALL INTERNAL MACHINING TO BE ∇
- ALL EXTERNAL MACHINING TO BE ∇



ITEM 2 - SPIKE FOR VIKING 7' 44MM SOCKET

- MATERIAL - DURALUMIN BAR H30 (DESIGNATION 6082) CONDITION TF
- NOTE: SURFACE OF SPIKE TO BE MACHINED ∇

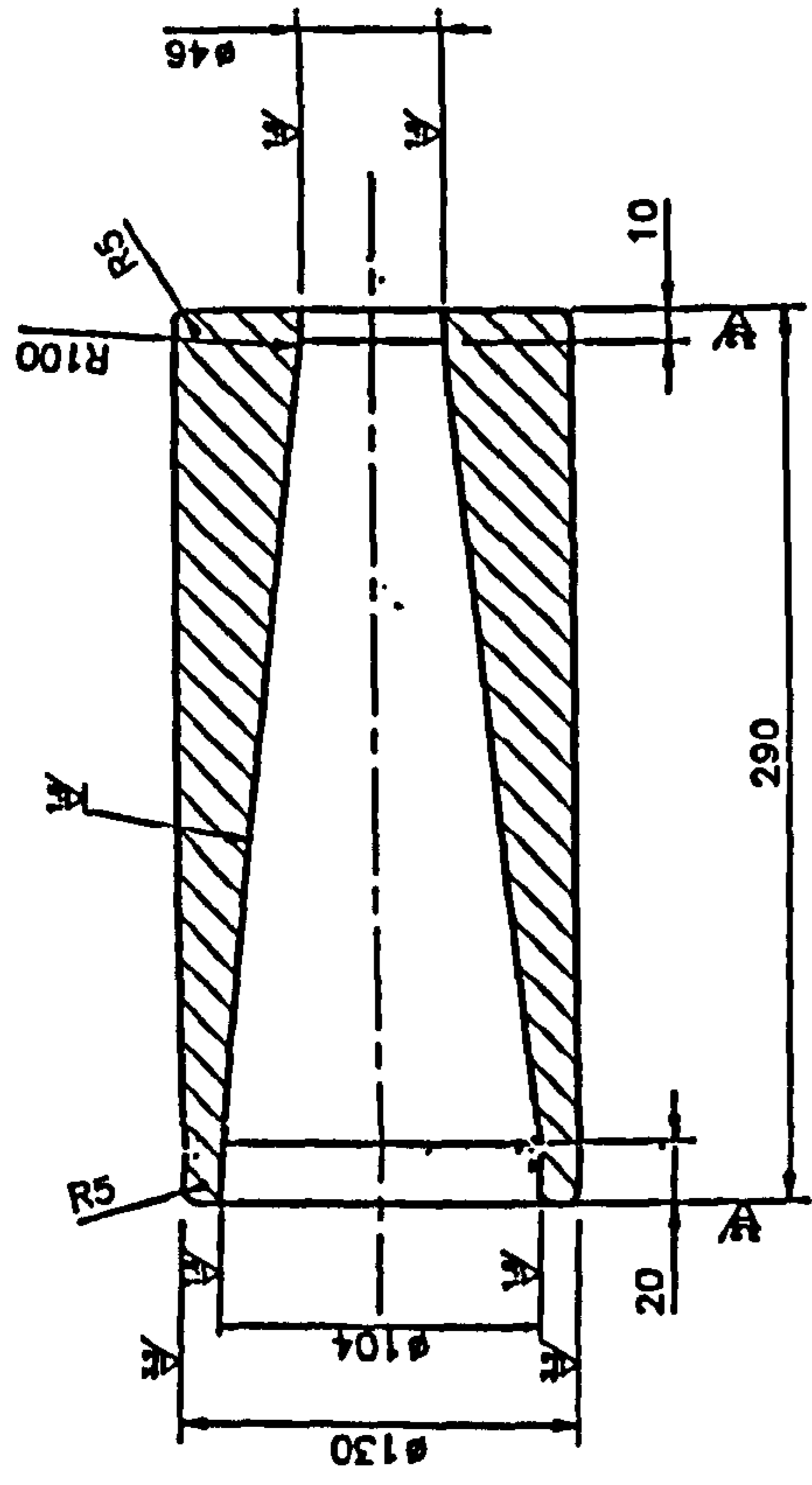


ITEM 3 - TUBE FOR VIKING 7' 44MM SOCKET

- ALL INTERNAL MACHINING TO BE ∇
- ALL EXTERNAL MACHINING TO BE ∇

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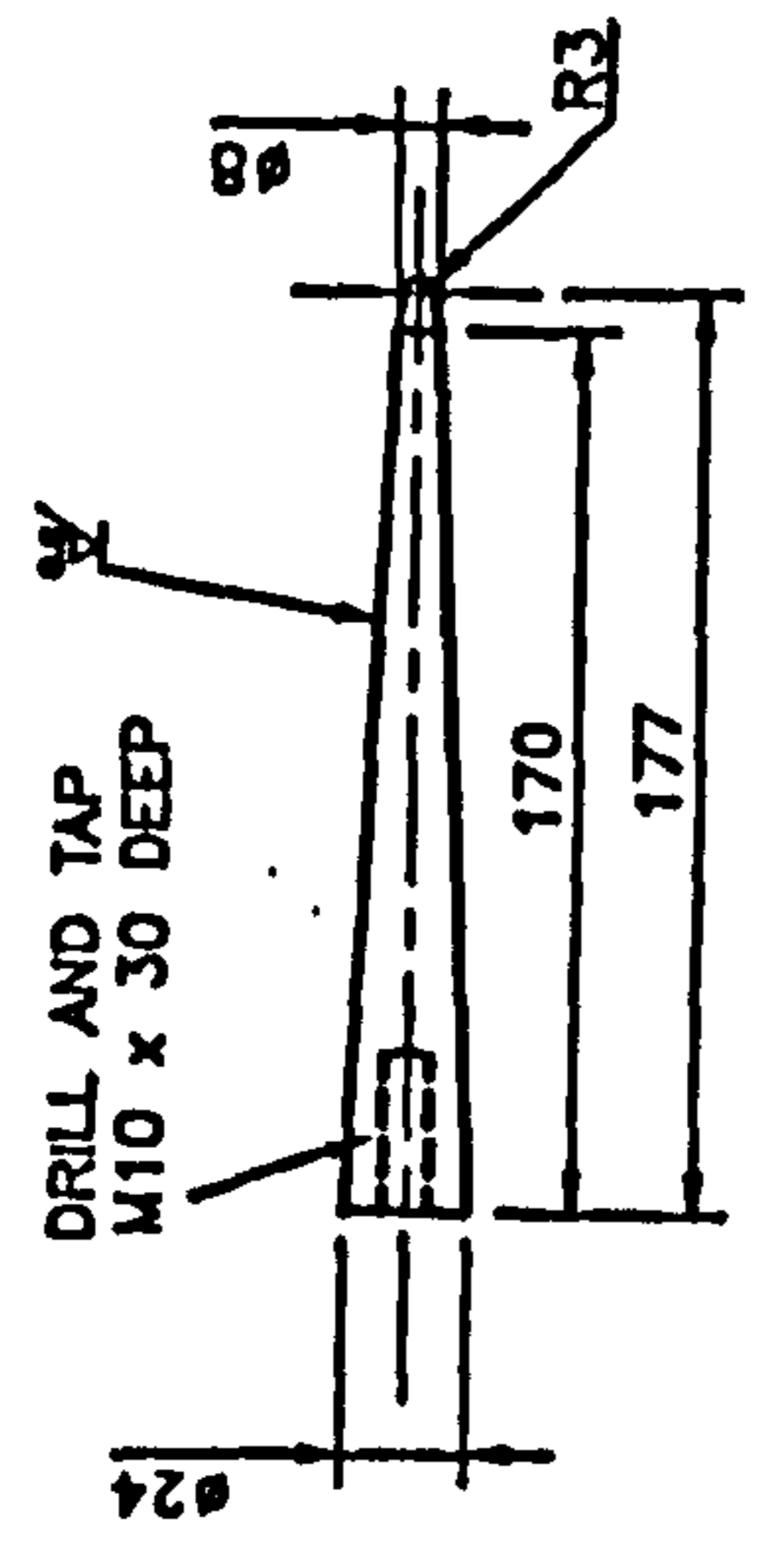
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LETTER	DESCRIPTION		
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SECTION A-A

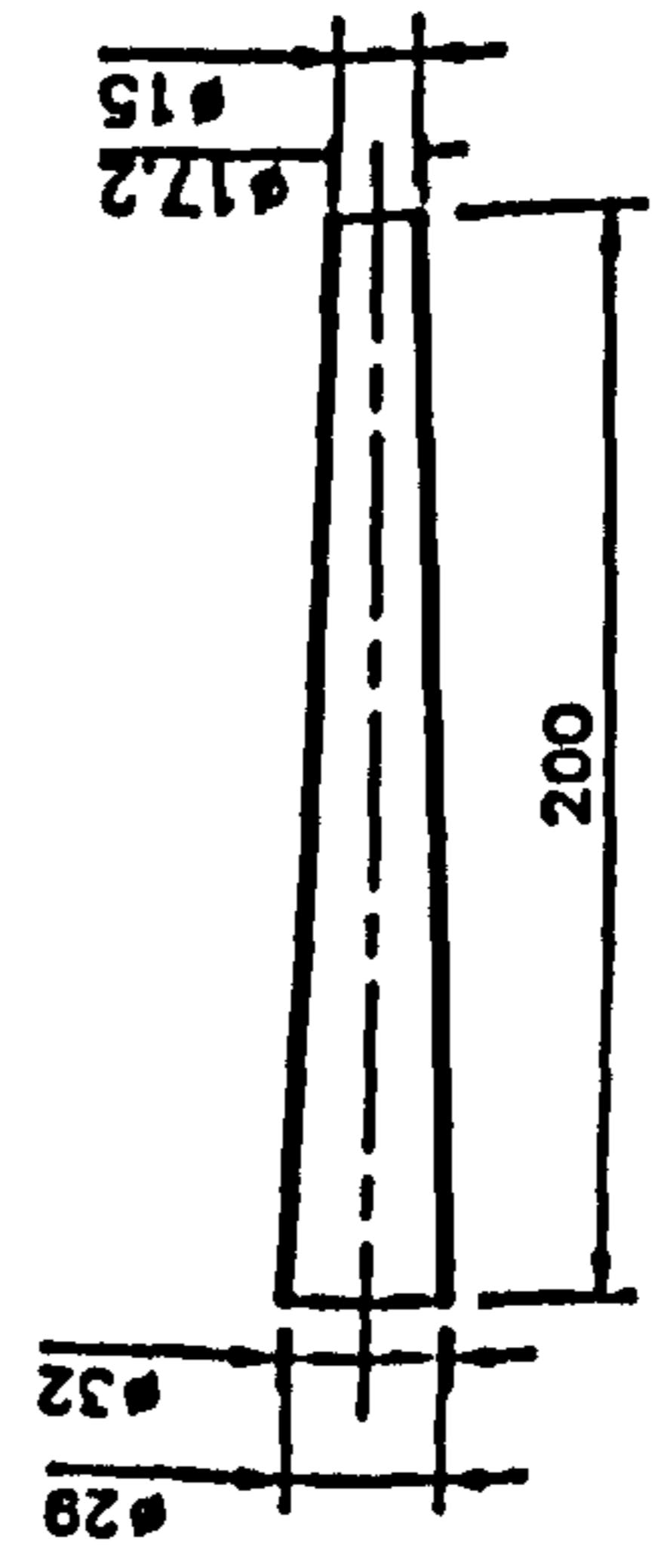
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- MATERIAL - DURALUMIN BAR H30 (DESIGNATION 6082) CONDITION TF
- ALL INTERNAL MACHINING TO BE A
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- MATERIAL - DURALUMIN BAR H30 (DESIGNATION 6082) CONDITION TF
- NOTE: SURFACE OF SPIKE TO BE MACHINED A



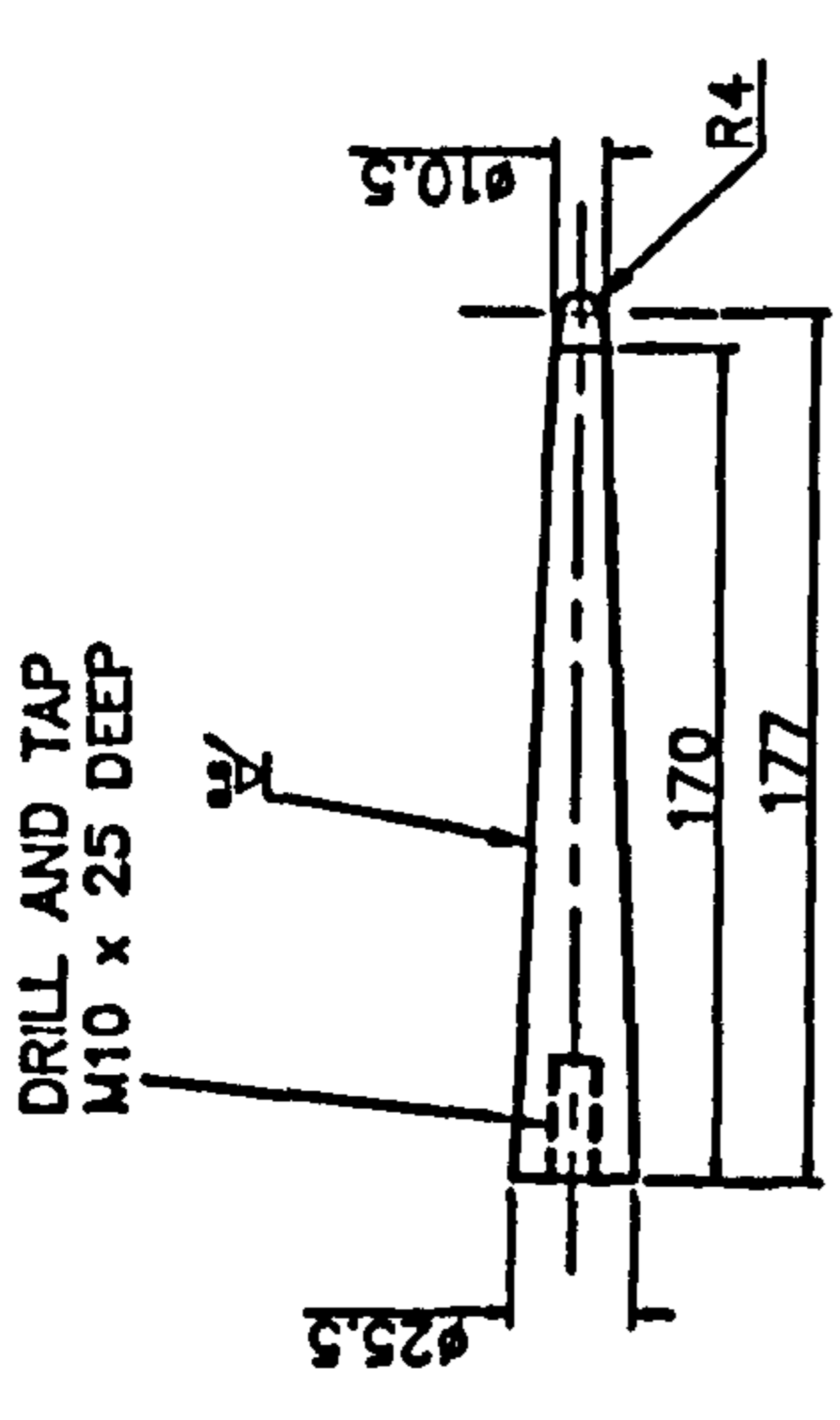
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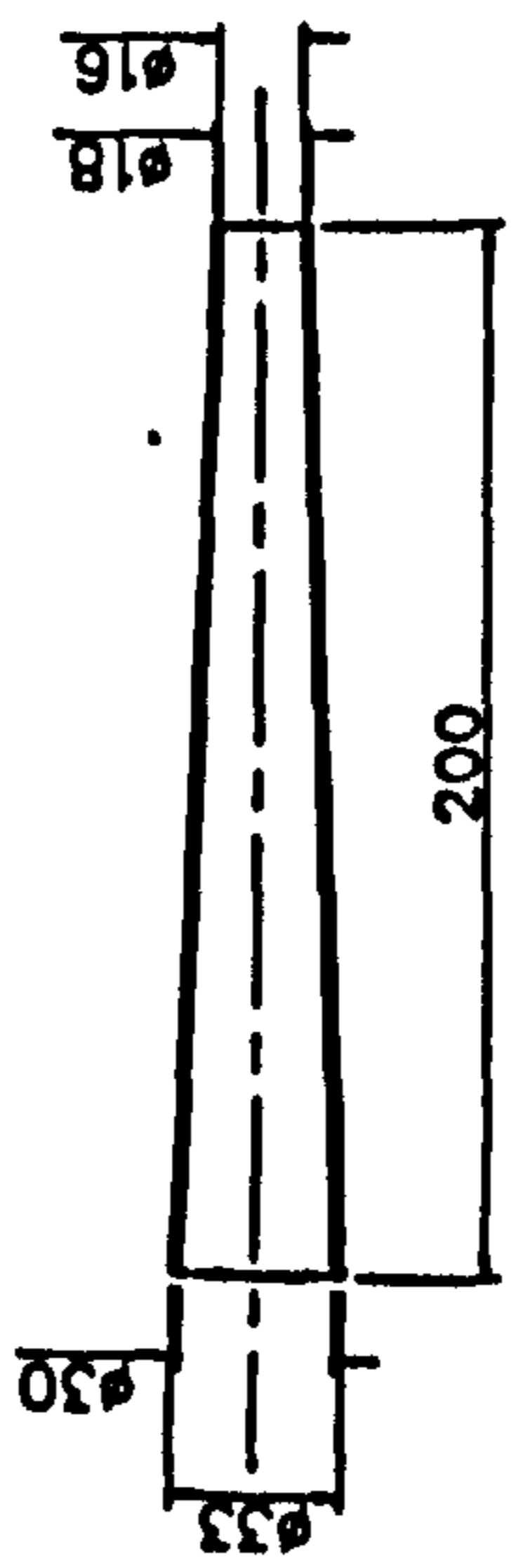
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<p>ITEM 1 - VIKING 7 44MM TEST SOCKET</p>			
<p>ITEM 2 - SPIKE FOR VIKING 7 44MM SOCKET</p>			
<p>ITEM 3 - TUBE FOR VIKING 7 44MM SOCKET</p>			
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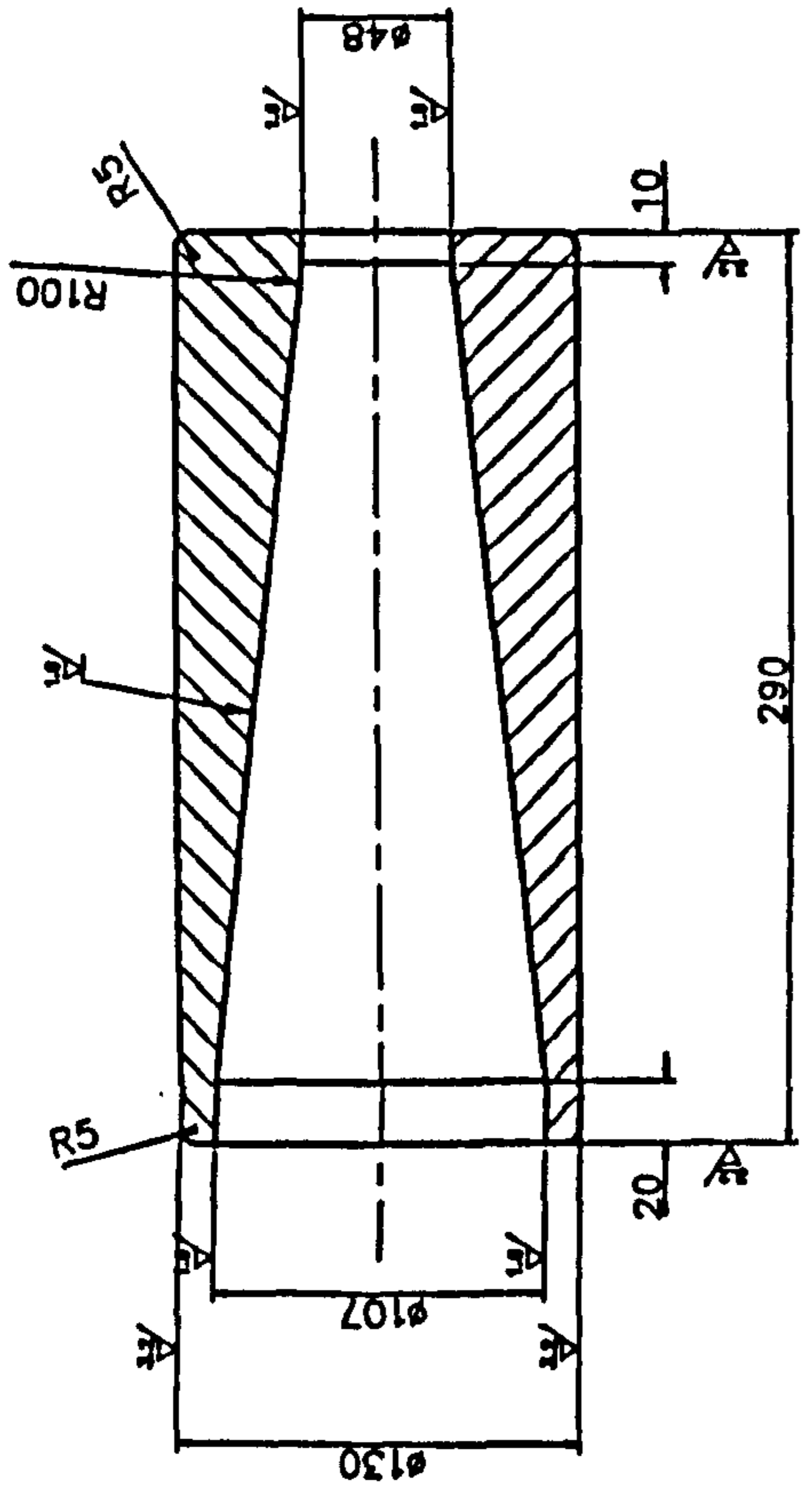
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1				UPDATED		



ITEM 2 - SPIKE FOR 'VIKING 7' 44MM SOCKET
 - MATERIAL - DURALUMIN BAR H30 (DESIGNATION 6082) CONDITION TF
 - NOTE: SURFACE OF SPIKE TO BE MACHINED \sqrt{A}

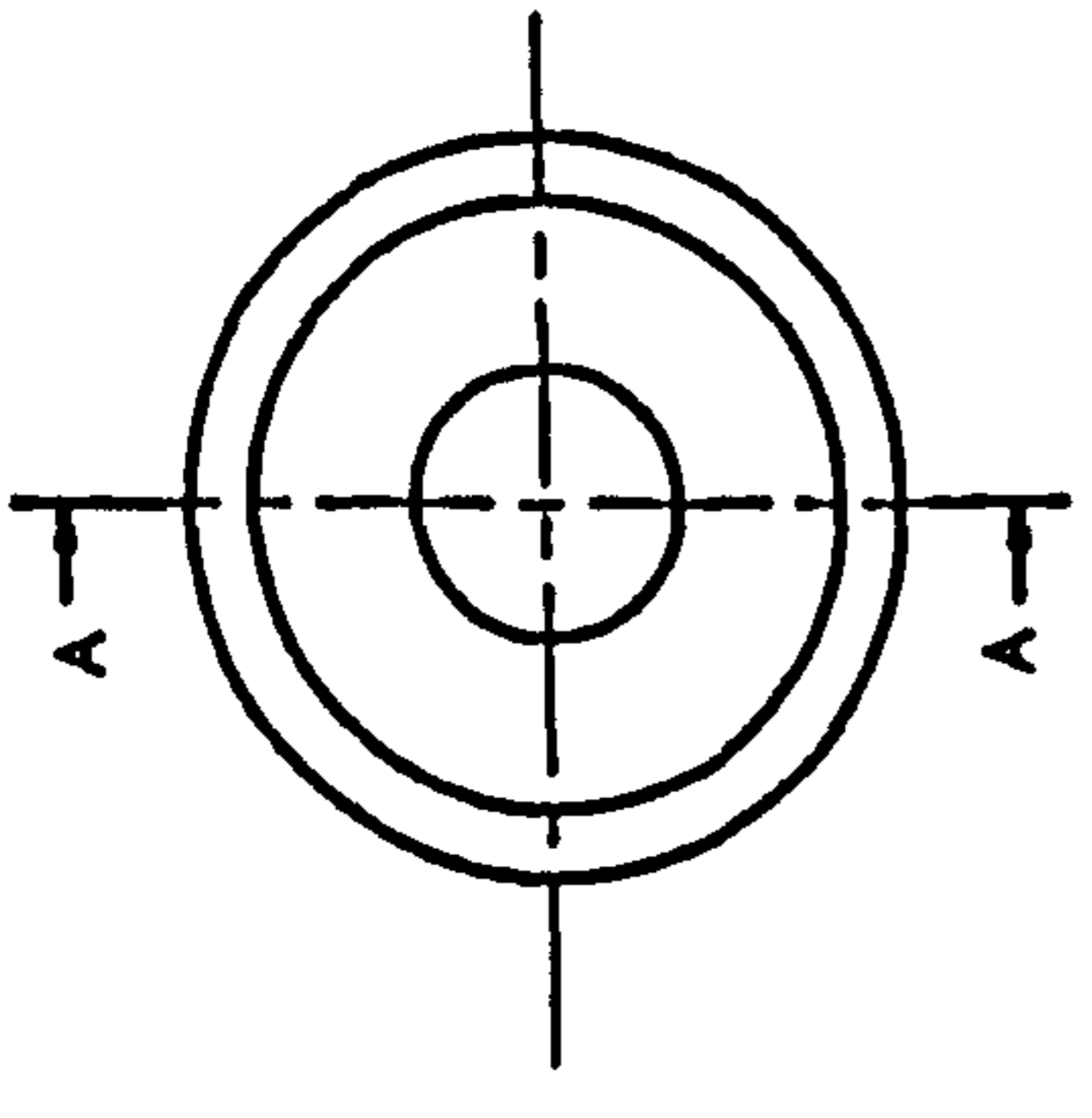


ITEM 3 - TUBE FOR 'VIKING 7' 44MM SOCKET
 - ALL INTERNAL MACHINING TO BE \sqrt{A}
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SECTION A-A

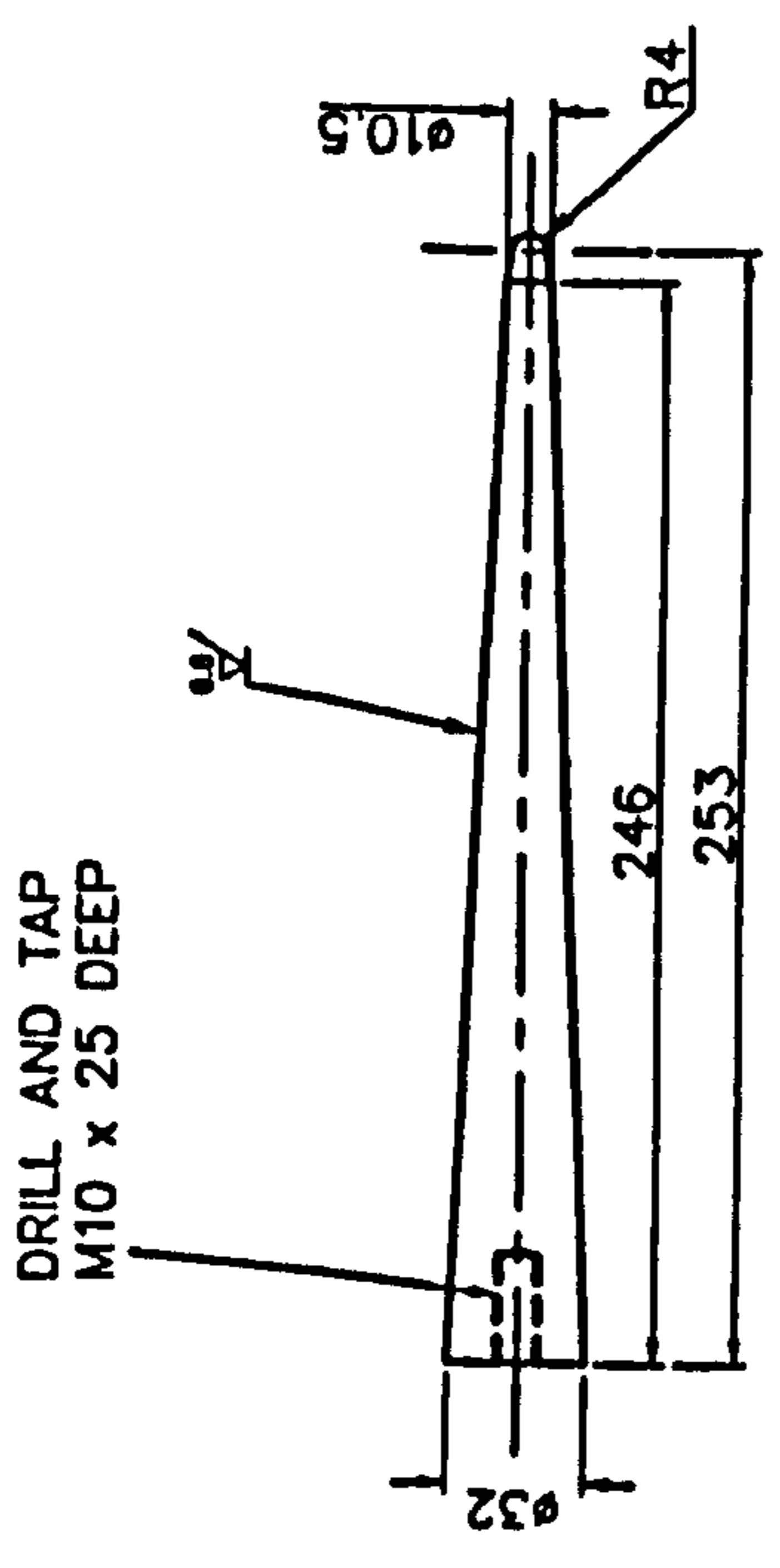
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 - ALL EXTERNAL MACHINING TO BE \sqrt{A}



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CHARLTON			
SCALE: 1:1			
SHEET 1 OF 2			
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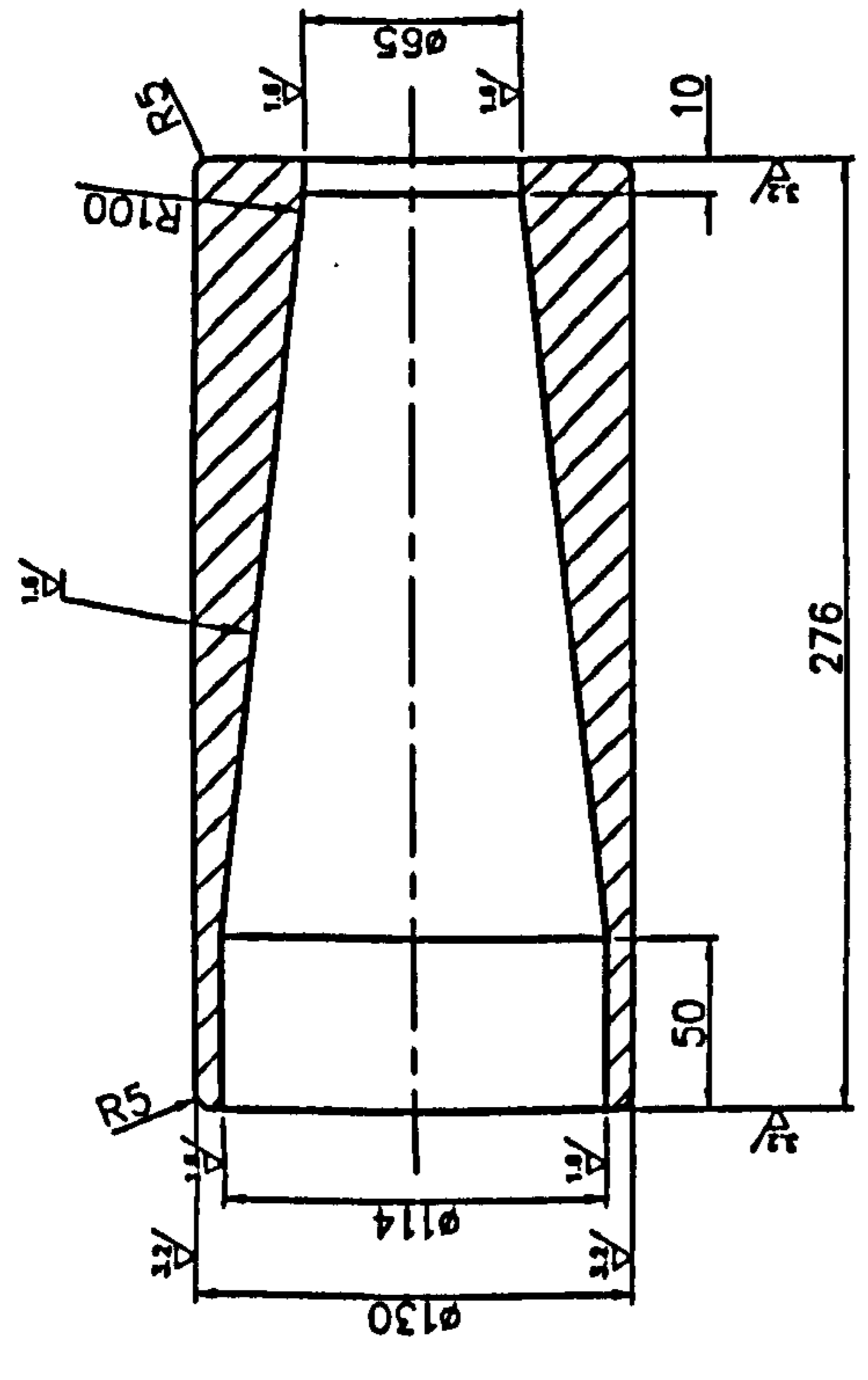
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AMENDMENTS	NO	DATE	DESCRIPTION	CHK	APP



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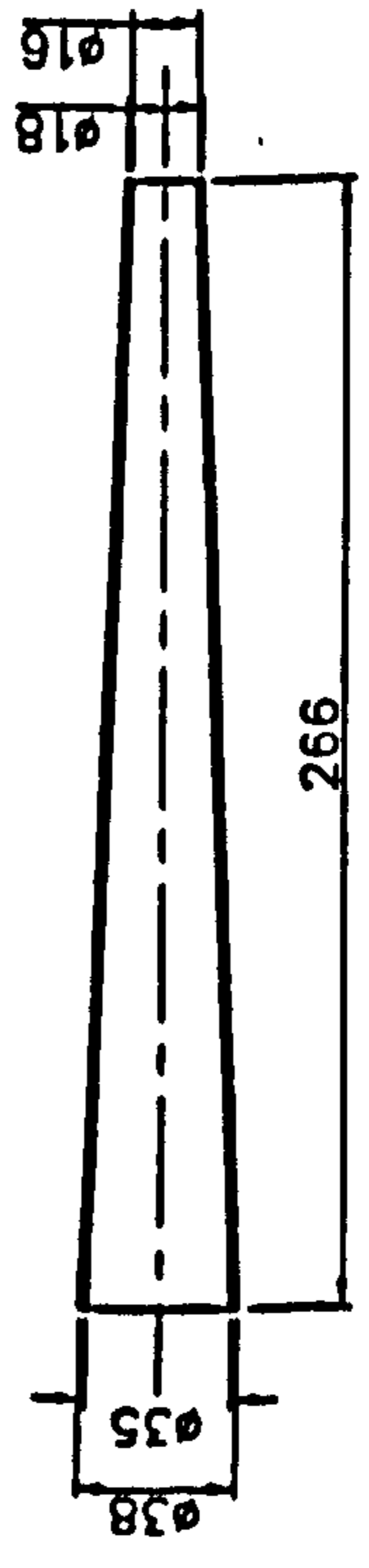
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- NOTE: SURFACE OF SPIKE TO BE MACHINED \sqrt{A}



SECTION A-A

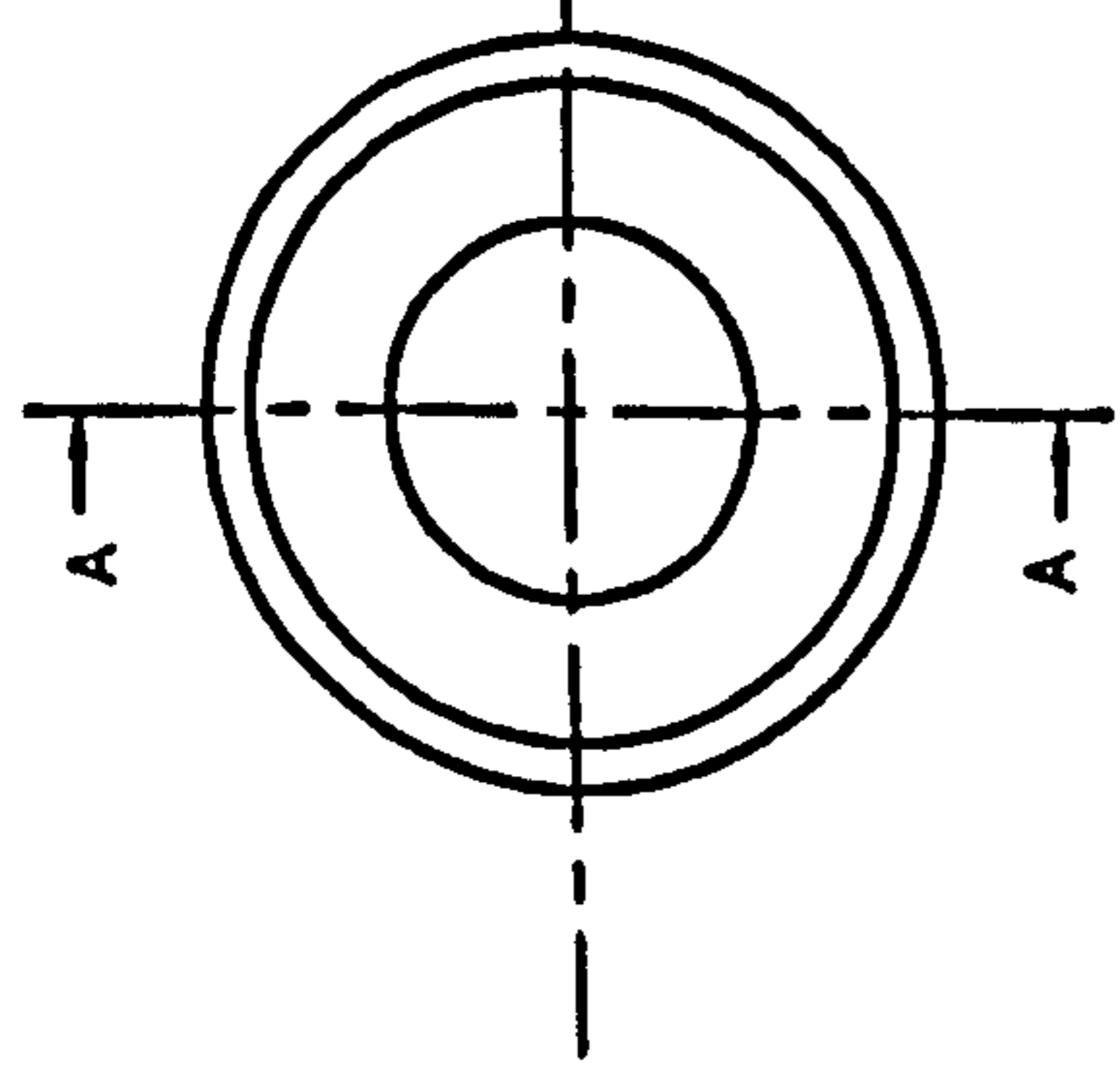
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- MATERIAL - STEEL EN16 CONDITION 'R'
- ALL INTERNAL MACHINING TO BE \sqrt{A}
- ALL EXTERNAL MACHINING TO BE \sqrt{A}



ITEM 3 - TUBE FOR 'VIKING 7' 65MM SOCKET

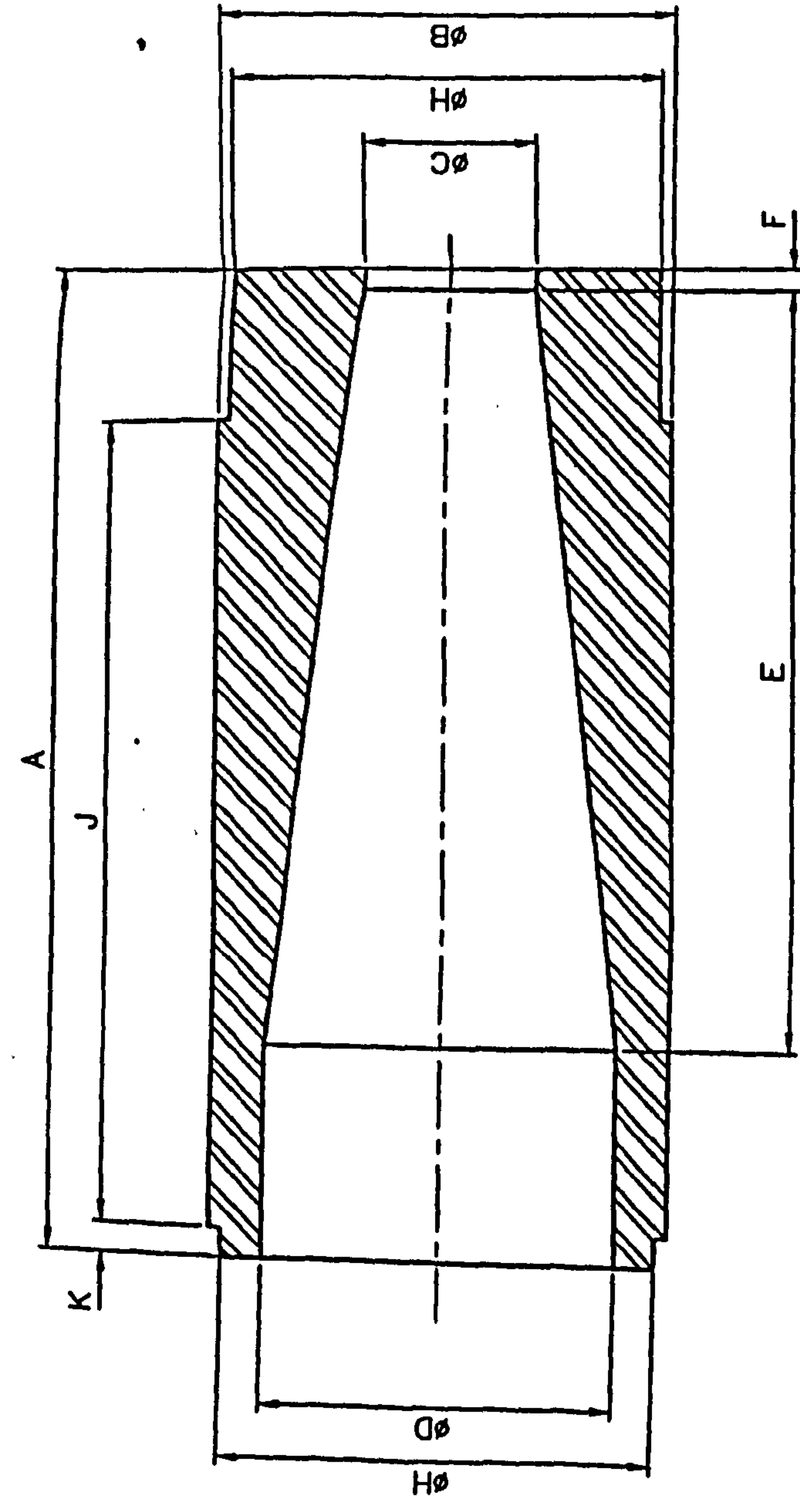
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- ALL INTERNAL MACHINING TO BE \sqrt{A}
- ALL EXTERNAL MACHINING TO BE \sqrt{A}



DRAWING NUMBER/SPECIFICATION	ITEM	DESCRIPTION	REVISION

PARTS LIST	DESCRIPTION	REVISION

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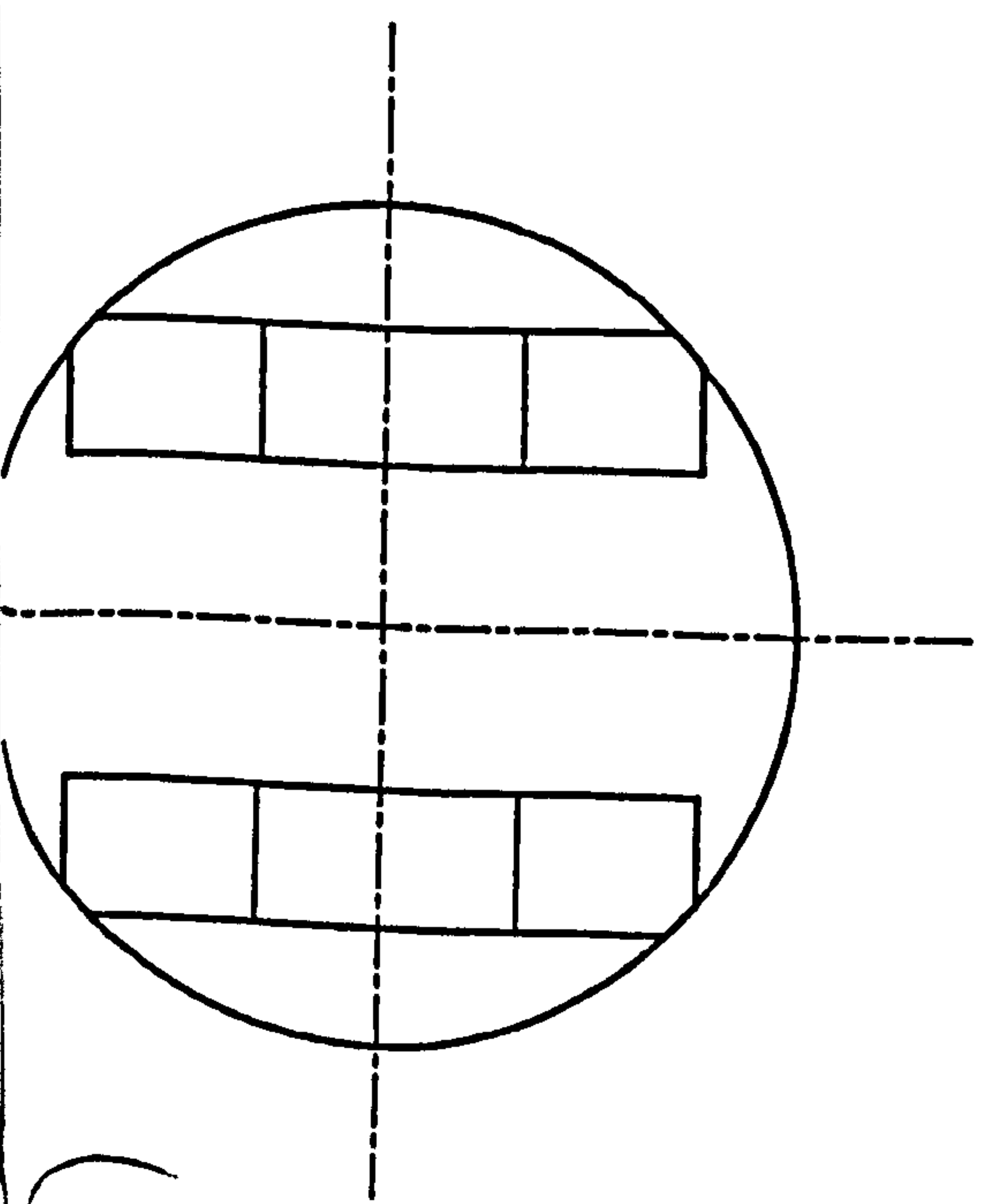
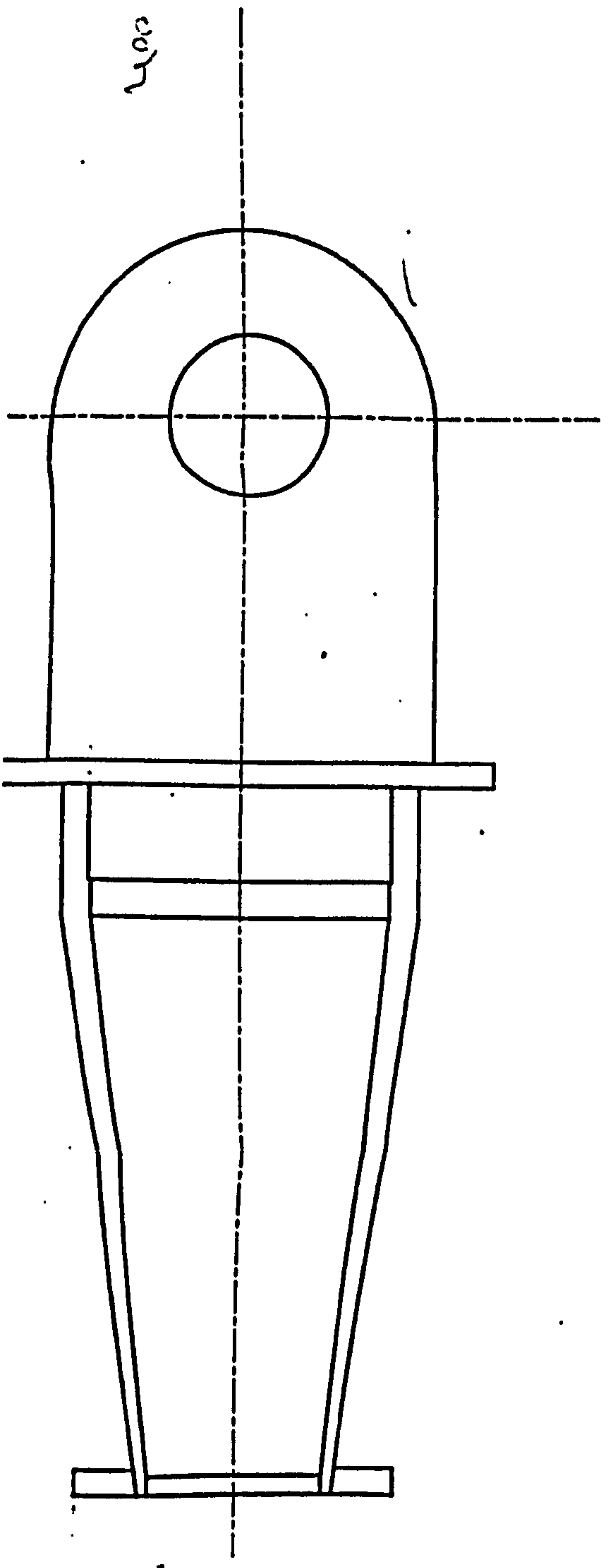
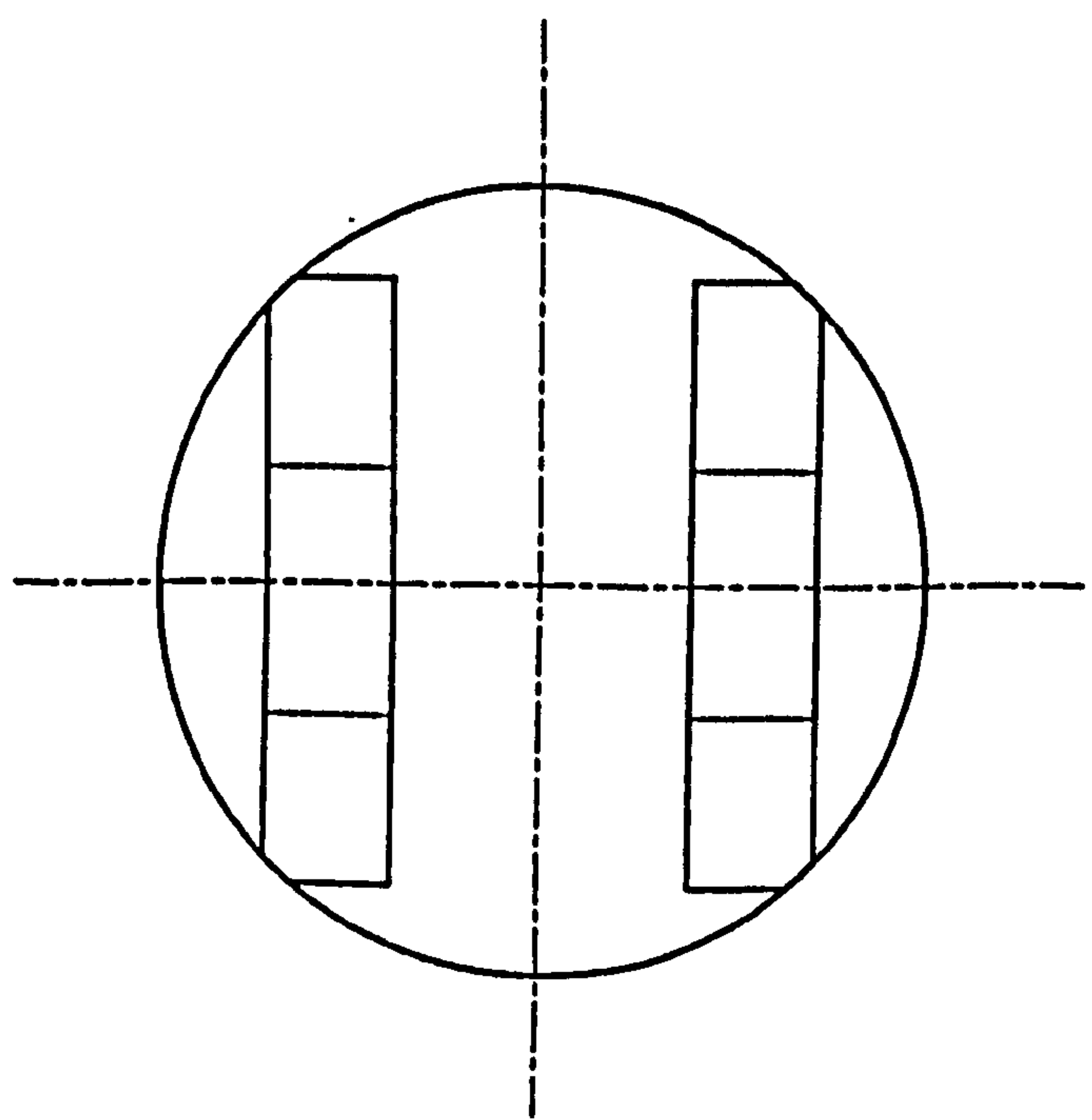
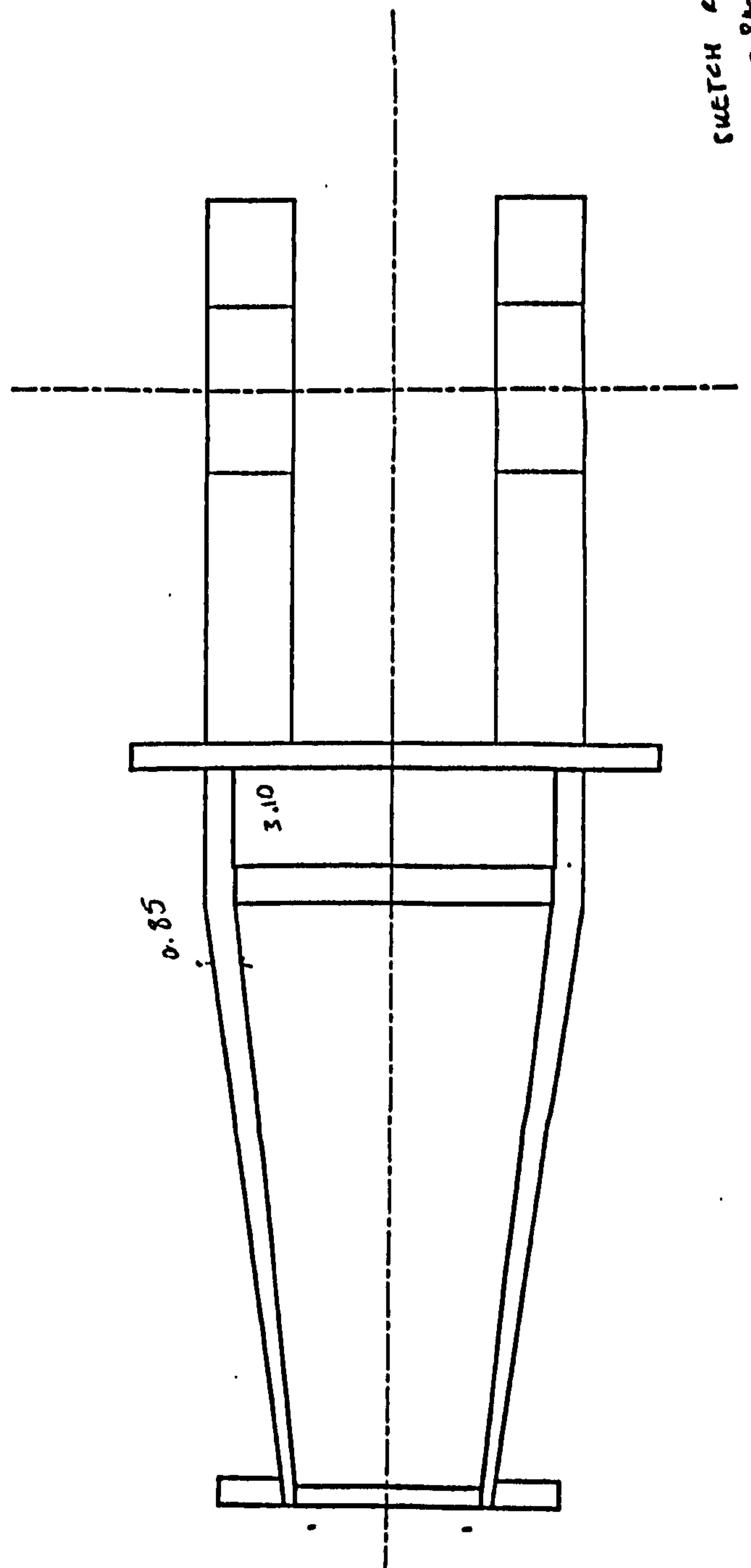
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(425)

LETTER	DATE	INITIALS	DESCRIPTION	CHG	APP

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THIS DRAWING IS IN 24 UNITS UNLESS OTHERWISE STATED SURFACE TEXTURE SHALL BE AS PER MACHINE FINISH UNLESS OTHERWISE SPECIFIED. DIMENSIONS SHALL BE TO UNLESS OTHERWISE SPECIFIED.	DRAWING OFFICE PRACTICE TO B.S. 308 	PROCON BROOK International Ltd BROOKING COURT, SOUTHAMPTON HANTS RG2 1JH	DIMENSIONS OF TEST SOCKETS [DARTFORD TYPE]

SKETCH FOR
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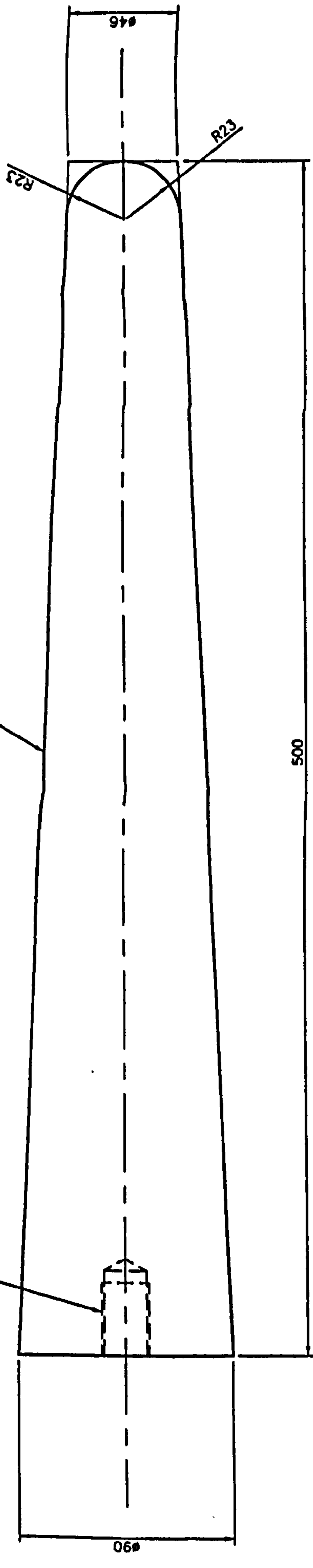


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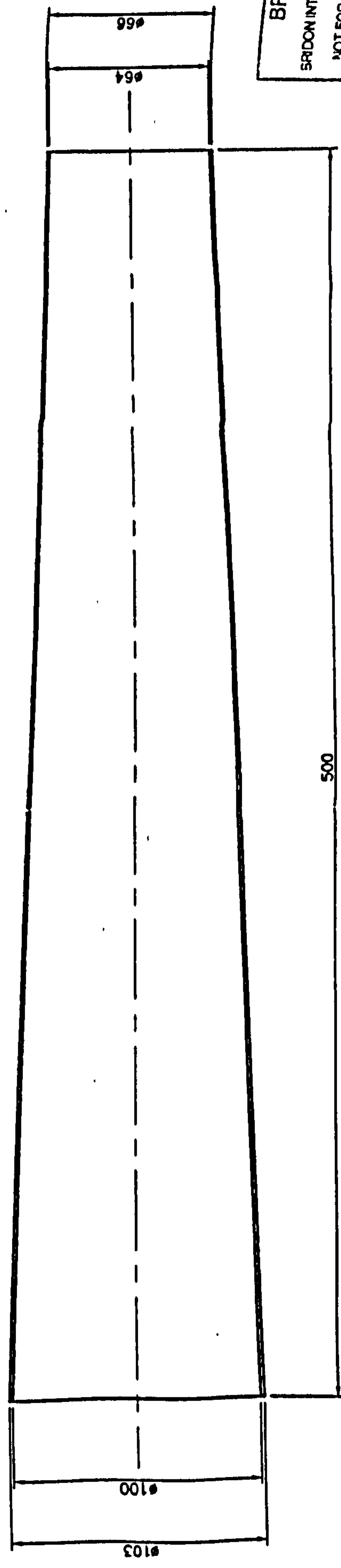
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FOR MANUFACTURING
PURPOSES

LETTER	DATE	INITIAL	DESCRIPTION

AMENDMENTS



ITEM 1 -- SPIKE FOR VIKING 7 #120MM SOCKET
 - MATERIAL - DURALUMIN BAR H30
 (DESIGNATION 6082) CONDITION TF
 - NOTE: SURFACE OF SPIKE TO BE MACHINED ∇



ITEM 2 -- TUBE FOR VIKING 7 #120MM SOCKET
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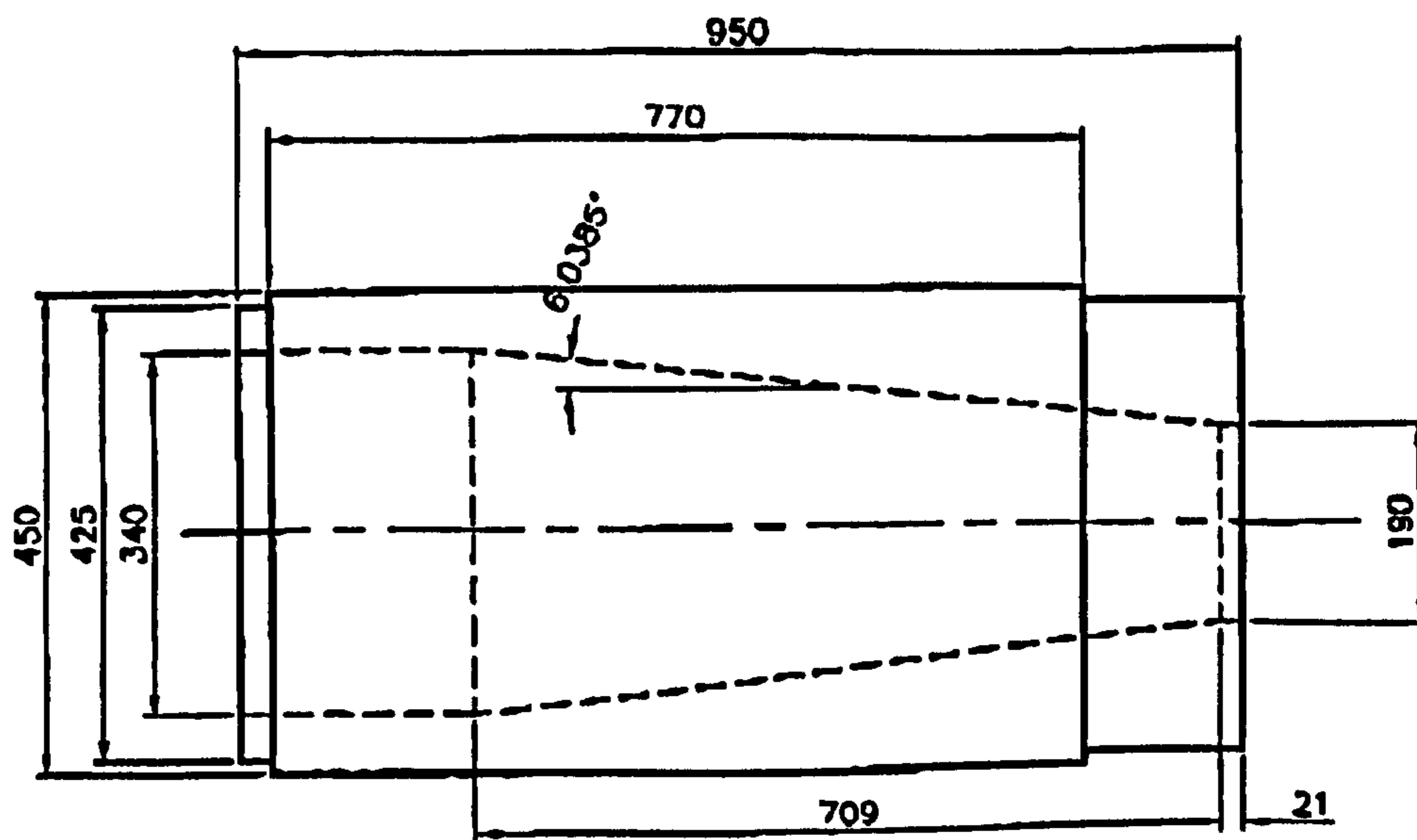
BRIDON
 BRIDON INTERNATIONAL LTD
 NOT FOR MANUFACTURE

DRAWING NUMBER/SPECIFICATION	ITEM	DESCRIPTION	NO.
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THIS DRAWING IS IN 20 PARTS			
SURFACE FINISH VALUES IN μ M			
FINISH SYMBOLS AND SHARP EDGES			
REFERENCES UNLESS OTHERWISE STATED IN DIMENSIONS & FIT			
ANGLE IN DEGREES & R'			
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30000000 TO 100000000 1.10			
100000000 TO 300000000 1.20			
300000000 TO 1000000000 1.30			
1000000000 TO 3000000000 1.40			
3000000000 TO 10000000000 1.50			
10000000000 TO 30000000000 1.60			
30000000000 TO 100000000000 1.70			
100000000000 TO 300000000000 1.80			
300000000000 TO 1000000000000 1.90			
1000000000000 TO 3000000000000 2.00			
3000000000000 TO 10000000000000 2.10			
10000000000000 TO 30000000000000 2.20			
30000000000000 TO 100000000000000 2.30			
100000000000000 TO 300000000000000 2.40			
300000000000000 TO 1000000000000000 2.50			
1000000000000000 TO 3000000000000000 2.60			
3000000000000000 TO 10000000000000000 2.70			
10000000000000000 TO 30000000000000000 2.80			
30000000000000000 TO 100000000000000000 2.90			
100000000000000000 TO 300000000000000000 3.00			
300000000000000000 TO 1000000000000000000 3.10			
1000000000000000000 TO 3000000000000000000 3.20			
3000000000000000000 TO 10000000000000000000 3.30			
10000000000000000000 TO 30000000000000000000 3.40			
30000000000000000000 TO 100000000000000000000 3.50			
100000000000000000000 TO 300000000000000000000 3.60			
300000000000000000000 TO 1000000000000000000000 3.70			
1000000000000000000000 TO 3000000000000000000000 3.80			
3000000000000000000000 TO 10000000000000000000000 3.90			
10000000000000000000000 TO 30000000000000000000000 4.00			
30000000000000000000000 TO 100000000000000000000000 4.10			
100000000000000000000000 TO 300000000000000000000000 4.20			
300000000000000000000000 TO 1000000000000000000000000 4.30			
1000000000000000000000000 TO 3000000000000000000000000 4.40			
3000000000000000000000000 TO 10000000000000000000000000 4.50			
10000000000000000000000000 TO 30000000000000000000000000 4.60			
30000000000000000000000000 TO 100000000000000000000000000 4.70			
100000000000000000000000000 TO 300000000000000000000000000 4.80			
300000000000000000000000000 TO 1000000000000000000000000000 4.90			
1000000000000000000000000000 TO 3000000000000000000000000000 5.00			
3000000000000000000000000000 TO 10000000000000000000000000000 5.10			
10000000000000000000000000000 TO 30000000000000000000000000000 5.20			
30000000000000000000000000000 TO 100000000000000000000000000000 5.30			
100000000000000000000000000000 TO 300000000000000000000000000000 5.40			
300000000000000000000000000000 TO 1000000000000000000000000000000 5.50			
1000000000000000000000000000000 TO 3000000000000000000000000000000 5.60			
3000000000000000000000000000000 TO 10000000000000000000000000000000 5.70			
10000000000000000000000000000000 TO 30000000000000000000000000000000 5.80			
30000000000000000000000000000000 TO 100000000000000000000000000000000 5.90			
100000000000000000000000000000000 TO 300000000000000000000000000000000 6.00			
300000000000000000000000000000000 TO 1000000000000000000000000000000000 6.10			
1000000000000000000000000000000000 TO 3000000000000000000000000000000000 6.20			
3000000000000000000000000000000000 TO 10000000000000000000000000000000000 6.30			
10000000000000000000000000000000000 TO 30000000000000000000000000000000000 6.40			
30000000000000000000000000000000000 TO 100000000000000000000000000000000000 6.50			
100000000000000000000000000000000000 TO 300000000000000000000000000000000000 6.60			
300000000000000000000000000000000000 TO 1000000000000000000000000000000000000 6.70			
1000000000000000000000000000000000000 TO 3000000000000000000000000000000000000 6.80			
3000000000000000000000000000000000000 TO 10000000000000000000000000000000000000 6.90			
10000000000000000000000000000000000000 TO 30000000000000000000000000000000000000 7.00			
30000000000000000000000000000000000000 TO 100000000000000000000000000000000000000 7.10			
100000000000000000000000000000000000000 TO 300000000000000000000000000000000000000 7.20			
300000000000000000000000000000000000000 TO 1000000000000000000000000000000000000000 7.30			
1000000000000000000000000000000000000000 TO 3000000000000000000000000000000000000000 7.40			
3000000000000000000000000000000000000000 TO 100 7.50			
100 TO 300 7.60			
300 TO 1000 7.70			
1000 TO 3000 7.80			
3000 TO 100 7.90			
100 TO 300 8.00			
300 TO 1000 8.10			
1000 TO 3000 8.20			
3000 TO 100 8.30			
100 TO 300 8.40			
300 TO 1000 8.50			
1000 TO 3000 8.60			
3000 TO 100 8.70			
100 TO 300 8.80			
300 TO 1000 8.90			
1000 TO 3000 9.00			

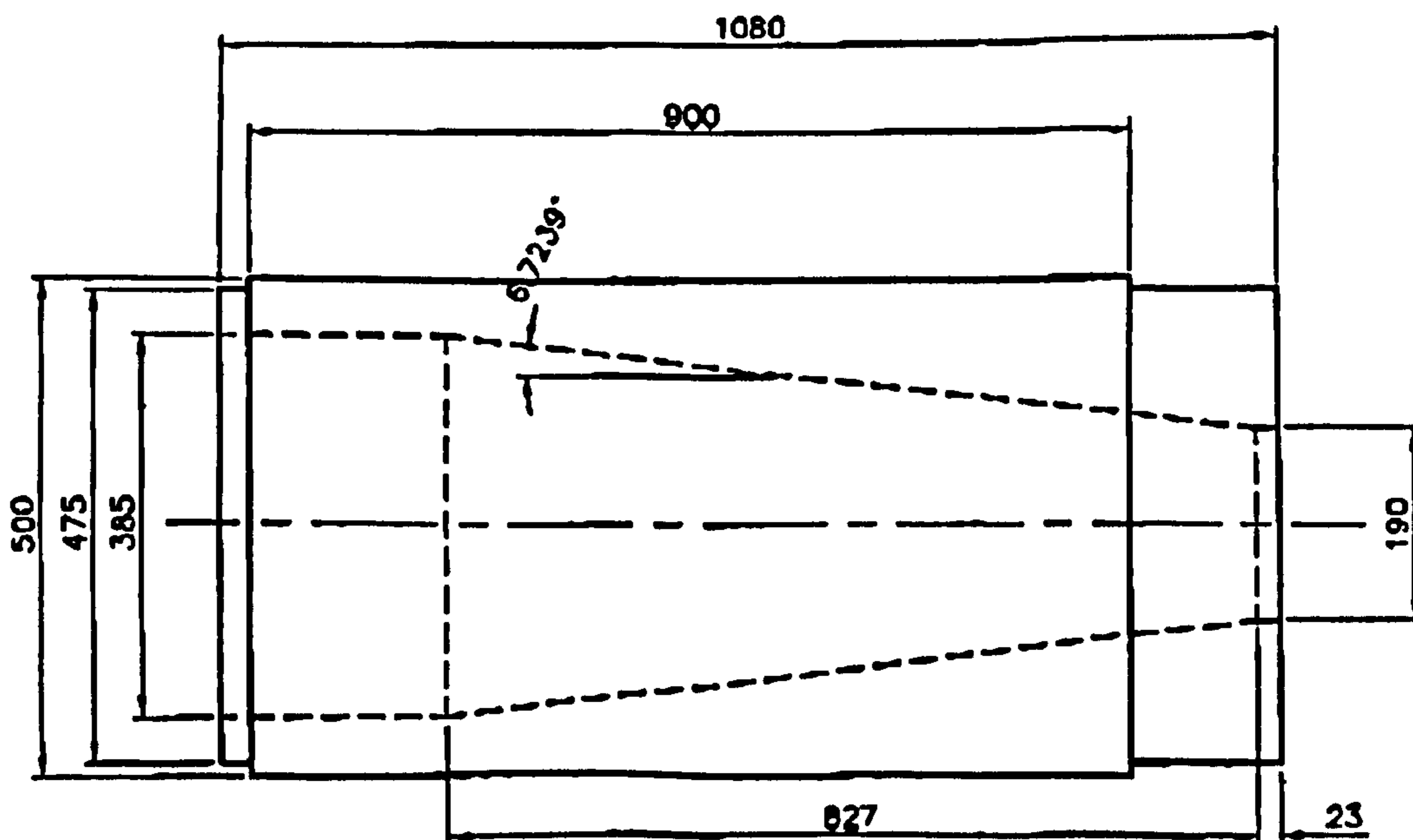
BRIDON
 BRIDON INTERNATIONAL LTD
 DETAIL OF SPIKE AND TUBE
 FOR #120MM SOCKET
 VIKING 7 DEVELOPMENT
 DRG. No. M-13037
 SHEET 1 OF 1

DRAWING NUMBER/SPECIFICATION	ITEM	DESCRIPTION	NO.
BRIDON OFFICE PRACTICE TO S.A.S. 200			
THIS DRAWING IS IN 20 PARTS			
SURFACE FINISH VALUES IN μ M			
FINISH SYMBOLS AND SHARP EDGES			
REFERENCES UNLESS OTHERWISE STATED IN DIMENSIONS & FIT			
ANGLE IN DEGREES & R'			
TOLERANCES - UP TO 300 0.10			
300 TO 1000 0.15			
1000 TO 3000 0.20			
3000 TO 10000 0.30			
10000 TO 30000 0.40			
30000 TO 100000 0.50			
100000 TO 300000 0.60			
300000 TO 1000000 0.70			
1000000 TO 3000000 0.80			
3000000 TO 10000000 0.90			
10000000 TO 30000000 1.00			
30000000 TO 100000000 1.10			
100000000 TO 300000000 1.20			
300000000 TO 1000000000 1.30			
1000000000 TO 3000000000 1.40			
3000000000 TO 10000000000 1.50			
10000000000 TO 30000000000 1.60			
30000000000 TO 100000000000 1.70			
100000000000 TO 300000000000 1.80			
300000000000 TO 1000000000000 1.90			
1000000000000 TO 3000000000000 2.00			
3000000000000 TO 10000000000000 2.10			
10000000000000 TO 30000000000000 2.20			
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300000000000000 TO 1000000000000000 2.50			
1000000000000000 TO 3000000000000000 2.60			
3000000000000000 TO 10000000000000000 2.70			
10000000000000000 TO 30000000000000000 2.80			
30000000000000000 TO 100000000000000000 2.90			
100000000000000000 TO 300000000000000000 3.00			
300000000000000000 TO 1000000000000000000 3.10			
1000000000000000000 TO 3000000000000000000 3.20			
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1000000000000000000000 TO 3000000000000000000000 3.80			
3000000000000000000000 TO 10000000000000000000000 3.90			
10000000000000000000000 TO 30000000000000000000000 4.00			
30000000000000000000000 TO 100000000000000000000000 4.10			
100000000000000000000000 TO 300000000000000000000000 4.20			
300000000000000000000000 TO 1000000000000000000000000 4.30			
1000000000000000000000000 TO 3000000000000000000000000 4.40			
3000000000000000000000000 TO 10000000000000000000000000 4.50			
10000000			

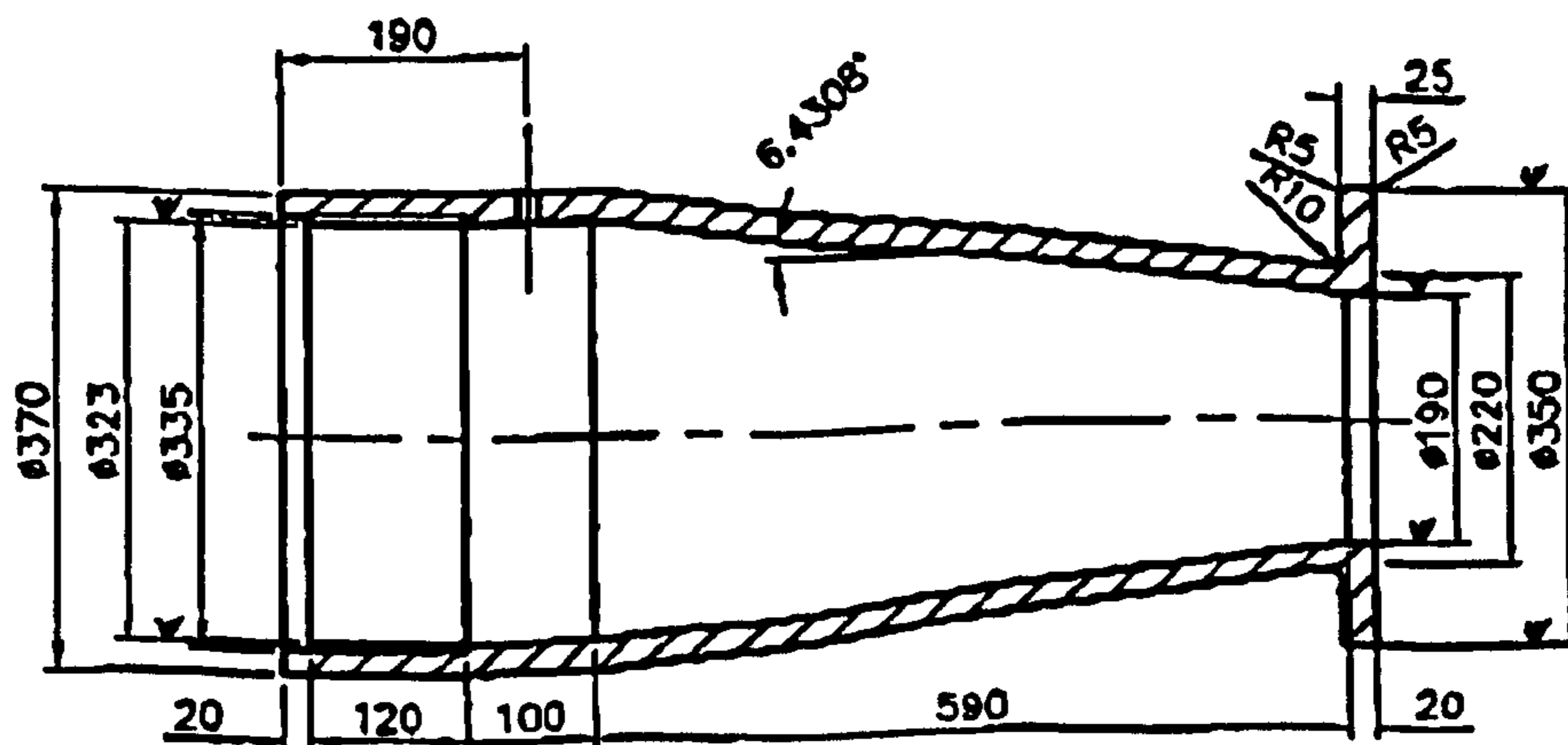
VIKING 7 Ø120MM TEST SOCKETS



SMALL VIKING 7 Ø120MM SOCKET (BRIDON)

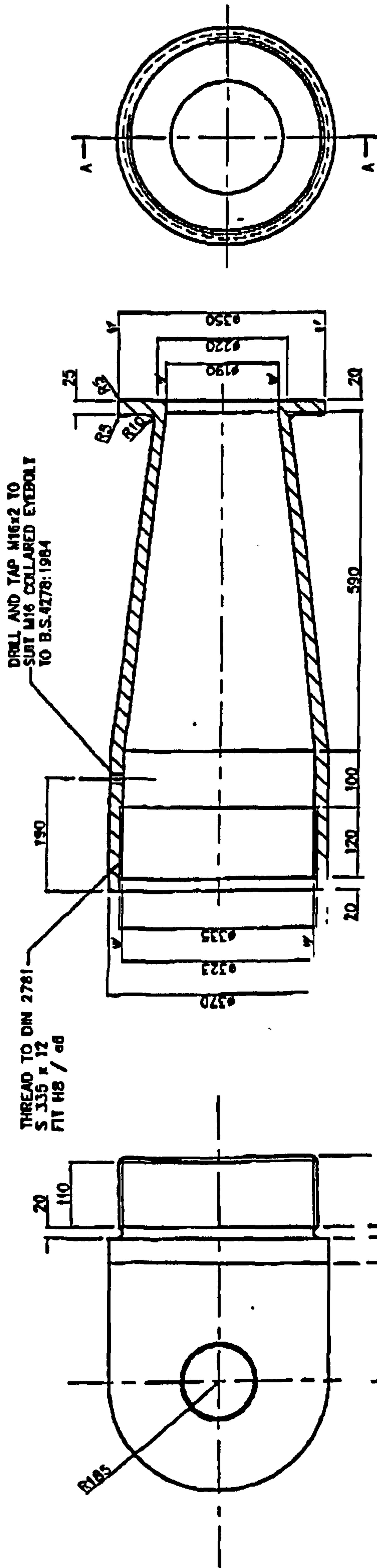


BIG VIKING 7 Ø120MM SOCKET (BRIDON)



MACHINED VIKING 7 Ø120MM SOCKET

AMENDMENTS			
LETTER	DATE	DESCRIPTION	BY
C	11/11/96	UPDATED	SC



SECTION A-A

ITEM 1 - WING 7 1120MM SOCKET

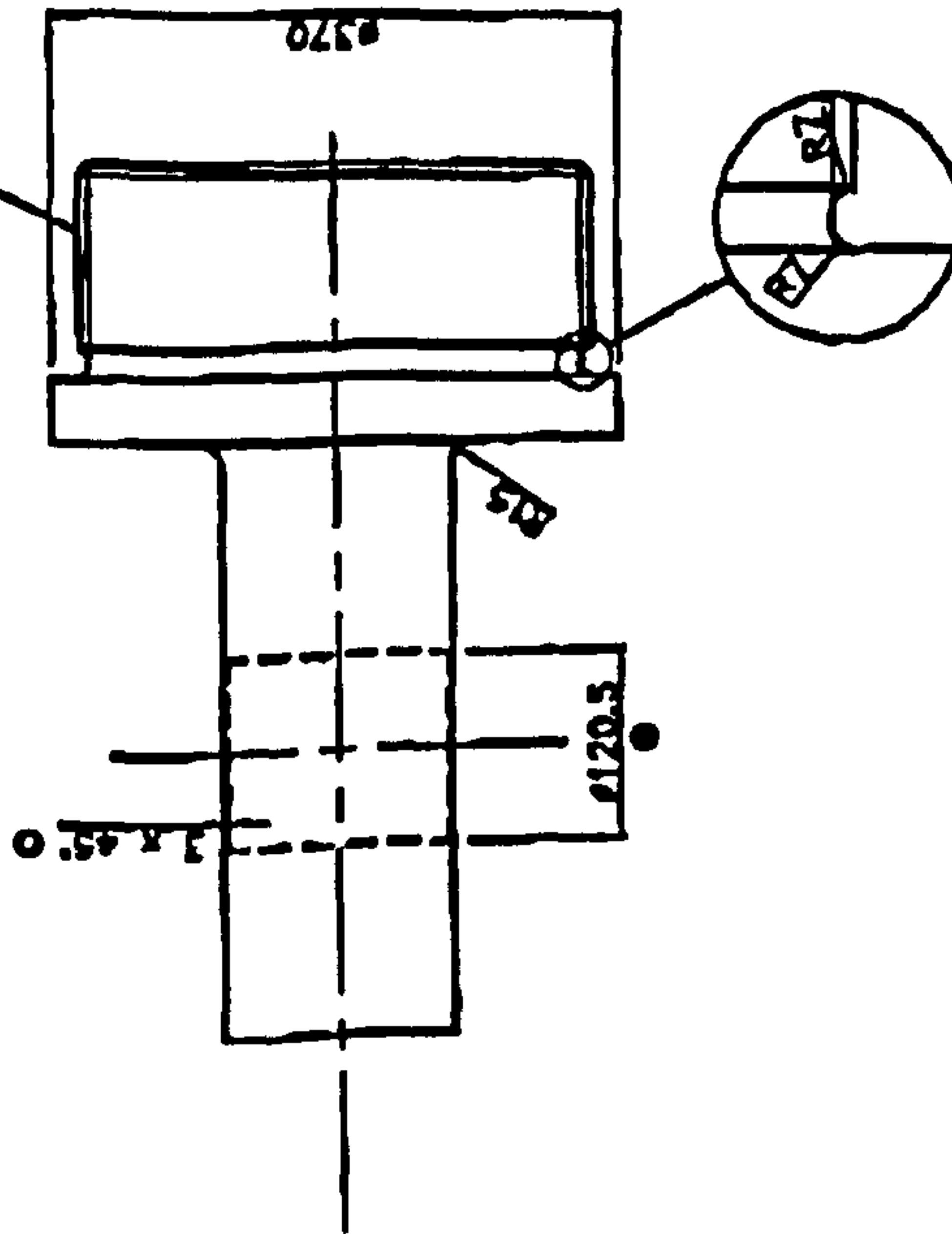
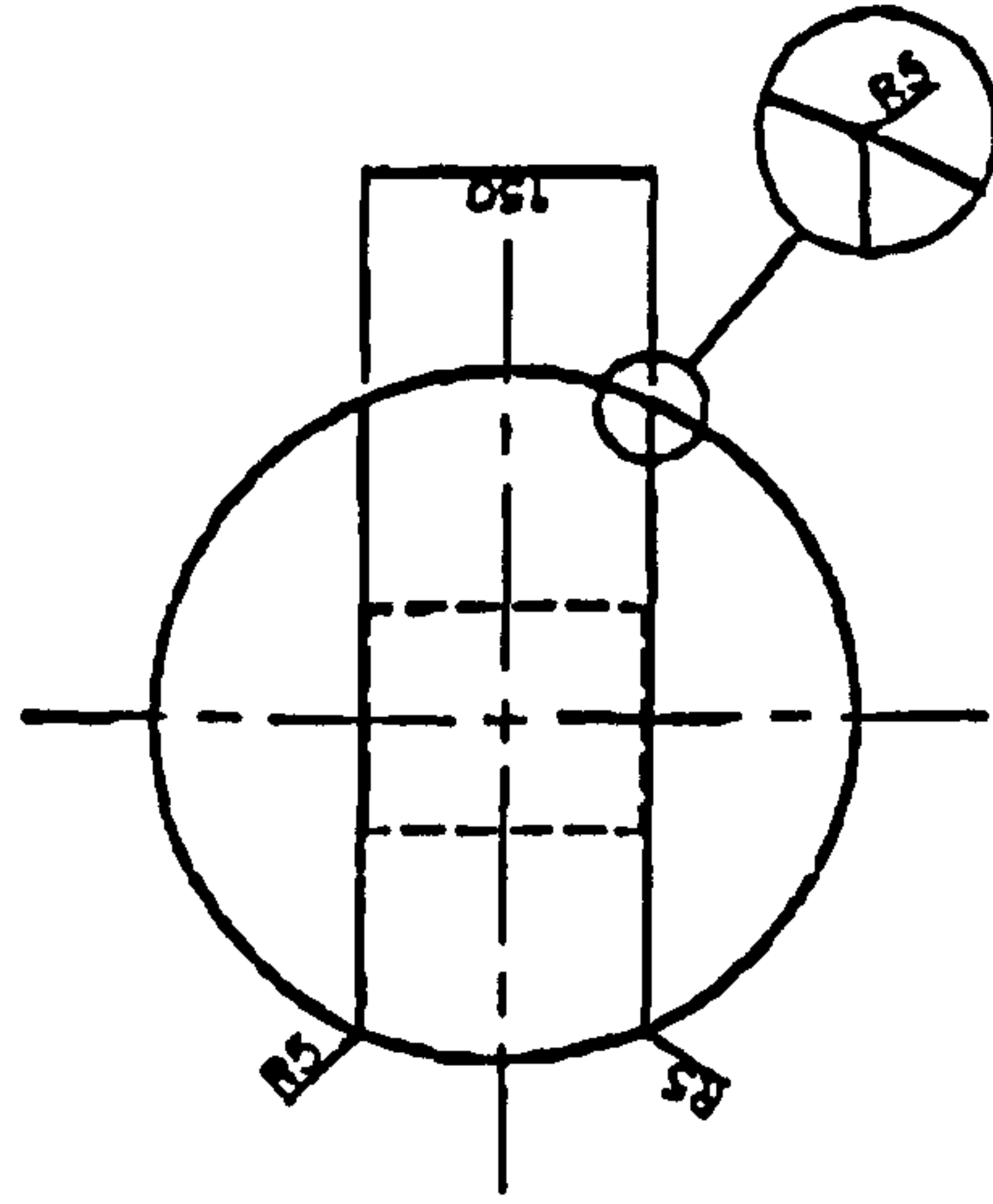
MATERIAL - B.S.970; PART3: 1991
GRADE 817M40 CONDITION R

- ESTIMATED WEIGHT 140KG.
- EACH SOCKET TO BE SUPPLIED COMPLETE WITH M16 COLLARED EYEBOLT

BRIDON
BRIDON INTERNATIONAL LTD.
130, E. J. STREET, LFE

THREAD TO DIN 2781
S 335 x 12
FIT H8 / e8

THREAD TO DIN 2781
S 335 x 12
(BUTRESS THREAD)



ITEM 2 - WING 7 1120MM EYE CONNECTION

MATERIAL - B.S.970; PART3: 1991
GRADE 817M40 CONDITION R

- ESTIMATED WEIGHT 265KG.

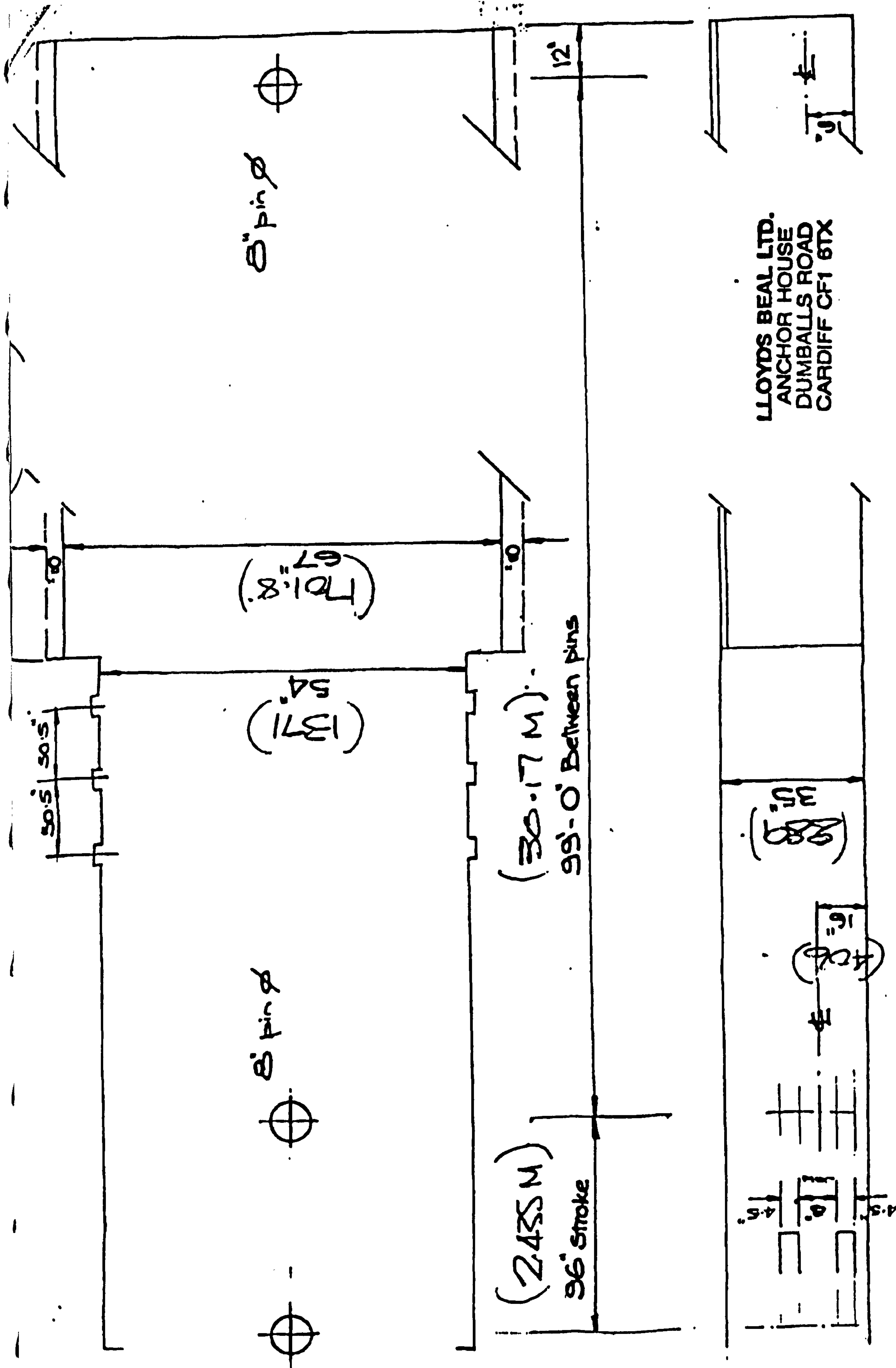
DRAWING NUMBER/SPECIFICATION	ITEM	DESCRIPTION	MARKS
1120MM SOCKET	1	WING 7	
1120MM EYE CONNECTION	2	CHARLTON	

BRIDON
BRIDON INTERNATIONAL LTD.
130, E. J. STREET, LFE

WING 7

CHARLTON

SCALE: 1:1



LLOYDS BEAL LTD.
 ANCHOR HOUSE
 DUMBALLS ROAD
 CARDIFF CF1 6TX

750 tonne capacity long bed test machine.
Lloyds South Wales Testing House. Cardiff.

12.11.86

w.t.f.

PROPOSED CONNECTION TO PETROBRAS TEST MACHINE

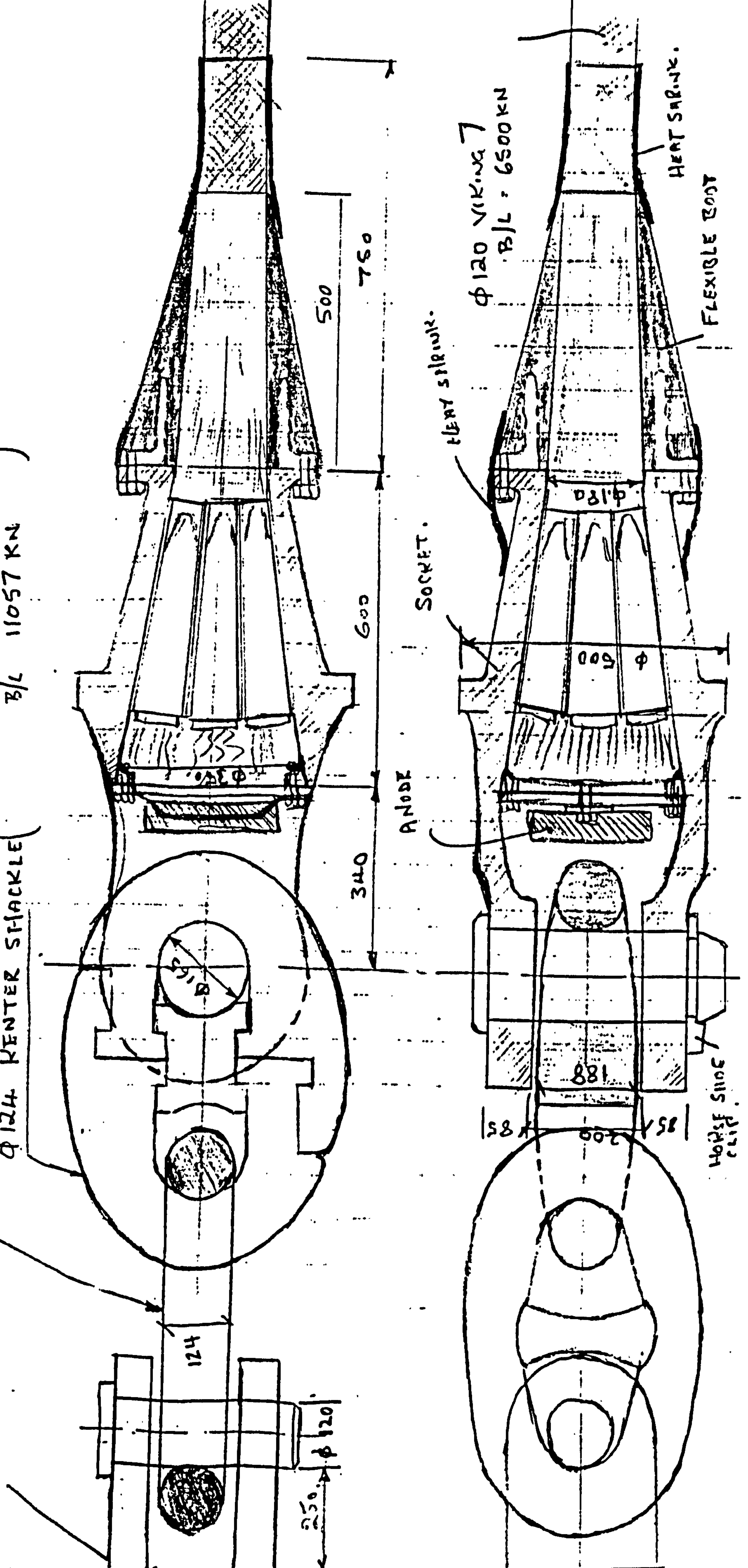
FOR $\phi 120$ VIKING 7 SOCKET

18/3/96

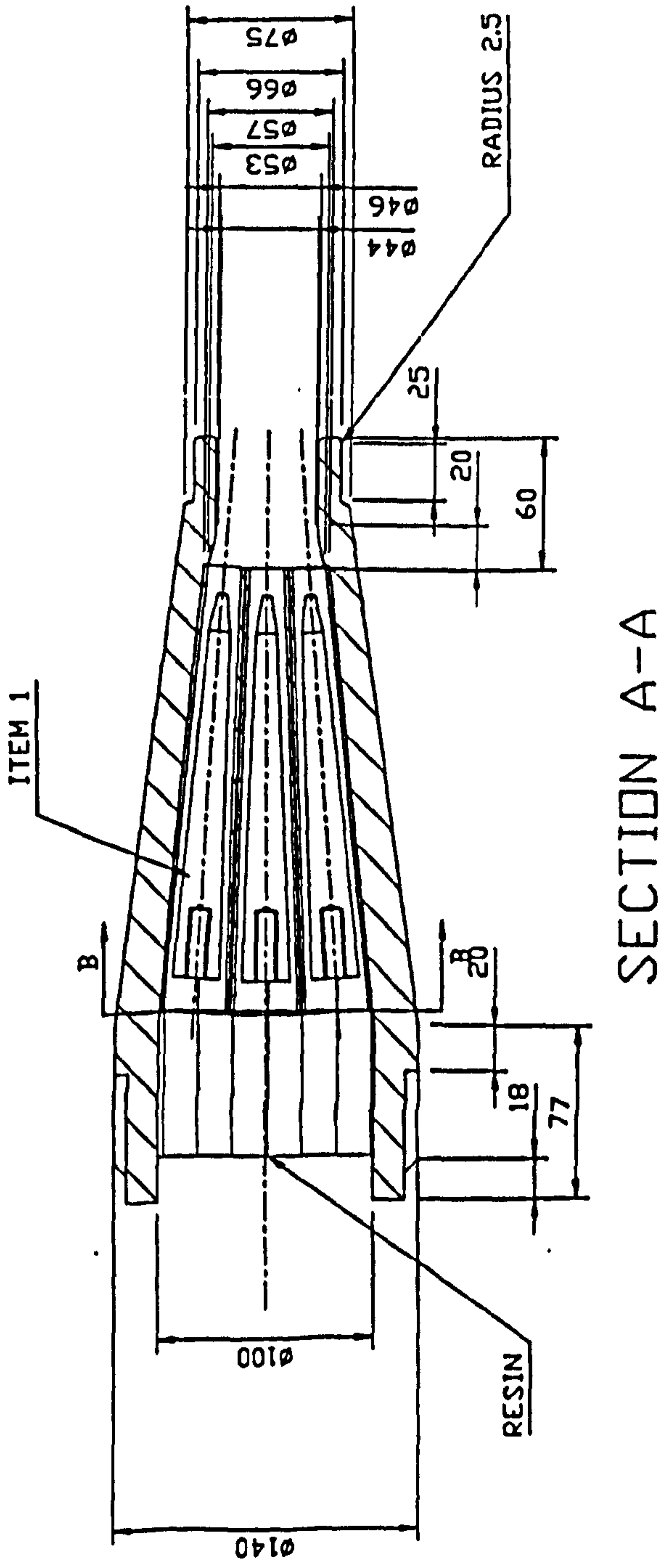
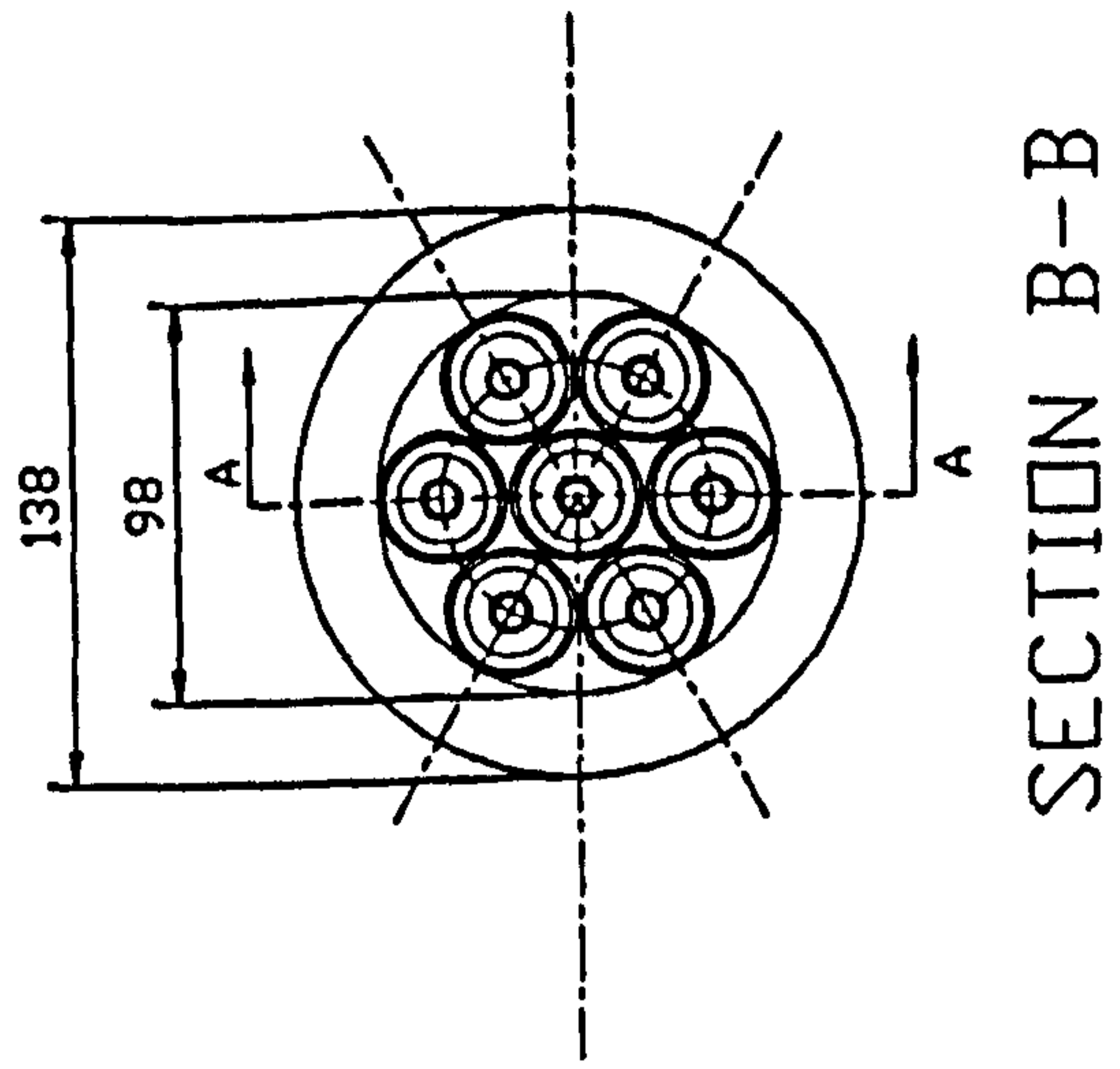
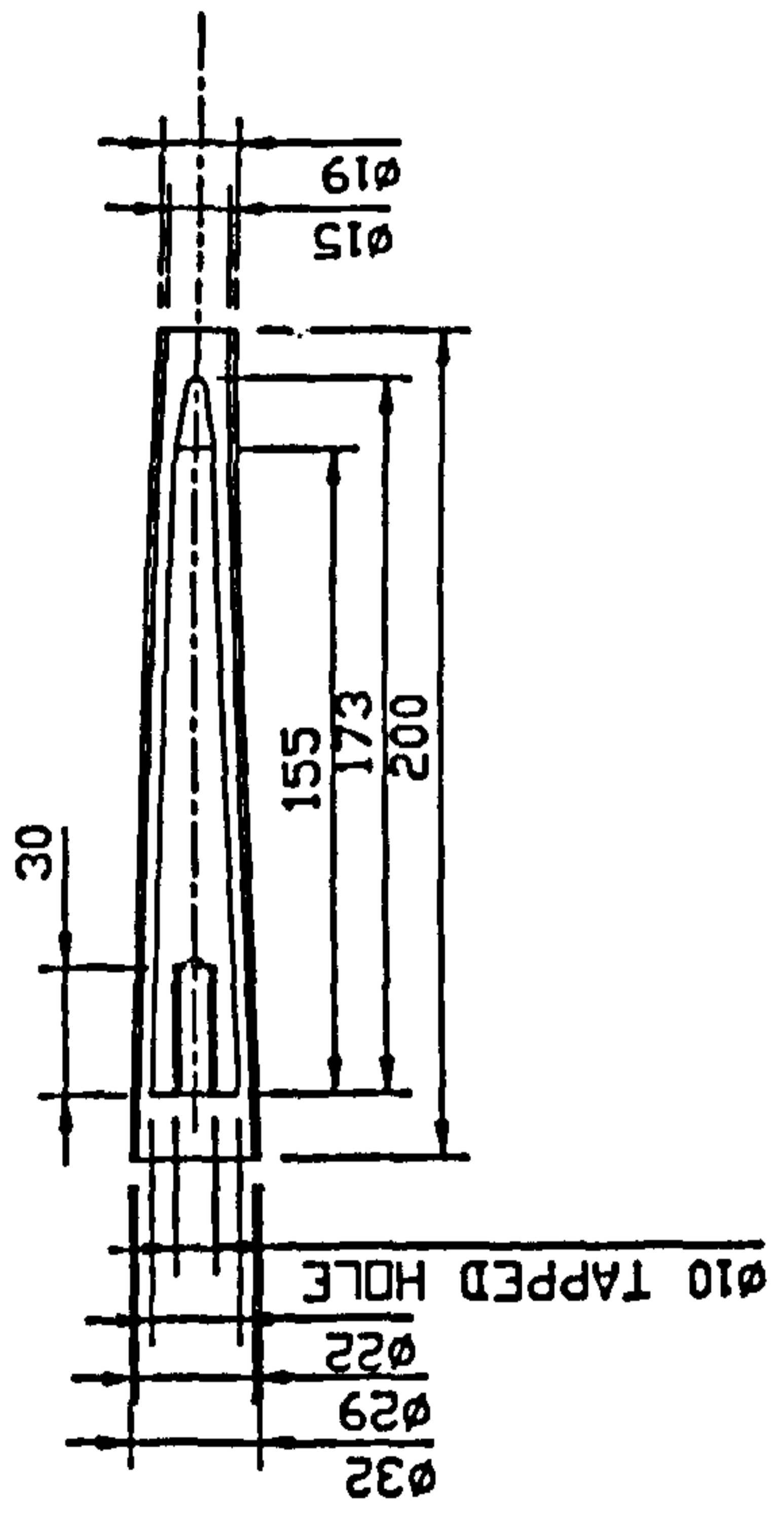
$\phi 124$ COMMON LINK. (RQ3 PROOF LOAD 7336 KN. B/L 11057 KN)

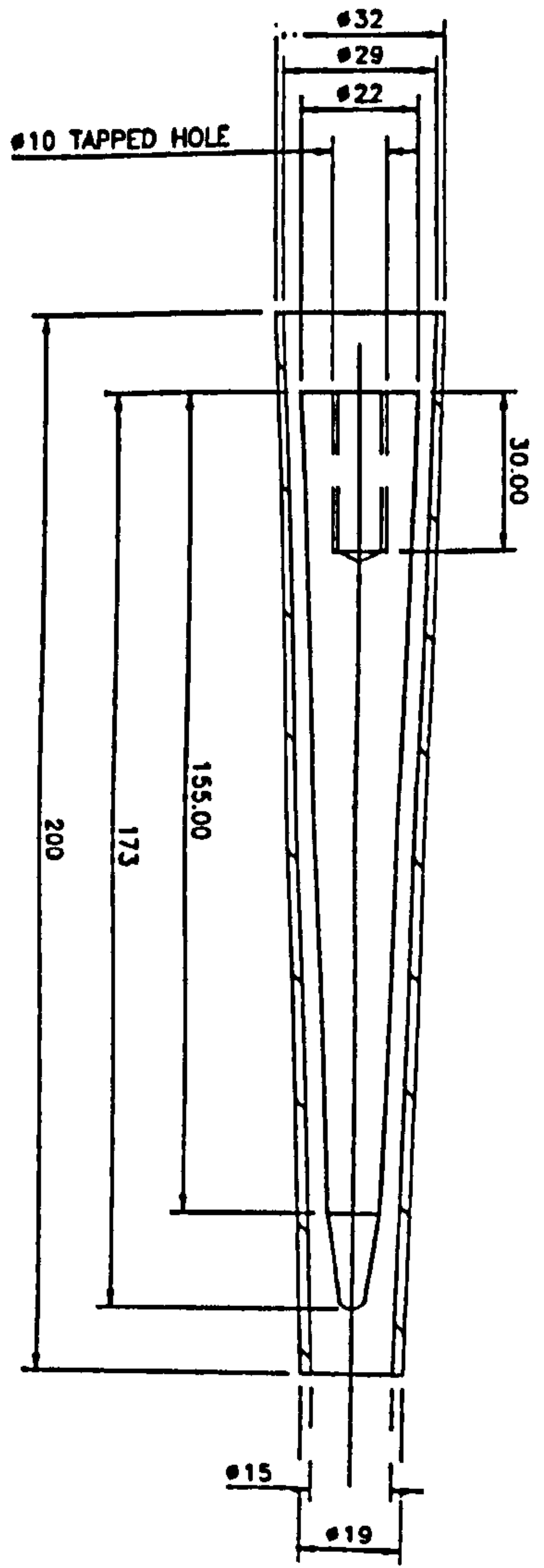
PETROBRAS TEST MACHINE

$\phi 124$ KENTER SHACKLE (RQ3 PROOF LOAD 7336 KN. B/L 11057 KN)

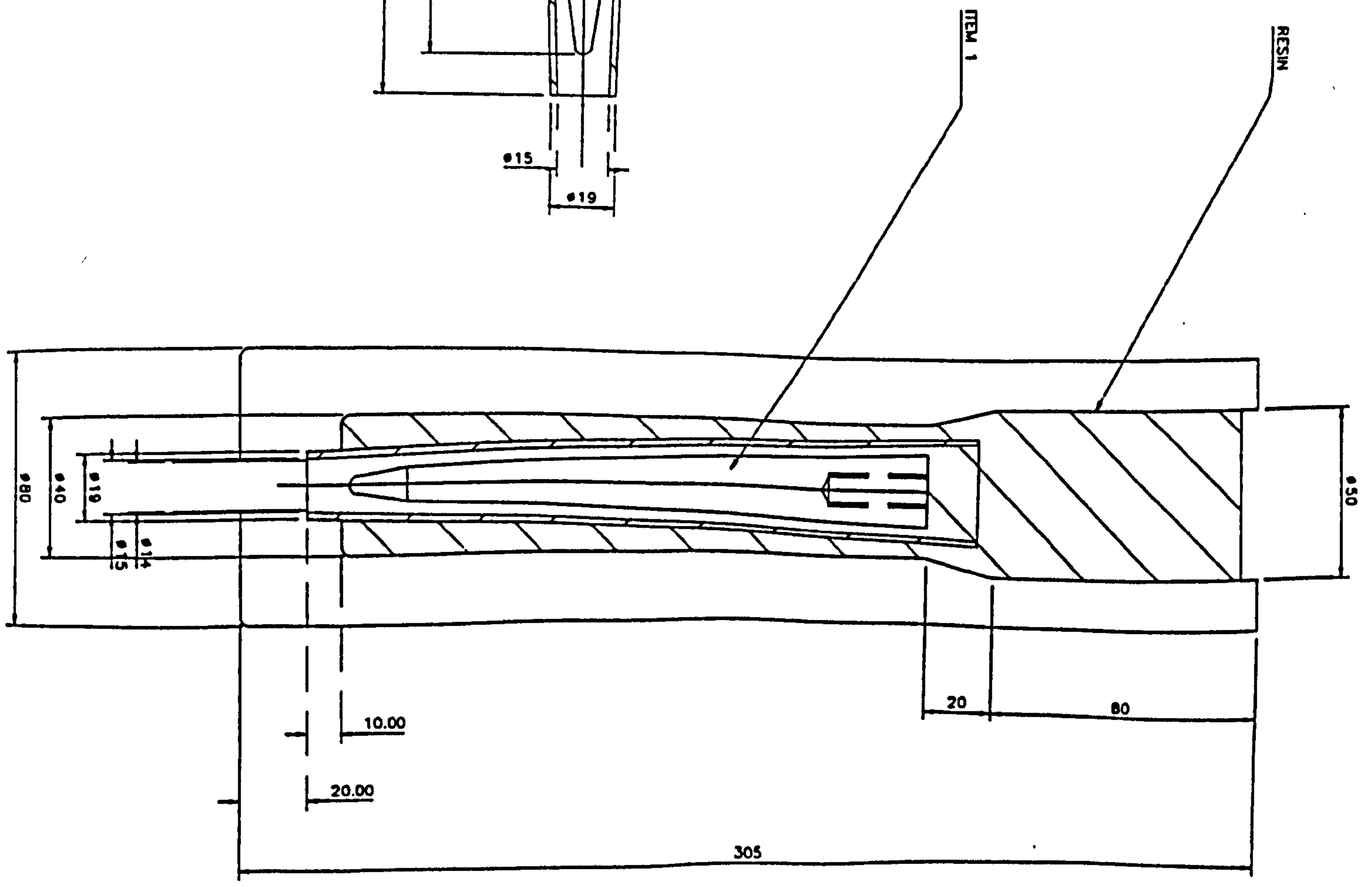


ITEM 1





ITEM 1



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