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Fatigue and Length Effects in Fibre Ropes

Effets de fatigue et de longueur pour des câbles en fibre

Ermüdungserscheinungen und Längeneffekte in Faserseilen

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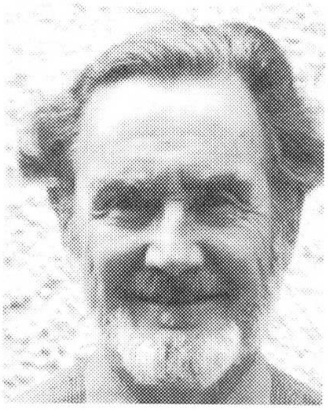

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SUMMARY
The advances in high-performance fibres and their potential for use as tension members in bridges and other structures are outlined. The general length effect problems, which involve the weak-link effect and load sharing, are discussed in terms of limitations of understanding in theory and practice. Six fatigue mechanisms in fibre ropes are described, and their influence in length effects on parallel-lay and structured ropes illustrated by examples of analysis of the mechanics.

RÉSUMÉ
Les progrès réalisés dans les fibres à haute performance et leur possible utilisation en tant qu'éléments de tension dans les ponts et autres structures sont esquissés. Les problèmes généraux d'effet de longeur incluant l'effet de maillon faible et celui de partage des charges et ses limites de la compréhension à la fois théorique et pratique de ces effets sont dicutées. Six mécanismes de fatigue de câble en fibre sont décrits, ainsi que leur influence sur les cordes structurées ou en couche parallèle dans le cadre des effets de longueurs - le tout illustré par des exemples d'analyse du mécanisme.

ZUSAMMEMFASSUNG
Die Fortschritte in der Entwicklung von hochleistungsfähigen Fasern und deren Potential zur Zugkraftaufnahme in Brücken und anderen Bauwerken werden umrißen. Allgemeine Längenprobleme, insbesondere das Auftreten von Schwachstellen und eine ungleichmäßige Verteilung der Lastaufnahme der Fasern, werden unter Berücksichtigung der begrenzten theoretischen und praktischen Kenntnisse erörtert. Sechs Ermüdungsmechanismen in Faserseilen werden beschrieben, und deren Einfluß auf Längeneffekte in parallel liegenden und geflochtenen Seilen wird anhand mechanischer Analyse erläutert.

1. INTRODUCTION

1.1 Development of fibre ropes

From the time of the ancient civilisations, man has fabricated ropes from natural fibres, such as sisal, hemp and cotton. These were used as cables in primitive bridges and for many other structural purposes. However, the advent of steel wire ropes in the 19th century displaced fibre ropes from any serious uses in structural engineering, though they continued to be used for many marine and other applications. The situation has changed in the second half of the 20th century with the invention and production of high-performance man-made fibres. The first synthetic fibre, nylon, was introduced into rope manufacturing in the 1940's and led to stronger ropes. However nylon has a relatively low modulus and high extensibility, which makes it very suitable for uses where stretch and energy absorption are needed, but not for structural members. The stimulus for the development of fibre ropes for stays and cables came partly from the development of parallel-lay (®Parafil) polyester ropes and, more strongly, from a second generation of synthetic fibres with strengths more than double those of nylon and polyester.

The need to bind short natural fibres together led to twisted rope structures, such as the common three-strand rope, but the use of continuous filaments, effectively infinite in length, has removed this requirement. Consequently, new rope constructions have been introduced. The situation is now very complicated, with the number of combinations of fibres, blends and constructions available to rope designers running into millions. What follows is a brief outline of the main features as an introduction to the problems of fatigue and length effects.

The main fibres used in ropes today are listed in Table 1, with those of most concern for this paper shown in bold. Important properties of these fibres are compared in Fig. 1.

cheaper fibres with adequate performance for common uses		
regular melt-spun polyethylene (PE)	polypropylene (PP)	
intermediate performance fibres		
polyamide (PA): nylon 66 and nylon 6	**polyester (PET)**	glass
high performance fibres fibres formed by liquid crystal processing		
aramid (®Kevlar, ®Twaron, ®Technora)	**LCAP (®Vectran)**	**polybenzoxazole (PBO)**
other high modulus, high strength (HMHT) fibres		
HMPE (®Spectra, ®Dyneema)	carbon	

Table 1 Fibres for ropes

Although polyester does not compare well with the newer high-modulus high-tenacity (HMHT) fibres in strength and stiffness relative to bulk or weight, the special forms of yarn designed for engineering uses must be considered when high strength and stiffness is needed at low cost. However for maximum strength and stiffness at minimum weight, the prime candidates are the highly oriented linear polymer fibres formed from liquid crystals. These are represented in Fig. 1 by the aramids, but LCAP and PBO have somewhat similar properties, and the technology is still developing.

Because of their creep properties, the gel-spun or super-drawn HMPE fibres are unlikely to be suitable as load-bearing members in permanent structures. Carbon and glass fibres are too brittle in bending for use as independent fibres in ropes; and their use as pultruded composite rods has more mechanical similarity to wire ropes than to fibre ropes.

The main categories of fibre rope construction, with approximate strength conversion efficiencies, are: *parallel-lay (®Parafil), 50% ; multi-rope, 40%; low-twist "wire-rope" constructions, 40%; braided and plaited ropes, 25%; traditional twisted ropes, 25%.* Generally, the effects of introducing more structure, in the form of twisting or braiding, are, as with wire ropes: (1) to reduce strength and stiffness, due to obliquity effects; (2) to allow movement of yarn from the compression to the tension side of a rope in bending, and so reduce bending stiffness; (3) to bind components more closely together.

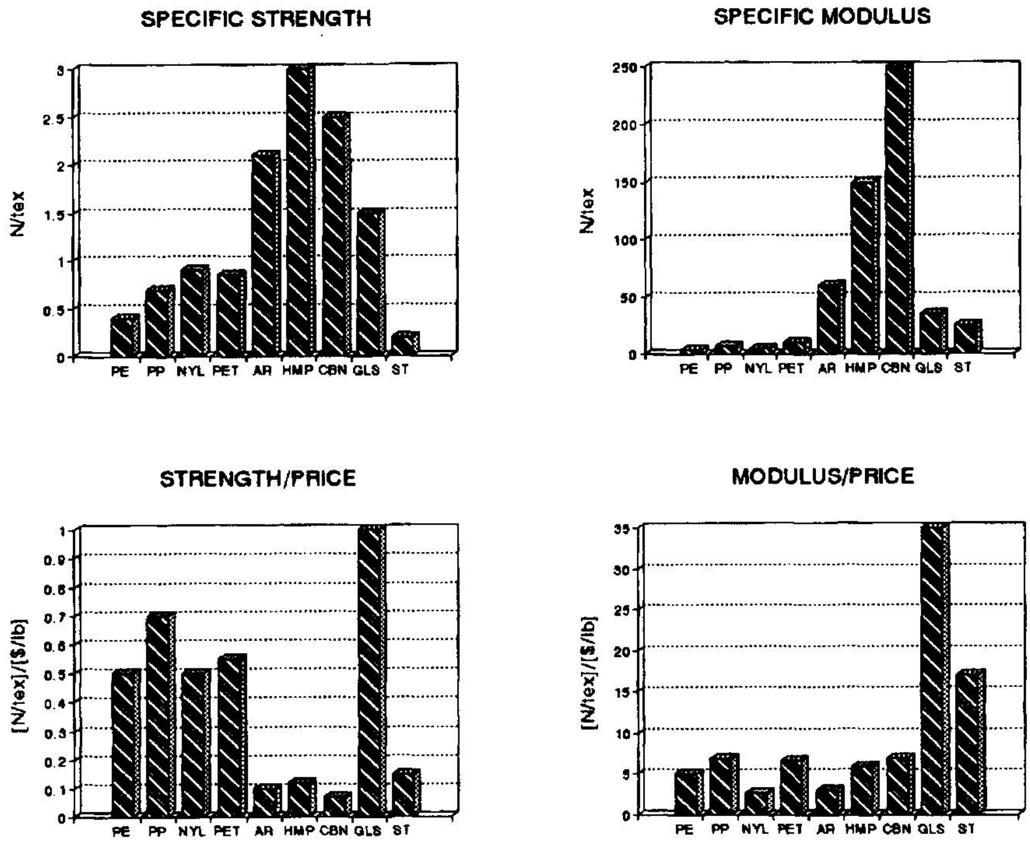

Fig. 1 Fibre property values: indicative only (all values cover a range for different types)
PE=polyethylene; PP=polypropylene; NYL=nylon; PET=polyester; AR = aramid; HMP=high-modulus polyethylene; CBN=carbon; GLS=glass; ST=steel
Unit of specific stress: N/tex = GPa/(g/cm^3)
Unit of linear density: tex = g/km

1.2 Potential of fibre ropes in bridges and other structures

Fibre ropes offer distinct advantages over steel wires in some structural applications. An example of a building structure is a bus station recently erected in Cambridge with the roof supported by aramid Parafil ropes. However, the most important use is in bridges, and three particular examples are most clearly defined.

Tendons in prestressed concrete are normally made from 7-wire spiral steel strand, with a low lay angle. These tendons are protected from corrosion by the high alkalinity of the concrete, which passivates the steel. The tendons are placed in ducts in the concrete, which are filled with grout after tensioning. However, in recent years, there have been growing concerns about the effectiveness of this grouting, which leads to worries about corrosion, and some bridges have collapsed due to tendon corrosion [1]. Replacing the steel with aramid, glass or carbon, which are inherently resistant to attack by water or most chemicals, is attractive, and a number of structures have already been built. Several use pultrusions of fibres with a resin matrix, which can be bonded to concrete, but there are concerns about the wisdom of bonding these brittle materials and also about the long-term effectiveness of the resin. This leads to the idea that unbonded, parallel-lay ropes will prove, in the long run, to be the most suitable form for the use of new materials as tendons [2]. The Department of Transport in the UK is expected, in the near future, to insist on the use of inspectable, removable and replaceable tendons, and the added costs of providing corrosion protection to steel tendons will negate the cost differences in the basic materials. In addition to problems of corrosion, there is a loss of tendon prestress due to creep and shrinkage of the concrete, which has been greater than expected in many bridges in the UK. Tendons encased in grout cannot be restressed, and the only prospect for repair is to use external tendons, for which aramid parallel-lay ropes are strong contenders. Their lower modulus, compared with steel, is an advantage, since it reduces the loss of prestress due to the contraction of the concrete.

Suspension bridges are used to provide the largest spans, and the Akashi bridge under construction in Japan will have a span of 2 km. However as the span increases, the weight of the main cables comes to dominate the design, and it is believed that a span of about 2.5 km is the largest that can practically be achieved with the use of steel. Aramid and carbon offer the possibility of much larger spans, with serious consideration being given to spans well in excess of 5 km [3], which would make possible, for instance, a crossing of the Straits of Messina.

Cable-stayed bridges are currently used for spans between about 200 and 800 m. They are stiffer than suspension bridges, and less susceptible to dynamic problems. The dead load of the deck can be kept quite small, so that the live load becomes dominant, which means that the limiting factor for most designs is the fatigue resistance of the cables. Steel cables are frequently restricted to stress ranges of about 200 MPa, and fibres offer the possibility of significantly better performance, although much testing is required to ensure that this capability is achievable in full size ropes.

In all these cases, the effects of length on both strength and fatigue will be important. Prestressing tendons are often several hundred metres long, especially if unbonded, and are the most highly stressed of all structural elements, regularly being tensioned to 70% of their ultimate strength. If some engineers' aspirations are achieved, cables in suspension and cable-stayed bridges may well have lengths of several kilometres.

1.3 General length effects

The basic principles of the interrelation between specimen or component lengths and mechanical failure, namely the extreme value statistics of the weak link effect and the nature of the load sharing, are the same for fibre ropes as for wire ropes. Indeed, much of the work on the subject, starting with the paper by Pierce published 66 years ago [4], and continuing through Daniels [5,6], Coleman [7], and Spencer-Smith [8] to Phoenix [9] and his colleagues, has been driven by textile research interests.

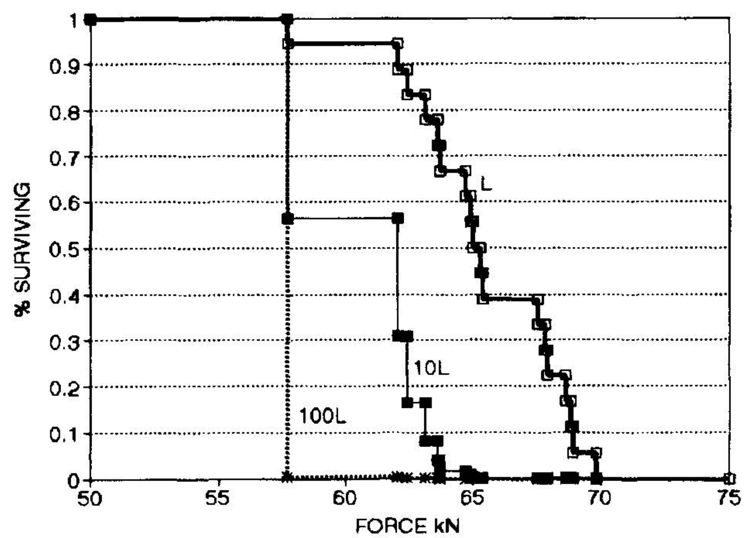

Fig. 2 Statistics of failure for aramid Parafil rope breaks [10].
Line L is for 18 test results at length L = 500 mm. Lines 10L and 100L are cumulative distributions for ropes of length 10L and 100L, made up randomly from the 18 test values.

It is worth dramatising the problem facing engineers by a simple example. Fig. 2 gives breaking loads in 18 tests on 500 mm lengths of 5 tonne (approximately 10 mm diameter) Parafil Type A (polyester core) ropes, carried out by Amaniampong [10]. If, unjustifiably, we make the assumption that longer lengths could be treated as a random sequence of the 18 test pieces, then the survival diagrams for different lengths would be as shown. This highlights a number of problems.

- It is rare to get as many as 18 tensile test results even on small ropes, and prohibitively expensive for fatigue tests on large ropes.
- The direct numerical procedure, as used above, which may give good predictions when the ratio of lengths is much less than the number of test results, is clearly useless for longer lengths when it predicts that almost all would fail at the same lowest value. In order to make predictions, it is necessary to know extreme values of the distribution. What are the probabilities of failure at loads, or lifetimes, lower than the lowest observed experimentally? Any appreciable extrapolation, based on fitting the central values of the distribution, may be seriously misleading, even if there is a single mode of failure responsible for the total distribution of breaks.
- It is also possible that there may be infrequent defects giving rise to other modes of failure, which make the real distribution multimodal and extrapolation invalid.
- Does the nature of the break change when the length is greater than the test length?
- To what extent does correlation between the properties of neighbouring elements, as considered by Spencer-Smith for textile yarns [8], invalidate any theory based on a random sequence of units?
- Can laboratory tests on small ropes be applied to the behaviour of large ropes in real structures?

The technology of fibre ropes in relation to these problems differs from that of wire ropes in the following ways.

- There is no base of engineering experience in use. Uncertainties in theory and experiment need to be covered by large safety factors, which may destroy the economic advantage. Or, as a distinguished old theoretician of the subject commented: "A few bridges will have to fall down before we solve the problems!".
- Whereas wire ropes are made up of a comparatively small number of wires, a large fibre rope will contain millions of fibres. This affects the real nature of failure, especially in fatigue, as well as the difficulty of hypothetical modelling.
- The lengths over which failure spreads may be much larger. In unstructured ropes, the filaments, yarns or sub-ropes may not take up a full share of load until several metres from a break.
- Although polymer science has made great advances in the 60 years since macromolecules have been recognised as constituents of materials, understanding of mechanical properties, especially fracture and fatigue, is less advanced than in metals, which have simpler structures and are not anisotropic or visco-elastic.

One way forward is the high-risk route of empirical solutions based on rough calculations and safety factors, progressively improved as an experiential data-base is built up. The only alternative appears to be a programme of well-designed experiments on fibres, yarns and cords, to determine relevant material properties, combined with theoretical modelling of fibre assemblies, validated by numerous tests on small ropes and a few tests on large ropes. But this is a formidable undertaking, which will partly be explored later in this paper.

2. FATIGUE MECHANISMS IN FIBRE ROPES

2.1 The identification of fatigue mechanisms

There have been a number of studies of what can broadly be described as fatigue in ropes in the last 15 or 20 years, but these have mostly been related to the wide range of marine uses. In addition, the advent of the scanning electron microscope and the development of new fatigue tests have led to recognition of various modes of fracture and fatigue in fibres in different circumstances [11].

The first requirements for a rope member in an engineering structure are strength and extensibility relative to the design load. These already involve the complications of length effects. Then there may be issues of chemical degradation, though this would be expected to be a uniform weakening over whole lengths and should be avoidable by a suitable choice of material. External abrasion, if it occurs, is likely to be localised and obvious, and can be mitigated by protection. This leaves the most important factor in determining long-term durability as fatigue failure within ropes. Parsey [12] has identified six modes as occurring in ropes. The problem might therefore seem to be to calculate the lifetimes under whichever of the six modes are likely to occur, taking into account the length effects, and see which is shortest. However, two reservations should be made about the implied simplicity of this approach. At least two modes are catch-all titles for a collection of effects, and many interact strongly with one another.

2.2 Creep rupture

Creep rupture is a significant effect in polymer ropes under high sustained loads, as demonstrated by Mandell [13]. His equation is a variant of that proposed for time-dependence of fibre strength by Meredith [14] many years ago:

$$S_u = S_g\,[1 - k\,\log(t_u/t_g)] \qquad (1)$$

where S is strength, t is time, subscripts u and g refer to unknown (use) time and given (test) time, and k is the strength-time coefficient.

Table 2 illustrates the extreme sensitivity to the value of k. For nylon, Meredith found k = 0.08; and Mandell found k = 0.05 for polyester. Current indications are that aramid has a value less than 0.05, and that polyethylene, including HMPE, is near 0.2, but more reliable experimental data are needed.

k	time to fail at per cent of 1 second break load 20%	50%	80%
0.05	300 million years	300 years	3 hours
0.1	3 years	1 day	2 minutes
0.2	3 hours	5 minutes	10 seconds

Table 2 Effect of strength-time coefficient on time to fail

The length effects in creep rupture are essentially the same as in slow tensile testing. The difference is that the sequential break of fibres, leading eventually to rope failure, occurs as time passes instead of as load increases.

2.3 Hysteresis heating; internal abrasion; tensile fatigue

Hysteresis heating during repeated loading is due both to energy losses within fibres and to friction between fibres. It can be controlled by increasing the efficiency of heat transfer from the rope. The direct effect is the reduction of fibre strength as temperature increases, and the length effects will be similar to those in tensile testing.

Mandell's paper [13] confirms other studies [15] that internal abrasion is a prime cause of failure in tension-tension cycling of structured ropes at low loads. It results from cyclically varying shear forces at contacts where there is relative motion of components. This will not occur in tension cycling of parallel-lay ropes. However, it may be a major factor if there is rope bending or lateral strumming.

The occurrence of the special forms of tensile fatigue [11], found in nylon and polyester fibres cycled from zero load to a fraction of the normal break load, seems to be an infrequent occurrence in ropes in practice, though they have occasionally been observed.

2.4 Bending, buckling and compression; structural fatigue

The most severe fatigue occurs in fibres when cyclic compressive or shear forces are present. Bending, buckling and compression cover a variety of forms of disturbance within rope structures, which may lead to such stresses. At the fibre level, repeated axial compression leads to breakdown at kinkbands; and cyclic shear stresses, resulting from variable curvature, lead to splitting of fibres.

Any oriented linear elements will buckle when subject to axial compression. For a free length of rope as a whole, this usually gives a mild curvature, which will have a negligible effect on the fibres, but sometimes it can lead to severe bending and twisting of the rope. When the axial compression is applied to elements confined by neighbouring elements, either as strands, yarns or fibres within a rope, or as fibrils or polymer molecules within a fibre, compression leads to a sharp kinking, which can be seriously damaging.

Axial compression within a rope will occur on the inside of bends and can also come from differential length changes on twisting. Some recent studies have indicated that this problem may arise in unexpected circumstances. For example, there is a well-documented study [16] of the failure of a Kevlar rope after deployment on buoys prior to mooring an oil-rig. Wave motion had caused a rise and fall, which generated torque waves and consequent compression and failure in the rope. A careful redesign, so as to avoid torsion and provide the right degree of restraint from the cover, solved the problem. In other situations relative movement of components can cause problems: this may occur at terminations or result from lack of control in manufacture causing length disparities in components.

Structural fatigue is another ill-defined fatigue mode, which can be regarded as a more severe form of buckling and compression. It involves such substantial disturbance of the rope structure that some components cease to carry load and others carry more and break. Hockling, which sometimes occurs on the sudden release from tension of three-strand ropes, is an extreme example of the effect.

3 VARIOUS ASPECTS OF LENGTH EFFECTS IN FATIGUE

3.1 The total system

The long-term durability of a fibre rope used as a tension member depends on the interactive response of the total system as illustrated in Table 3. It would be an impossible task to develop a usable model applicable to any combination of environment, structure and rope. Some basic features can usefully be studied by academic exercises, but there is a danger that uncritical application of mathematical theory may lead to false predictions. Real engineering progress will only be made by working in detail on design studies, including experiment, theory and computation, for particular installations.

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structural integrity of system

EXTERNAL LOADING - traffic, wind, waves, structure etc
WHOLE STRUCTURE RESPONSE - system dynamics
FORCES ON ROPE + TERMINATION - rope properties
RESPONSE OF SUCCESSIVE ROPE ELEMENTS - system dynamics
FORCES ON LOCAL ROPE ELEMENTS - rope properties
FORCES ON FIBRES - rope micro-mechanics
DAMAGE TO FIBRE STRUCTURE - fibre properties

structural integrity of fibres

Table 3 Total system response

For similar reasons, our specific contribution to this workshop consists of a number of separate items, which bring out significant aspects of the problem. It is noted above that many of the fatigue mechanisms likely to operate in fibre ropes lead to a sequence of failure that is similar in principle to failure in a tensile test. Consequently a priority is to find ways of handling the unresolved problems of length effects on the breaking load of ropes. If we can understand this properly, the approach to length effects in fatigue should be much clearer.

3.2 Yarn tests

Even when carried out manually, and more so with automatic testers, it is practical to make very large numbers of yarn tensile tests, and thus satisfy the statistical needs of experimental input into models. The validity of predictions could be tested by extending such studies to small cords, which represented characteristic features of rope construction. Yarn testing is also of particular interest for the light it throws on the applicability of extreme value statistics and the problems of interpretation, where the practising engineer may fall into error, especially as the views of the experts do not always coincide.

Amaniampong [10] carried out a series of tests on Kevlar and polyester yarns at different test lengths. Both break force and break elongation were measured, and the corresponding values of break stress and strain determined. Amaniampong then used the Kolmogorov-Smirnov tests to indicate which gave the best fit among the often used normal and log-normal distributions and the theoretically preferable Weibull and Gumbel distributions. He found that all four forms were variously predicted, with no very clear pattern for different parameters, test lengths or fibre types. This indicates the difficulty of interpreting yarn test data properly. The use of K-S tests may also be criticised [17] on the grounds that they should not, in principle, be used to discriminate between various distributions but only to validate a previous choice, which ideally would be made on physical grounds. The normal distribution is defined for $-\infty \leq x \leq \infty$, and should not be used when, as with tensile strength values, x cannot take negative values. In addition, as pointed out by Peirce [4], weak link theory shows that, if the distribution were normal at one length, it would not be normal at any other; in contrast to this, the Weibull form remains valid at all lengths. On the other hand, it might be argued that, in the absence of a good physical model and provided the extrapolation is not too large, the best empirical fitting may be the most appropriate.

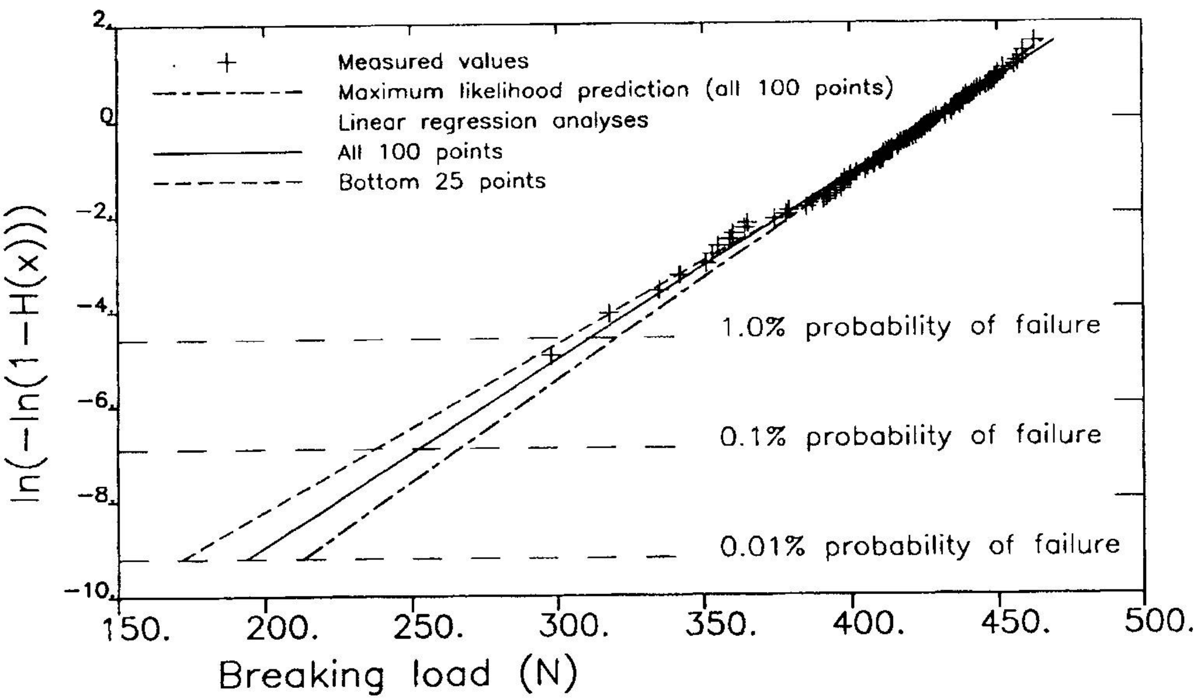

Fig. 3 Weibull plots of 100 yarn strength values measured by Amaniampong [10]

The problem becomes acute, and of practical importance, when the analysis is required to find extreme values, which lie beyond the range of observed values, as is often necessary for long ropes. As one example, Fig. 3 shows the results of 100 tests on Kevlar 49 yarns, each taken from a different spool. The cumulative distribution function H(x), when plotted in the form ln(-ln(1-H(x))) against the measured value, should give a straight line if the Weibull or Gumbel distributions apply. Various attempts, reflecting different theoretical approaches to statistics, have been made to fit straight lines through the data. A maximum likelihood prediction gives less weight to the outliers in the distribution, and fits the main sequence of tests well. However, the lower outliers may well be important, so a simpler linear regression analysis would be more appropriate, and predicts a lower strength at the bottom of the distribution. The process can be taken further, and, as suggested by Castillo and Sarabia [18], only the tail data used. Another line in Fig 3 is a linear regression for the bottom 25 points, which gives even more weight to the lower extreme values. The predicted failure strengths at the 1% probability level range from 304 to 321 Newtons, with greater variation at lower probabilities of failure. These variations are significant, since it has been found [19] that Parafil ropes have their maximum strength when about 1-2% of the weakest yarns have failed.

To complicate matters even further, the low outliers in some test sets plotted in the form of some distributions are stronger than the central values suggest, while in some other test sets, or for other forms of distribution in the same set, they are weaker. In some cases, the results for force and nominal stress show different behaviour, indicating that the cross-sectional area is not constant along the length. For some rope constructions, it is not stress but strain that must be considered, and again different distributions apply.

3.3 Fatigue and length effects in parallel-lay ropes

Several of the fatigue problems associated with structured ropes disappear when parallel-lay ropes are used, although other considerations arise. Of the six causes of fatigue identified above, most are eliminated or simplified in parallel-lay ropes when subject solely to tensile loads, though they will occur, and may become serious, if bending or twisting deformations are imposed. There is considerable evidence that "fatigue" in tension of many types of fibre is related to duration of loading, rather than number of cycles [13]. It is thus likely that long-term life in parallel-lay ropes is related to creep rupture, possibly enhanced by increased temperature due to hysteretic heating within fibres (but not to friction between fibres), although this simplification to a single factor needs thorough investigation and validation.

The length effects of particular interest in parallel-lay ropes, whether for failure in simple tensile loading or in long-term creep rupture, are associated with the degree of interaction between fibres. A broken filament can clearly carry no load at the break. But how far along the rope is it before that filament carries a full load? If there is no interaction, the whole length of the filament becomes inoperative, and the strength of the rope will be the sum of the weakest places in what may be several kilometres of each filament. In contrast to this, if there is strong interaction, the load-carrying capability builds up rapidly, weak places are supported by neighbouring fibres, and the strength is given by the weakest single cross-section.

In practice, the component yarns in Parafil ropes are twisted to a small extent, but sufficient to ensure that the individual filaments are mutually supported, and it is interaction between yarns that must be considered. In multi-rope constructions, the interaction is between sub-ropes. In the simplest idealised model of parallel components, there is no basis for any transverse forces. Consequently, if the classical law for frictional contact is assumed, there is no interaction. In actual parallel-lay ropes, interaction will occur due to causes such as pressure from the jacket, possibly transverse forces from some secondary structural features, and adhesive forces between fibres. This means that there will be a transfer of load to broken filaments over a length which can be regarded as a characteristic length for rope failure. The terms "effective length" and "recovery length" are used for similar concepts. In parallel-lay ropes, it has been estimated that the characteristic length may be as much as several metres. This has important consequences both as regards the relation between test results on short lengths of rope and the use of long lengths, and as regards the internal structural mechanics of ropes.

Amaniampong [10] has taken the bundle theory, as developed by Daniels [6], and extended it to allow for variable slack in the yarns and non-linearity of the stress-strain curve. He combined this with his own yarn test data, and the idea of a characteristic length, to produce predictions of the strength of ropes of different sizes and lengths. Ropes carry their maximum load when only a small proportion of the weakest yarns break, so that the variation in strength is caused by the variation in the number of yarns in the lower tail of the distribution. As ropes get larger, the shape of this tail gets closer to that of an infinite population, so that the chance of getting a random set of very low values, causing greater variation in rope strength, is reduced. In a long rope, which can be regarded as a series of characteristic length pieces whose strengths are independent, the weakest link principle is applied and the strength decreases as the rope gets longer. But, if the variability is low, as in large ropes, the length effect can be quite small. Amaniampong calculates that, over a length of 3 km, a 60 tonne Kevlar Parafil rope loses only about 2% of its characteristic strength (as measured at less than 6 m), whereas a 6 tonne rope would lose 5%. He also applied bundle theory to creep rupture behaviour of aramid parallel-lay ropes. Working only from data on filaments, he predicted that these ropes would fail after 100 years, when loaded to 60% of their shortterm strength. This is in close agreement with predictions based on empirical data by Guimares [20].

3.4 Length effects in structured ropes

The increased interaction due to the generation of transverse forces in structured (twisted and braided) ropes means that the characteristic length will usually be less than the rope diameter, so that the weak link effect will be operative at any test length. If interaction is extremely strong, as in a homogeneous solid, then breaks will propagate continuously across the material. This situation would not occur in ropes, though there is the statistical problem of the tendency of some neighbouring components to break. Some structure optimises strength, but also results in deterioration due to obliquity as mentioned previously and can lead to the occurrence of fatigue due to internal abrasion, kinkbands and structural changes.

Many studies of braided and twisted nylon ropes for marine uses have shown that internal abrasion is the prime cause of failure in tension-tension cycling at low loads. For example, a braided nylon rope cycled wet from a low load to 50% of its normal break load failed after 970 cycles [21], when internal abrasion had cut through the filaments and reduced them to short fibres. This, as well as other reasons, leads to the choice of other fibres and less structured rope constructions in structural engineering. However, an interesting point of general principle arises in connection with the modelling of loss of strength due to internal abrasion.

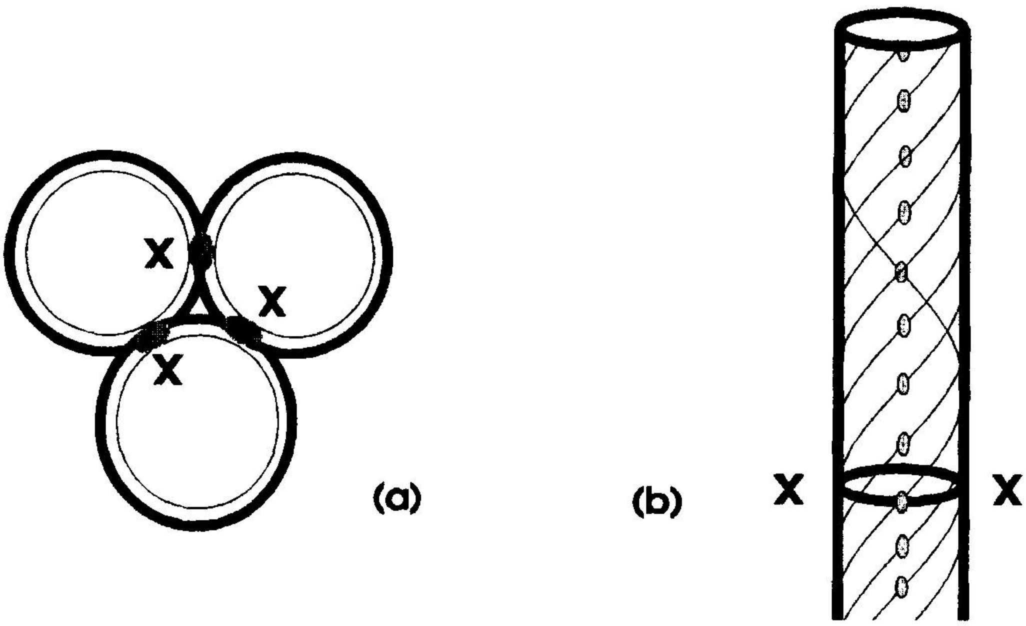

Fig. 4 Localised abrasion at contacts: (a) in cross-section; (b) along yarn

GEN-ROPE, which is a modelling program developed by TTI Ltd, incorporates the special feature that contact forces and displacements between components in twisted ropes during cyclic loading can be calculated. In principle, since these are the controlling factors, this should make it possible to predict the rate at which portions of fibres are worn away. In practice, adequate experimental data on rate of fibre wear is not available at present, and special experimentation would be needed in any particular design study. In addition, there is a length problem in relation to the effect of fibre wear on the rope mechanics, which is not completely addressed by any of the current models. Wear occurs at many different contacts, but let us concentrate attention on the most severe: inter-strand abrasion in a three-strand rope. In a given cross-section, the actual wear will be localised at the contact regions X in Fig. 4(a). After a given number of cycles the shaded portion of the strand will consist of fibre debris, which cannot carry load. If the rest of the cross-section is assumed to remain fully effective, the models would predict the revised rope load-elongation, and indicate failure when the residual strength had fallen to the level of the maximum applied load. However this ignores the fact that, due to the helical path of yarns in the strands, as shown in Fig. 4(b), neighbouring fibres will have been abraded at a cross-section that is a short distance along the strand. All outer fibres in the strand will be subject to abrasion within one turn of the helix.

The safest assumption would therefore be to assume that all fibres at the given depth from the strand surface in a complete ring cease to be load-bearing. However, this is too severe a requirement. In order to make a better prediction it will be necessary to modify GEN-ROPE by introducing the stress transfer and build-up of tension along the length of fibres away from the worn regions. Raoof [22] has examined the related questions of recovery length in wire ropes and strands.

3.5 Terminations and rope length

Various types of termination are used for fibre ropes: splices, potted ends, barrel-and-spike fittings etc. A practical problem, which worries design engineers, is that tensile and fatigue tests may result in failure at the termination. As with wire ropes, considerable attention is being paid to the design of terminations in order to minimise this problem. When there is failure at a termination, it seems that one is not gaining information on rope performance. In fact, the test result is a lower bound for strength or durability. A related and more difficult question is whether end effects change the static or fatigue performance in the rope away from the ends.

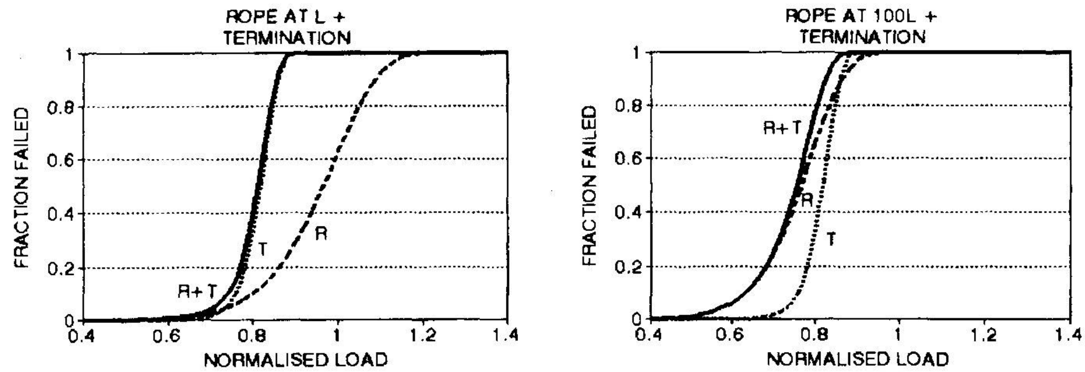

Fig. 5 Cumulative Weibull distributions, showing competitive failure of rope and terminations. For rope at length L, $\alpha = 1$ and $\rho = 10$. For termination, $\alpha = 0.83$ and $\rho = 25$. For rope at length 100L, calculation gives $\alpha = 0.79$ and ρ remains equal to 10.

In actual use with long lengths, breakages away from the termination often become the norm. This is because the weak-link effect comes into play, as indicated by the exaggeratedly severe Weibull plots in Fig. 5. The probability distribution for the terminations is unaltered, but the distribution for the rope itself shifts to lower values at the long length. With the selected values, the failures for rope plus termination follow close to the termination line for the length L with just a few rope breaks, whereas at 100L the rope breaks are dominant.

4 CONCLUSION

Ropes made from the new high performance fibres offer ways of achieving very high strength and stiffness, at lower weights and even in smaller diameters than wire ropes. In addition, polyester fibre ropes give excellent properties at lower cost. However considerable theoretical and experimental work is needed in order to determine the optimum choices of fibre and rope constructions needed for particular applications. Six fatigue mechanisms have been identified, but testing is needed in order to generate an adequate data-base of material properties and actual rope performance.

The length effects are similar in principle to those occurring in wire ropes, resulting from weak link and bundle effects. Although statistical methods help in the use of limited data, there remains the problem of uncertainty as to what is the real distribution of weak places with probabilities much less than can be directly predicted from experimental data. However some recent work does indicate that the use of moderate safety factors will be sufficient to allow for these problems.

REFERENCES

1. WOODWARD R.J. and WILLIAMS F.W., Collapse of Ynys-y-Gwas Bridge, West Glamorgan. Proc. Inst. Civil Engrs., Part I, **84**, 635, 1988.
2. Burgoyne C.J., Guimares G.B. and Chambers J.J., Tests on Beams Prestressed with Unbonded Polyaramid Tendons. Cambridge Univ. Engr. Dept. Tech. Report CUED/D - Struct/TR 132, 1991.
3. RICHMOND B. and HEAD P.R., Alternative Materials in Long-span Bridge Structures. Proc. 1st Oleg Kerensky Memorial Conf., London, 11/5, 1988.
4. PEIRCE F.T., Tensile Test for Cotton Yarns. J.Textile Inst., **17**, T355, 1926.
5. DANIELS H.E., The Statistical Theory of Strength of Bundles of Threads. Proc. Royal Soc. London, **A183**, 45, 1945.
6. DANIELS H.E., The Maximum of a Gaussian Process whose Mean Path has a Maximum, with an Application to the Strength of Bundles of Fibres. Adv. Appl. Probability, **21**, 315, 1989.
7. COLEMAN B.D., On the Strength of Classical Fibres and Fibre Bundles. J.Mech.Phys.Solids, **7**, 60, 1958.
8. SPENCER-SMITH J.L., The Estimation of Fibre Quality. J.Textile Inst., **38**, P257, 1947.
9. PHOENIX S.L., Statistical Models for the Tensile Strength of Yarns and Cables. Mechanics of Flexible Fibre Assemblies, ed. J.W.S.Hearle et al, Sijthoff and Noordhof, page 113, 1980.
10. AMANIAMPONG G., Variability and Visco-elasticity of Parallel-lay Ropes. Ph.D. thesis, University of Cambridge, 1992.
11. HEARLE J.W.S., LOMAS B., COOKE W.D., and DUERDEN I.J., Fibre Failure and Wear of Materials', Ellis Horwood, 1989.
12. HEARLE J.W.S. and PARSEY M.R., Fatigue Failures in Marine Ropes and their Relation to Fibre Fatigue. Polymers in a Marine Environment Conference, IMarE, June 1983.
13. MANDELL J.F., Modelling of Marine Rope Fatigue Behavior. Textile Res. J., **57**, 318, 1987.
14. MEREDITH R., 'The Effect of Rate of Extension on the Tensile Behaviour of Viscose and Acetate Rayons, Silk and Nylon', J. Textile Inst., **45**, T30, 1954.
15. PARSEY M.R., BANFIELD S.J. and HEARLE J.W.S., Life of Polymeric Ropes in the Marine Environment. Polymers in a Marine Environment Conference, IMarE, October 1987.
16. RIEWALD P.G., WALDEN R.G., WHITEHILL A.S. and KORALEK A.S., Design and Deployment Parameters Affecting the Survivability of Stranded Aramid Fiber Ropes in the Marine Environment. Oceans 86 Conference Proceedings, IEEE and MTS, Baltimore and New York, September 1986.
17. CHRYSSANTOPOLOS M.S., Private Communication.
18. CASTILLO E. and SARABIA J.M., Engineering Analysis of Extreme Value Data: Selection of Models. J. Waterway, Port, Coastal, and Ocean Engineering, **118**, Paper No. 26569, March/April, 1992.
19. BURGOYNE C.J. and FLORY J.F., Length effects due to yarn variability in parallel-lay ropes. MTS-90, Washington DC, 1990.
20. GUIMARES G.B., Parallel Lay Aramid Ropes for use in Structural Engineering. PhD thesis, University of London, 1988.
21. FLORY J.F., Hawser Test Report. Oil Companies International Marine Forum, Witherby and Co. Ltd, London, 1982.
22. RAOOF M., Wire Recovery Length in Steel Cables. Proc. Conf. Offshore Mechanics and Arctic Engineering, Vol.III-B, 449, ASME, 1992.