Polyaramid ropes for tension structures

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Modern materials offer new opportunities and challenges to engineers. To use them successfully, the materials must be appreciated in their own right, not as 'substitutes' for conventional materials.

This paper describes the form, properties and applications of Parafil ropes for tension structures. In particular, we concentrate on Type G Parafil, which has as its core yarn Kevlar 49, the highest modulus version of polyaramid fibres so far available.

Background

Over the centuries, many materials have been used as structural tension members: in Ancient Greece, flax ropes, stressed, it is believed, to about 30 Tonnes by means of a Spanish Windlass, were used to prestress the hulls of the Triremes used to maintain Athenian Sea power (1,2).

With the advent of wrought iron, and later steel wire, most of the alternative materials have fallen into disuse, due to the efficiency with which steel wire can be made and anchored. Tension members today are made almost exclusively of steel wire.

However, steel suffers from a number of drawbacks; most importantly, it corrodes and it is heavy. Other problems in some applications are caused by its electrical conductivity and its magnetic properties. Large amounts of money are spent getting round these problems, since until recently, there has been little alternative.

About 20 years ago however, a range of new polyaramid materials was developed. These are usually known by the names of Kevlar (a trade name of Du Pont), Twaron, (a trade name of Enka) or Tecnora (a trade name of Teijin). These materials are produced in the form of fine filaments, which are then given a surface coating and supplied as tows, each containing about 1000 filaments loosely twisted together.

The yarns are produced in different grades, depending on the heat treatment they receive during production. Unlike many materials, it is the elastic modulus which is most affected by the heat treatment, whereas the ultimate strength is unaffected.

	Kevlar		Prestressing Steel wire
	29	49	
Ultimate Strength (N/mm^2)	2760	2760	1860
Youngs Modulus (kN/mm^2)	62	124	200
Specific Gravity	1.44	1.44	7.86

Table 1. Fibre Properties

Table 1 shows the basic properties of Kevlar yarn, compared with those of cold drawn steel wire. The properties of Twaron and Tecnora are similar to those of Kevlar.

Clearly all the materials are stronger than steel, by about 50%, and on a specific strength basis (strength/weight), the aramids are about 8 times as strong as steel. They are however brittle, and have slightly worse creep and stress rupture behaviour; these will be discussed in more detail later.

In the form of individual filaments, or tows, the fibres are not of much use to engineers; although the stress capacity is high, the total load that can be carried is still small in structural terms. Nevertheless, the fibres are widely used in woven form in sails for racing yachts and as the strength elements in high performance composites in the aerospace industry. As chopped filaments (lengths < 2mm) they are used to reinforce moulded or extruded plastic components. Adaptations of these techniques may yet find their way into civil engineering applications, but they are not the concern of this paper.

Rope construction

For structural purposes we need to be able to gather together the fibres to allow the application of large forces (1 to 10000 tonnes), with suitable anchorages and stressing systems to allow full use to be made of the strength of the aramids.

There are a number of ways of aggregating the fibres, which we can classify as laid ropes, pultrusions or parallel-lay ropes.

In laid ropes, the fibres are twisted together to produce strands. These are then braided or twisted again to produce the final rope structure. Various forms of construction are used, depending on the application, but they all share a principal disadvantage from a structural point of view, in that individual filaments follow a helical path along the length of the rope. When tensioned, the axial stiffness of the rope is significantly reduced by the tendency of the helices to straighten, and significant inter-fibre stresses are developed (which become fretting movements if the load is cyclic). Ropes of this form are widely used in marine applications for mooring and towing, since they have very low flexural stiffness, but we shall not consider them further here due to the low axial stiffness.

Pultruded sections offer an alternative way of aggregating fibres. The fibres are drawn through a die, in which is injected a thermo-setting resin. This sets into the shape of the die, and yields a product which has considerable flexural stiffness. The advantage of pultruded sections is that they can be made in many shapes, with the amount of fibre reinforcement varied over the section, to suit the flexural properties required. Circular pultruded sections containing Twaron are produced under the name Arapree, and have been proposed as the pretensioning elements in concrete (3).

Parallel-lay ropes do not have any structure of their own, so the fibres have to be kept together in some way. This is usually done by means of a polymeric sheath extruded over the core bundle; the sheath has sufficient strength to maintain the integrity of the rope, but does not affect the axial properties of the fibre. It is possible to incorporate a resin or a thermo-plastic filler during fabrication, if it is required to eliminate the inter-fibre air voids. Parafil ropes are examples of ropes made in this way, and although such ropes can be made from a variety of core yarns, this paper will concentrate on the properties of such ropes made from the high modulus version of Kevlar (kevlar 49). Such ropes are known as Type G Parafil, which is a trade name of ICI.

Termination systems/bonding systems

The ability of an element to carry significant tensile forces is only as good as the mechanism for getting the force into, or out of, the tensile member.

If we consider, for a moment, the range of methods used to load steel wires, we can draw comparisons between these and the methods used for fibres.

Prestressing tendons are anchored by external wedges, button heads, or bond (4). Stay cables and wire ropes, on the other hand, which have more individual wires, are usually anchored by an internal spike, or by splaying out the wires and encapsulating the ends in a block of a low melting point metal (usually zinc) (5). Welding is not used because of the effect of the heat on the properties of the steel.

Which of these systems can work for elements made up from fibres? External wedges develop high circumferential compressive forces between the outer wires in a strand, but have significantly less effect on the inner wires. With seven wire steel strands, this is not a major problem, but nineteen wire strands, which have an extra layer of wires, are less popular for prestressing systems because of the difficulty of anchoring the central wire. Thus, the use of external wedges for systems containing millions of fibres is unlikely to be successful. Even in pultruded sections anchoring would be difficult because the anchoring loads of the inner fibres would have to be carried by high shear stresses in the matrix without the benefit of high radial compressive stresses.

Button heads in steel wires, as in the BBRV stressing system, rely on the deformability of steel, and the isotropic properties of steel. Modern high strength fibres have high axial strength, but little transverse strength, and they cannot be deformed, so we cannot envisage a similar system for fibres.

Tension elements can be anchored by the use of bond when the element itself has cohesion, and when some distribution of anchorage along the length is acceptable. Pultruded sections can be anchored in this way when used as pretensioning tendons, but the bond mechanism has the properties of the resin matrix, not those of the fibres. In particular, the creep and thermal properties will be significantly worse than those of the fibres. Anchorage by bond is only possible if the fibres within the rope are themselves bonded together. Tests have shown (6) that negligible load transfer capacity is possible on parallel lay ropes which do not have a resin matrix.

An anchorage can be formed by splaying the fibres out into a mould, and then casting a resin cone around them. The cone can then be anchored mechanically in whatever way is needed. As with the bond technique, the integrity of the anchorage relies on the properties of the resin, and the shape of the cone is crucial in ensuring even load transfer to all fibres.

The best method for anchoring parallel fibre ropes is the internal wedge (or spike). The gripping force is provided by radial forces between the spike and the external body, so all the fibres are anchored. The length of the spike can be chosen to ensure that the transverse stresses are within the capacity of

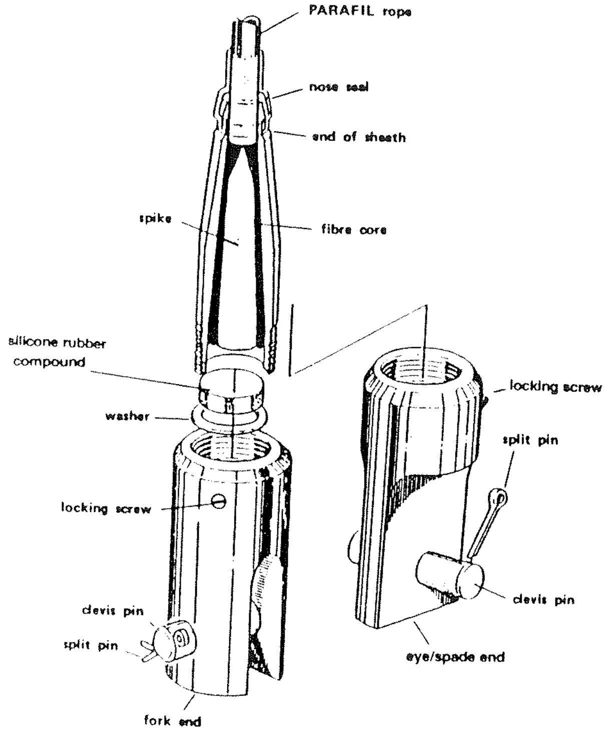


Figure 1. Termination for Type G Parafil.

the fibres. Figure 1 shows a typical termination for Type G Parafil ropes. Once the load has been transmitted from the fibres to the terminal body, further connection to the structure can be made by fitting a variety of connections, such as clevis pins, anchorage plates, or whatever is required. Figure 2 shows such a terminal modified for use as a prestressing tendon, in which the terminal body has two threaded regions. The inner thread is used for connection to a pull rod which is connected to the jack during stressing, while the outer thread is used to provide a connection for a permanent back nut, which also allows some adjustment to take account of slack. The anchorage is capable of achieving the full strength of the rope. Reasonable care must be taken to ensure that the spike is fitted centrally within the rope, but otherwise no special skills are needed. Parafil ropes with capacities between 1 and 1500 tonnes have been anchored using this system, and all the results in this paper have been obtained from tests on ropes fitted with such anchors. Failure normally occurs away from the termination in the main body of the rope.

Stressing systems

Given that an effective method exists for anchoring ropes, the details of the stressing systems can be left for particular applications. However, one example will be given which can be modified to suit other requirements. Figure 3, taken from reference (7), shows a typical stressing system used for prestressing. The rope is terminated to the required length and a pull rod attached which passes through the

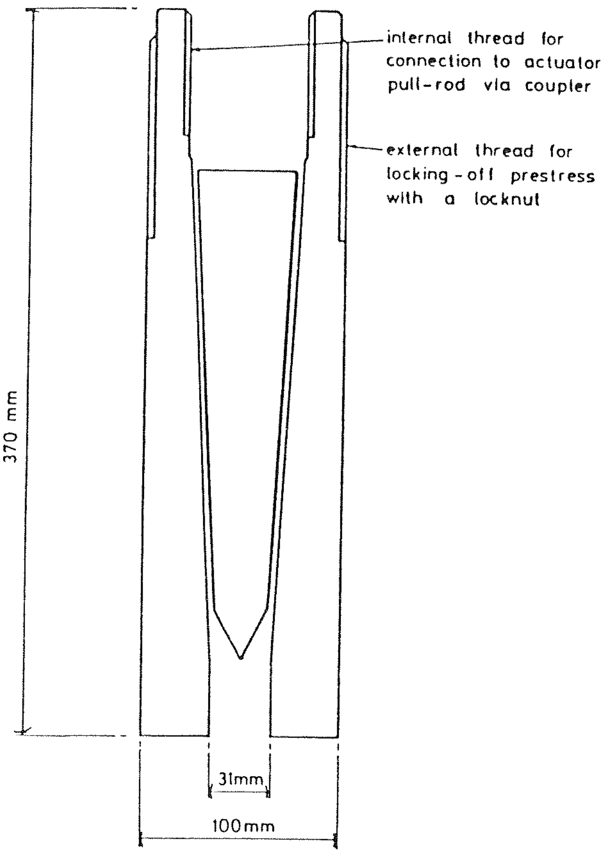
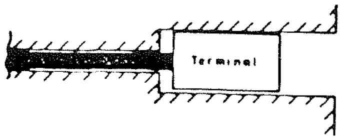
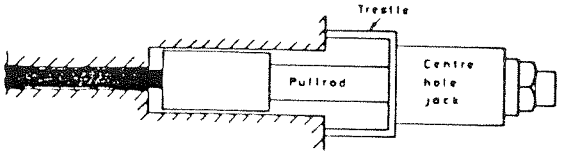


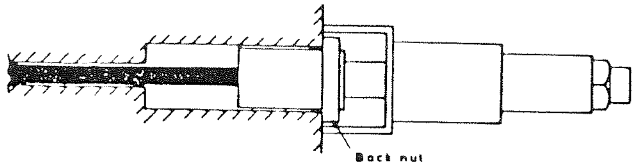
Figure 2. 60 tonne terminal modified for prestressing applications.



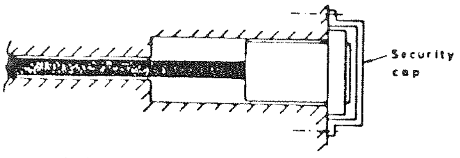
(a) TENDON INSTALLED IN DUCT



(b) JACK ATTACHED



(c) JACK EXTENDED



(d) PERMANENT ARRANGEMENT

Figure 3. Stressing system for Parafil.

centre hole of an hydraulic jack. When the jack is loaded, the rope extends; at the required load the back-nut is tightened to provide the permanent locking system. Finally, a security cover can be fitted if required.

Tensile properties

The tensile properties of Type G Parafil ropes are shown in Figure 4. The strength is typically about 1960 N/mm^2, with a Young's Modulus of about 118 kN/mm^2; there is no ductility.

Since the ropes are made from parallel filaments, there is little possibility for sharing load between fibres. The difference between yarn and rope properties can be accounted for by the statistical properties of bundles (8,9), which predicts that ropes containing many fibres will be weaker than ones containing few fibres. However, even small ropes with strengths of a few tonnes contain many thousands of filaments, so no significant additional fall-off in strength is expected for very large ropes. Strengths quoted by the manufacturer are based on a stress of 1925 N/mm^2, which has been achieved on the largest rope yet tested (1500 tonnes).

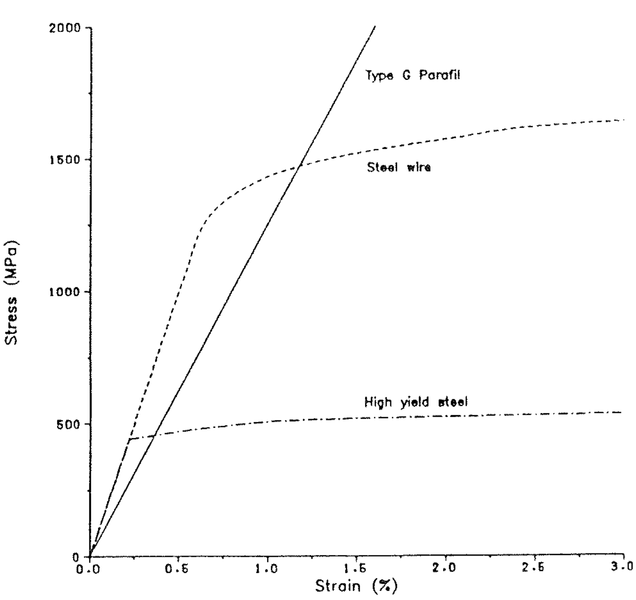


Figure 4. Typical stress-strain curve for Type G Parafil and steel.

The lack of ductility provides another reason for not anchoring the ropes by means of bond. Bond would ensure that high local strains in the main structure would be transmitted to the fibres in the core, which being brittle, would then fail. With no bond, only global strains affecting the length between the anchorages would have a significant effect on the fibres, thus reducing the possibility of premature failure.

Stress rupture properties

Many polymeric materials will creep to failure when loaded by constant loads. To make efficient use of these new materials therefore, it is important that this phenomenon is properly understood.

A number of Type G Parafil ropes of different sizes have been tested at different load levels over the last few years. For short 'times to break', up to a few months, it is feasible to load using electrically operated hydraulic pumps, but for longer periods of loading, dead weights are the only feasible system.

Figure 5 shows the results obtained to date on 1.5 tonne, 3 tonne and 60 tonne ropes (10,11). These are compared with the theoretical predictions of a study carried out at the Lawrence Livermore National Laboratory on epoxy/Kevlar 49 composites, which predicts a linear relationship between the applied load and the logarithm of the 'time to break', based on considerations of the activation energy required to initiate failure (12,9).

The results are in good agreement, and indicate that a load of 50% of the initial breaking load will cause failure after 100 years.

Chambers (9) has proposed a cumulative damage law which can take account of varying load levels. From this model, in which the damage accumulates as a proportion of the 'time to break' spent at each load level, significant increases in the lifetime of the rope are predicted at realistic operating stresses.

Stress relaxation and creep properties

In certain applications, particularly where the rope has to provide a force, rather than merely a reaction, the creep and relaxation properties of the rope are important.

Figure 6 shows typical creep curves for 60 tonne Type G Parafil ropes, at fairly high proportions of their nominal breaking load (NBL). At these load levels the ropes appear to have a virtually constant creep strain capacity of about 0.1% over and above the strain due to the initial elastic response. The rate of creep appears to drop significantly as the load level reduces (Figure 7), and at the load levels that would be commonly used in practice, is very small. Tests are currently underway to explore this phenomenon further, and to correlate the creep, stress rupture and relaxation behaviour.

The stress relaxation properties are related to the creep properties. Predictions of stress relaxation are given in Table 2 (10), while Figure 8 shows typical load vs time plots for large ropes.

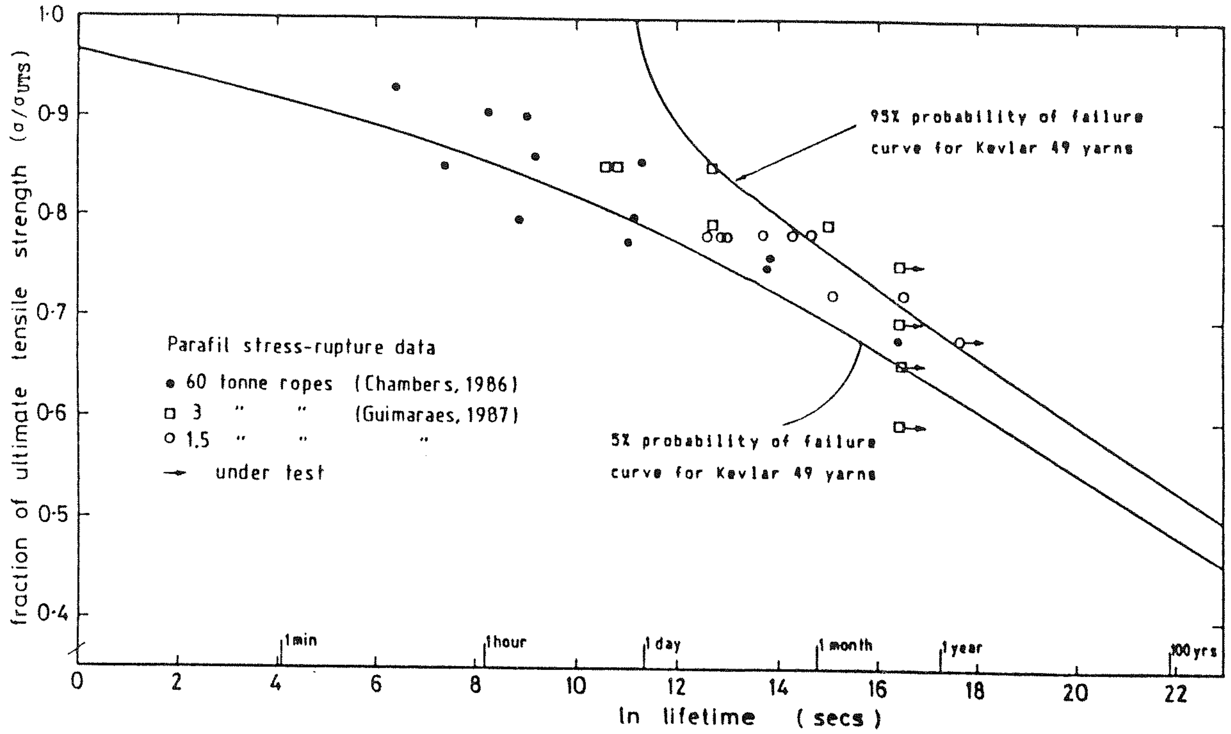


Figure 5. Stress-rupture results for Type G Parafil.

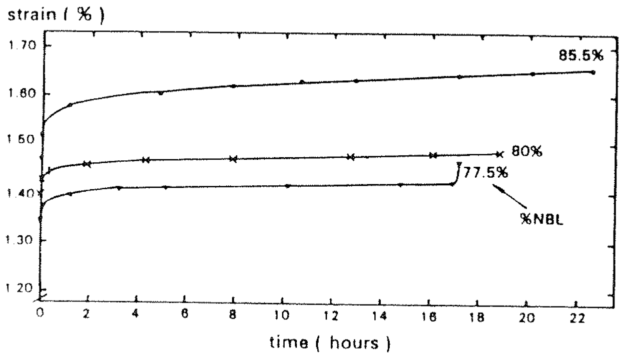


Figure 6. Typical creep behaviour for Type G Parafil.

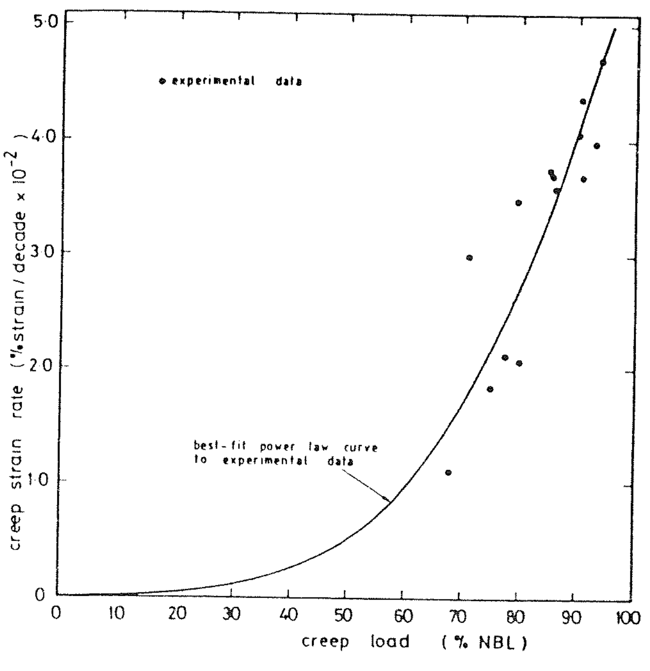


Figure 7. Creep rate results for Type G Parafil.

Fatigue properties

When we refer to the 'fatigue' properties of a material, we must be careful to define precisely what we mean. Work carried out on Nylon (13) has shown that failure in cyclic loading tests is a function of the total duration of the loading sequence, rather than the number of cycles; failure predictions should thus be based on stress rupture criteria, rather than conventional fatigue. In the same work, similar but less extensive results were presented for Kevlar.

Considerable testing of Parafil in tension-tension fatigue (with various core yarns) has been undertaken at the National Engineering Laboratory. These results show lifetimes for the ropes in excess of those for equivalent steel strands (14), but perhaps more importantly, it is concluded that the failure of the ropes is due to inter-fibre fretting, rather than straightforward fatigue. Parallel lay ropes in direct tension will not experience significant fretting, except in the immediate vicinity of the termination, and continued development of the termination is proceeding to

Nominal initial % NBL	Predicted relaxation at 100 years (%NBL)
30	7.0
40	7.4
50	7.8
60	8.2*
70	8.6*

* at these stresses, over long periods of time. Parafil may fail due to stress-rupture.

Table 2 Predicted 100 year stress-relaxation values for Parafil Type G ropes.

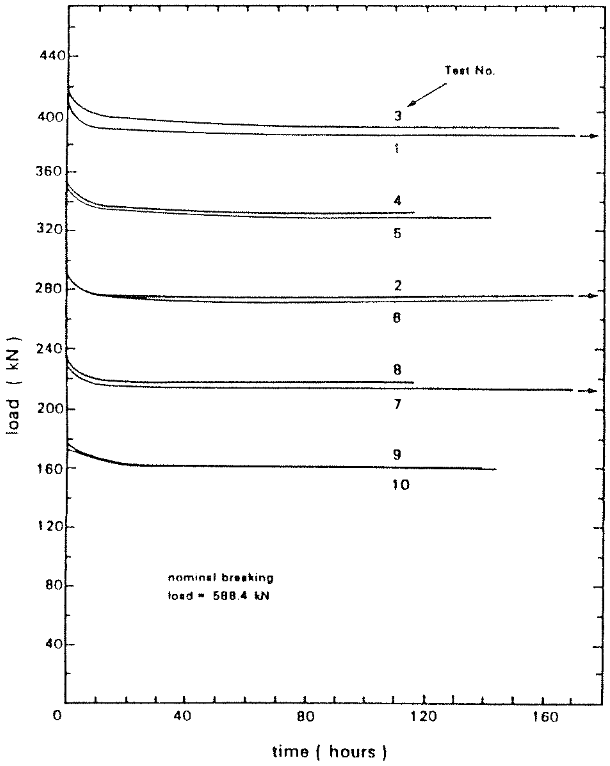


Figure 8. Stress-relaxation curves for Type G Parafil.

improve the figures further.

Parallel-lay ropes are not normally considered for use around sheaves and pulleys, or where flexing of the rope by lateral loads is expected, because of the assumption that their relatively high bending stiffness will cause problems to the outer fibres. However, tension bending and sheave bending tests have been carried out on Type G Parafil ropes, and the results are encouraging. Detailed presentations of these results will be made elsewhere (15).

Laid or braided ropes with Kevlar cores, although much more flexible, can be expected to have worse fatigue properties in both tension-tension and tension-bending modes because of the increased inter-fibre fretting that will occur.

The full spectrum of 'fatigue' results is not yet available for these materials. However, the early indications are that the ropes are at least as good in fatigue as steel wire in most applications.

Thermal properties

The thermal properties of a material that are most relevant to a structural engineer are the coefficient of thermal expansion, and the resistance to fire.

The thermal expansion coefficient of Kevlar is negative, so that the fibres shorten as they get warmer. The material consists of highly oriented crystals, which tend to return to their less oriented form as the temperature rises.

Recent tests (6,16), carried out on Kevlar 49 yarns, have shown that this response is a function of stress, with a larger negative coefficient of expansion as the load increases (Figure 9). The exact mechanism responsible for this phenomenon has still to be identified, but the coefficient of thermal expansion can be expressed as

$$\alpha = -3.7 - 9.9r \ (*10^{-6}/\mathrm{deg\ C})$$

where r is the ratio of stress to strength.

At normal operating stress levels of about 30% of the breaking load, the corresponding thermal expansion coefficient is thus -0.0000065. This compares with figures of between +0.000010 and +0.000012 for steel and concrete.

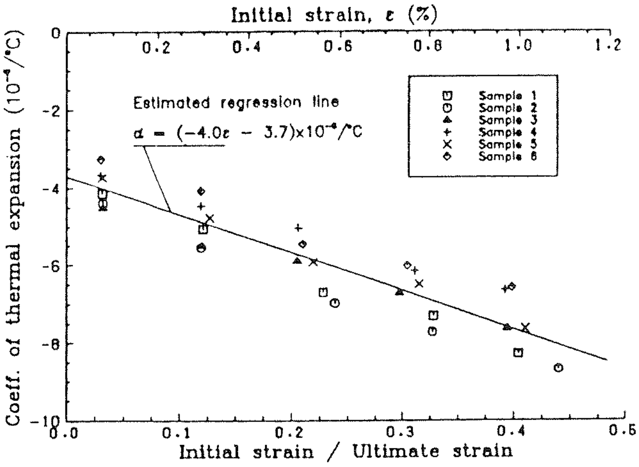


Figure 9. Coefficient of thermal expansion vs. initial strain for Kevlar 49 yarns.

One of the results of the study referred to above was that the response of the fibres was dependent on the time taken to carry out the tests. This was caused by the very low conductivity of the fibres, which meant that the core of the fibres, even when heated in a water bath, takes considerable time to change temperature. It has proved very difficult to measure the coefficient of thermal expansion of the ropes themselves, since not only does it take significant time (days not hours), for temperature changes to progress through the fibres, but heat must pass through the sheath which is also a good insulator. Thus, it is to be expected that large ropes in structural applications will only be significantly affected by slow temperature changes, not by quicker (daily) cycles.

The behaviour of a structural material in a fire is an obvious area for concern, and organic materials might be expected to behave badly in this respect. However, Kevlar is reasonably resistant to heat, losing strength only slowly as the temperature rises. It does not burn, but decomposes at about 450 deg C; it has about half of its initial strength at about 250 deg C. This figure compares with the 550 deg C used as the basis for fire protection for steel. The polymer sheath will melt at a lower temperature, but this can be made from a fire retardant formulation in critical applications; in any event the sheath does not play a critical role in the static strength of the rope once installed.

Application areas

It is clear from the summary given above that we have available a durable, strong, stiff material from which to produce tension members. Efficient connections are available which can develop the full strength of the ropes themselves.

We can now turn to a brief consideration of the areas of application. We will not give detailed consideration to the structural forms themselves, since these form the subject of other papers at this conference.

Guys and stays

The first application of Parafil (in 1967) was as stay cables to radio antennae (17), where the electrical insulation properties offered additional benefits over steel (Figure 10). Similar uses for supporting electrical conductors are quite widespread.

These applications involve relatively low loads, but structural applications as stay cables for bridges and roofs can also be envisaged. Here, the low weight and good fatigue resistance will offer significant benefits to designers.

Self stiffening structures, in which the stays are tensioned against one another (as in the Calgary Saddledome (Figure 11)), rather than against the dead weight of the structure are a logical application area.

Mooring lines

Offshore mooring systems for use in very deep water are one area which is being actively explored at present (18). In this area, it is the light weight of the cables which is the significant benefit. In water depths over about 300m, the weight of steel mooring lines, or of the tension legs of TLPs, imposes significant additional buoyancy requirements on the floating elements of the structure.

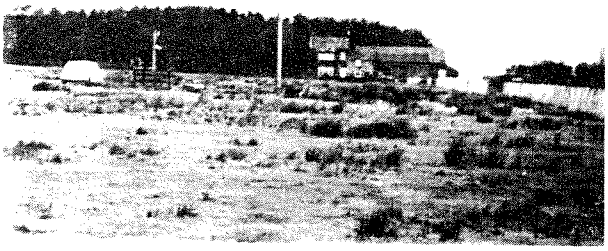


Figure 10. Early use of Parafil as antenna stays.

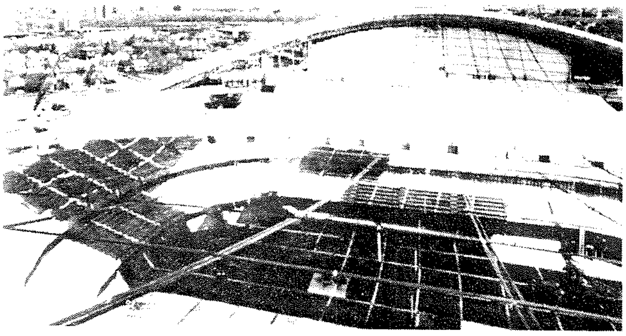


Figure 11. Calgary Saddledome under construction.

Studies (19) have shown that Parafil offers significant benefits for guyed towers, catenary moorings and tension leg platforms, both during operation and installation (Figure 12). It is possible to make the ropes in a production facility located on the dockside from equipment transportable in containers. Thus, ropes could be produced on shore, the terminations fitted, and then floated into location for immediate connection to the structure.

Prestressed concrete

The use of compressive forces to prestress structures, especially concrete, is well known. However, we have come to accept that the prestressing material is steel, and that it must, with few exceptions, be kept within the concrete so that the highly alkaline environment of the concrete protects the steel against corrosion.

Parafil however will not need such corrosion protection, so the tendons can be left outside the concrete (7,20), which can then be reduced in thickness, thus saving significant amounts of weight. This in turn, will have cost saving implications elsewhere.

The idea of external prestressing can then be extended to other areas. Repair of structures is one logical application, in which the application of an external prestress can close cracks and restore structural integrity (21). Similarly, prestressed brickwork is an ideal material for small- to medium-sized buildings or retaining walls, in which the cladding element, at relatively little cost, becomes the main load bearing member (22).

Cost

We have not yet referred in detail to the cost of Parafil as compared with steel, because simple comparisons can be misleading. The basic material cost per unit of force delivered to the structure is between 5 and 6 times that for normal steel strand. However, lack of corrosion, light weight and other benefits lead to significant consequential savings elsewhere in the structure. Thus, cost comparisons need to be made on the basis of complete structures, rather than structural elements; that comparison is dependent on the particular form of the structure concerned and of the innovation by the engineers.

Conclusions

Parafil offers a strong, stiff, durable and light-weight tension element. It can be anchored and installed easily, and offers considerable potential to the designers of tension structures.

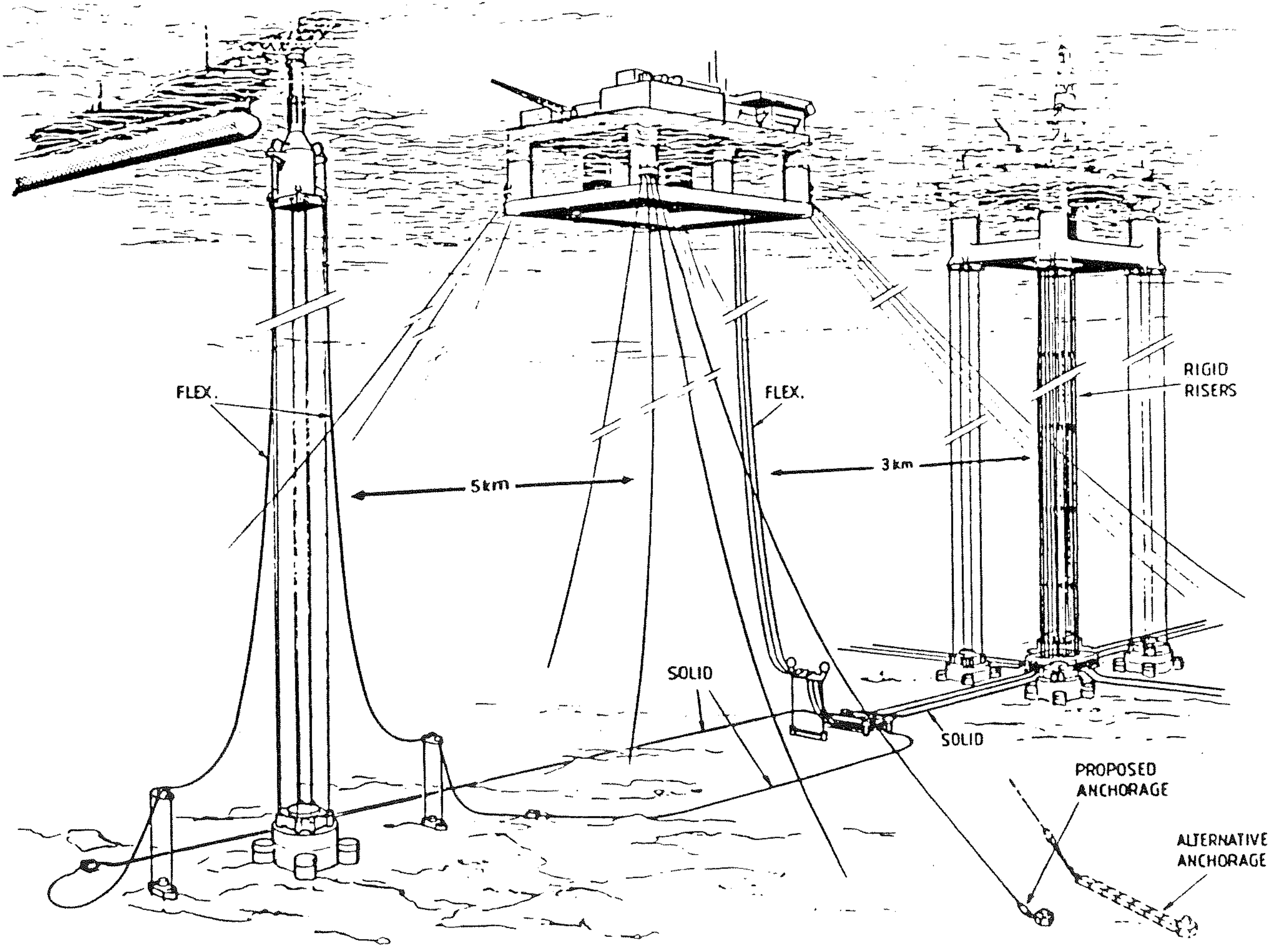


Figure 12. Application of Parafil for mooring offshore platforms.

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Self stiffening structures, in which the stays are tensioned against one another (as in the Calgary Saddledome (Figure 11)), rather than against the dead weight of the structure are a logical application area.

Mooring lines

Offshore mooring systems for use in very deep water are one area which is being actively explored at present (18). In this area, it is the light weight of the cables which is the significant benefit. In water depths over about [illegible] m, the weight of steel mooring lines, or of the tension legs of TLPs, imposes significant additional buoyancy requirements on the floating elements of the structure.

Figure 10. Early use of Parafil as antenna stays.

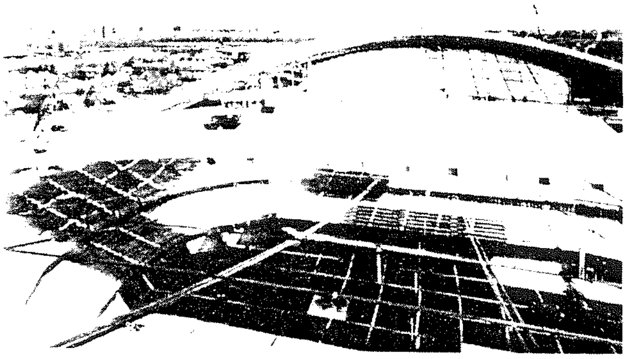

Figure 11. Calgary Saddledome under construction.

Studies (19) have shown that Parafil offers significant benefits for guyed towers, catenary moorings and tension leg platforms, both during operation and installation (Figure 12). It is possible to make the ropes in a production facility located on the dockside from equipment transportable in containers. Thus, ropes could be produced on shore, the terminations fitted, and then floated into location for immediate connection to the structure.

Prestressed concrete

The use of compressive forces to prestress structures, especially concrete, is well known. However, we have come to accept that the prestressing material is steel, and that it must, with few exceptions, be kept within the concrete so that the highly alkaline environment of the concrete protects the steel against corrosion.

Parafil however will not need such corrosion protection, so the tendons can be left outside the concrete (7,20), which can then be reduced in thickness, thus saving significant amounts of weight. This in turn, will have cost saving implications elsewhere.

The idea of external prestressing can then be extended to other areas. Repair of structures is one logical application, in which the application of an external prestress can close cracks and restore structural integrity (21). Similarly, prestressed brickwork is an ideal material for small- to medium-sized buildings or retaining walls, in which the cladding element, at relatively little cost, becomes the main load bearing member (22).

Cost

We have not yet referred in detail to the cost of Parafil as compared with steel, because simple comparisons can be misleading. The basic material cost per unit of force delivered to the structure is between 5 and 6 times that for normal steel strand. However, lack of corrosion, light weight and other benefits lead to significant consequential savings elsewhere in the structure. Thus, cost comparisons need to be made on the basis of complete structures, rather than structural elements; that comparison is dependent on the particular form of the structure concerned and of the innovation by the engineers.

Conclusions

Parafil offers a strong, stiff, durable and light-weight tension element. It can be anchored and installed easily, and offers considerable potential to the designers of tension structures.

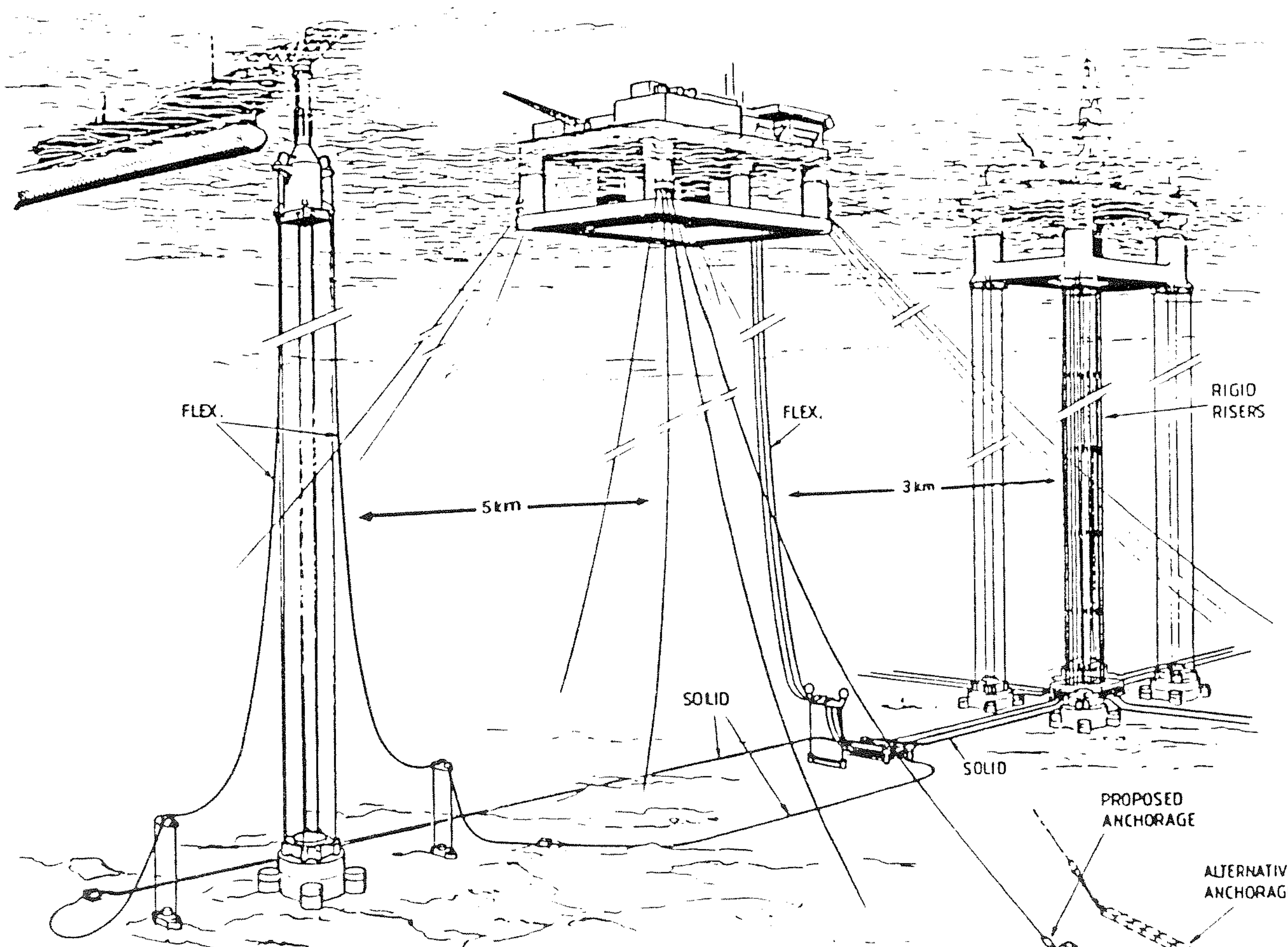

Figure 12. Application of Parafil for mooring offshore platforms.

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