# Structural Use of Parafil Ropes

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**Abstract**

*This paper describes the properties of Parafil ropes with aramid core yarns, which offer the civil engineer a totally new structural material with exciting properties. Some of the current research into the material is described, as are some actual and projected applications.*

## Introduction

We have become used to modern materials in our everyday lives; plastics, glass fibres and other composites are everywhere around us. But in the field of structural engineering, traditional materials have remained supreme. Steel, despite its severe corrosion problems and heavy weight, and concrete and masonry are widely used. Aluminium has found a specialist niche where lightweight fabrications are needed, but its high cost and some special corrosion problems have restricted its general use.

Composites have not yet found wide use for structural applications, although the potential of pultruded sections is becoming recognised. Many are too expensive to be considered on the scale needed for most applications, while Glass Reinforced Plastic (GRP) and Glass Reinforced Cement (GRC), although relatively cheap and easy to use, tend to be restricted to cladding panels and permanent formwork where their light weight, ease of fabrication and short-term strength are most useful.

*Parafil** ropes offer a new alternative. They possess a combination of properties which cannot be matched by existing materials. They are stronger than steel, stiffer than aluminium and do not corrode in most environments. They are light, do not burn and have very good creep properties.

## Aramid yarns

At the heart of the new material lie yarns of aramid. These fibres were first developed in 1958 by Du Pont and were made available under the trade name of *Kevlar*(+) in 1973. Various versions have been produced over the years, incorporating successively improved properties but the two in production today are called *Kevlar 29*(+) and *Kevlar 49*(+). They have the same tensile strength of about 2760 N/mm$^2$, but differ in their Young's Modulus. Kevlar 29 has a modulus of about 62 kN/mm$^2$, while Kevlar 49, which is believed to be a heat treated version of the other material, has a much higher modulus of 120 kN/mm$^2$. Most of the other properties of the two materials are identical. The specific gravity of the fibres is about 1.44 and both exhibit very high resistance to corrosion.

It is not believed that the theoretical limit of stiffness has yet been reached; new versions have not been announced although it is probable that development work is going on behind closed doors.

Kevlar has found wide-spread uses in its fibre form; its light weight and strength have been utilised in specialist fabrics, such as bullet-proof vests and sails for racing yachts. It is used in composites, in which mats of fibres are used to make lightweight structural panels for aircraft. The fibres can also be chopped into very small lengths and mixed with thermoplastic or thermosetting polymers for use in injection moulding, die moulding and extrusion machines to produce high strength plastic components.

The success of Kevlar made it inevitable that other manufacturers would attempt to emulate its properties, despite the existing patent protection. Some similar materials have been produced, of which the best developed is *Twaron*(**), produced by Enka. Two versions are made, as with Kevlar. One has properties very similar to Kevlar 29, but the higher modulus version is less stiff than Kevlar 49.

## Parafil Ropes

Parafil ropes were developed by the Fibres Division of Imperial Chemical Industries (ICI) about 15 years ago. They consist of a core of *Para*llel *fil*aments of a core yarn, surrounded by a thermoplastic sheath. The rope construction allows maximum use to be made of the strength and stiffness of the core yarn. If the rope were braided or twisted, the stiffness would be significantly reduced and there would be large transverse inter-fibre stresses.

The sheath serves two main purposes: it maintains the shape of the rope without itself becoming involved in the load carrying process and it serves to protect the core yarn from the effects of ultra-violet light, which can cause a degradation of the fibre properties.

Parafil ropes are produced in three versions, each with a different type of core yarn. Type A has a polyester core with a lower modulus (12kN/mm$^2$), and strength (600 N/mm$^2$); it is used primarily for guy ropes and other applications where high stiffness is not a prime requirement. Type F has a core of Kevlar 29, while Type G has a core of Kevlar 49; it is this high modulus version which is most useful in structural applications and with which we are primarily concerned in this paper.

All versions of Parafil share a similar termination system. Parallel-lay ropes cannot be terminated by most of the conventional rope anchoring systems such as eye splicing, since these rely either on the braided or twisted construction of conventional ropes, or on the development of high interfibre stresses which cannot be tolerated by highly aligned polymers such as Kevlar.

The termination system which has been developed relies on a single conical spike on the centre-line of the rope, which compresses fibres against a matching outer terminal body *(Figure 1)*. The spike and body can be made from aluminium alloy, stainless steel or galvanised steel, depending on the end use required. The terminal body can be threaded to accept a variety of fittings for connections to tensioning devices or anchors; terminals for smaller ropes are supplied with integral forks and clevis pins.

The exact shape of the spike and its mating surface on the body were carefully chosen after exhaustive testing, and the termination system is capable of developing the full strength of the rope. Provided the spike is placed centrally within the rope so that there is even load sharing between individual fibres, failure of the ropes will normally occur away from the termination in the main body of the rope.

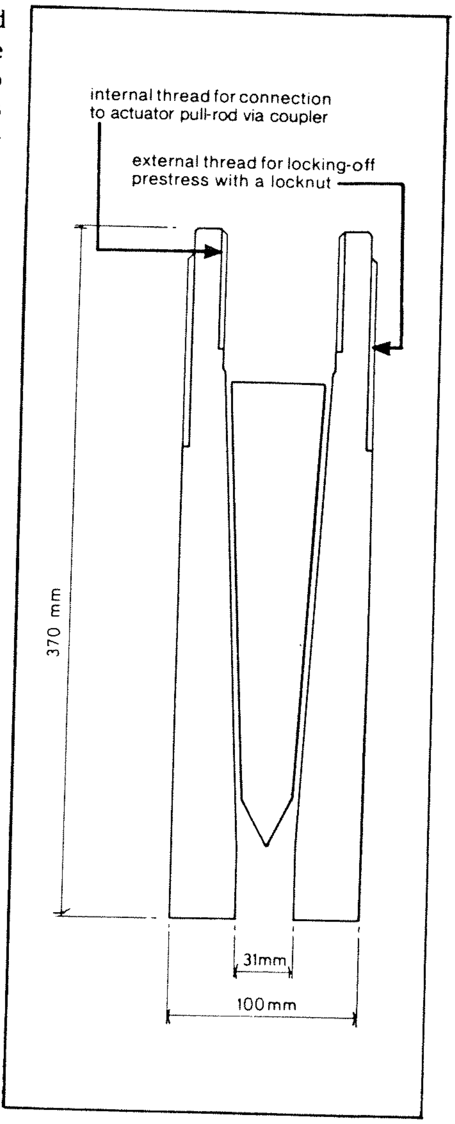

*Fig 1 Longitudinal section through 60 tonne Type G terminal, modified for prestressing*

Fitting the termination is quite straightforward. For small ropes (up to about 100 tonnes nominal breaking load), the process can be done manually with the terminal arranged vertically (*Figure 2*). The rope is passed through the terminal body and a length of the sheath removed; the fibres are then arranged symmetrically around the periphery and the spike placed in the centre. Finally, the rope is drawn back into the body, taking the spike with it – a light tap with a hammer ensures that the spike remains in place until the first load is applied.

For larger ropes, a jig arrangement is used since the weight of the terminal body and spike make hand fitting impractical. There is no difference in principle however from the process used for the lighter ropes.

The spikes have a relatively shallow included angle, so some draw-in can be expected on first loading. For this reason, ropes are normally pre-loaded to 60% of the breaking load after termination. This causes the spike to be drawn in to its final position and eliminates any non-linearity on the load deflection curve. When the rope is subsequently loaded in service, the load deflection curve will be sensibly straight.

## Material properties

The material properties of Type G Parafil most relevant to structural applications are outlined in *Table 1*.

A typical stress-strain curve for a 60 tonne nominal breaking load (NBL) rope is shown in *Figure 3*. The behaviour is practically linear although there is a slight stiffening after about 50% NBL. Failure occurs at a stress of about 200 N/mm$^2$, with a corresponding strain of about 1.75%; there is no ductility.

There is a small tendency for the fibres to work-stiffen. When the ropes have been under load for some time, the stiffness increases by a few per cent, but the breaking load is unaffected.

The difference between the breaking stress of individual yarns and that of yarns collected together in rope is a function of the variability of the yarns. Because 60 tonne ropes already contain a very large number of fibres, no significant variation in breaking stress will be observed in larger ropes, while smaller ropes will, if anything, be stronger.

If ropes are subjected to permanent high loads they will creep to failure. This stress-rupture behaviour should be taken into account when designing structural applications, since many loads in such cases are permanent. The precise mechanism for the phenomenon is not precisely understood, but there is reasonable evidence that the process is controlled by a thermally activated rate process. This leads to a linear relationship between the logarithm of the 'time to break' and the applied stress. The precise form of the relationship requires the measurement of empirical factors; test results from Imperial College on Parafil ropes, the Lawrence Livermore

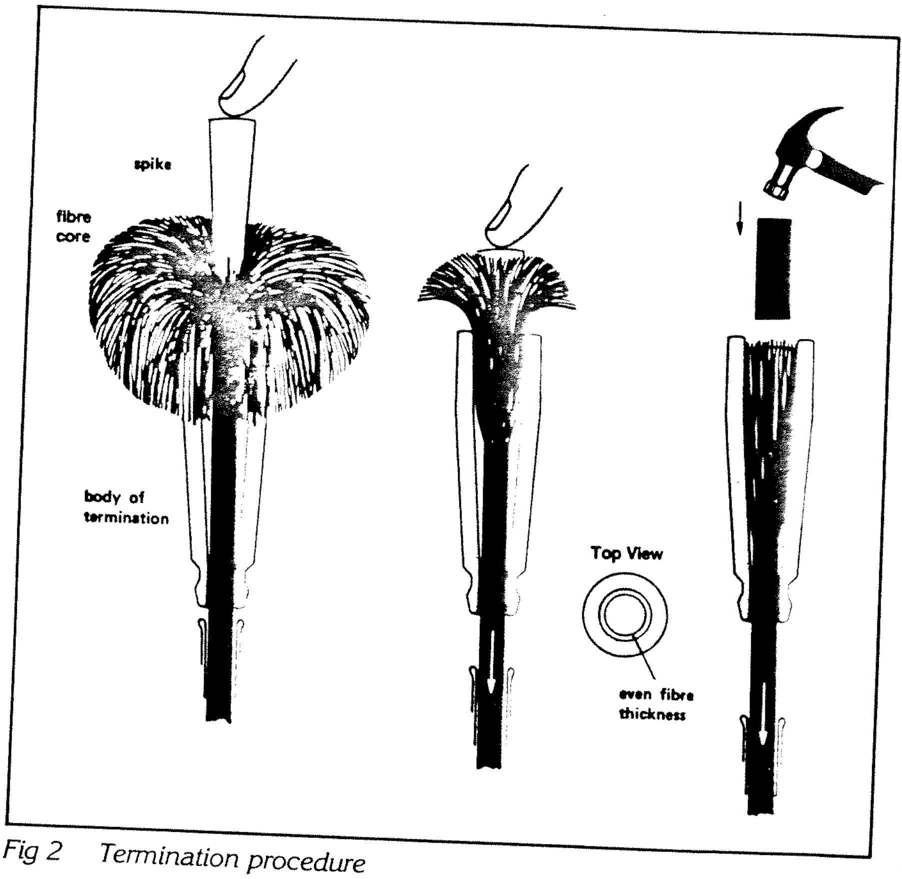

*Fig 2 Termination procedure*

**Structural Properties of Type G Parafil**

| | |
|---|---|
| Nominal strength | 1926 N/mm$^2$ |
| Young's modulus | 120 kN/mm$^2$ |
| Brittle | |
| Creep strain | 0.12% max |
| Stress relaxation | 8% max |
| Stress rupture | 50% load for 100 years |
| Specific gravity | 0.98 (dry)<br>1.09 (saturated) |
| Coeff. of thermal expansion | $-2.10^{-6}$ at zero stress |
| Bond to concrete | none |
| Tension-tension fatigue | excellent |
| Resistance to corrosion | excellent |
| Electrically insulating | |
| Non-magnetic | |

*Table 1 Structural properties of Type G Parafil*

National Laboratories on Kevlar 49/Epoxy composites(4) and the Ministry of Defence on Kevlar 49 yarns(6) have to be combined by Chambers(1) to produce the predicted stress-rupture curves shown in *Figure 4*. These show 5% and 95% confidence limits for the theoretical results. There is some nonlinearity for short life-times, but the linear relationship becomes clear for longer lifetimes.

Practical structural lifetimes are measured in years. Typically an oil rig might be designed for 25 years; the load which would cause failure after this period is about 55% NBL. For a bridge structure, a lifetime of 100 years has a corresponding stress of 50% NBL.

There is some evidence(1) that stress rupture is closely related to creep. Total creep strains of about 0.12% are observed just prior to failure, and at low stresses creep of about 0.02% per decade are quoted(5). This would lead to lifetime predictions similar to those for the thermally activated rate process. If creep rates are lower than 0.02% per decade at low stress levels, which seems reasonable, then lifetimes at structural operating stresses may be longer than those given above. Tests are underway now to determine creep rates at stress levels between 30% and 70% of the nominal breaking load of the ropes.

Stress relaxation is closely related to creep but it has not yet proved possible to find a single mathematical model which adequately describes both behaviours. Nevertheless, from tests it can be predicted that for a prestressed concrete application, a loss of prestress of about 8% over 100 years could be expected. This is larger than for low relaxation steel strand, but is not so high that it precludes the use of Parafil in applications where permanent loads are required.

The fatigue properties of Parafil are excellent. Fatigue testing carried out on Type F Parafil (with Kevlar 29 core yarns) have produced results that far exceed anything possible in steel wire ropes. For example, ropes subject to tension-tension fatigue tests up to 50% of the nomal breaking load have been removed from test machines after one million cycles. It has been predicted that the fatigue performance of Kevlar and some other polymers can best be modelled by a cumulative damage law, rather than a Miner's rule approach(8). This would indicate that a 'time under load' approach (based on stress-rupture data) rather than a 'number of cycles' approach is more valid when predicting fatigue lifetimes.

The thermal expansion of Kevlar 49 and hence Parafil is slightly unusual for engineers used to dealing with metals, in that the coefficient of thermal expansion is negative, the manufacturer's usually quoting a figure of $-2.10^{-6}$ at ambient temperature and zero stress. This behaviour is associated with the tendency of the long aligned molecules to curl up when heated, but the mechanism is not fully understood.

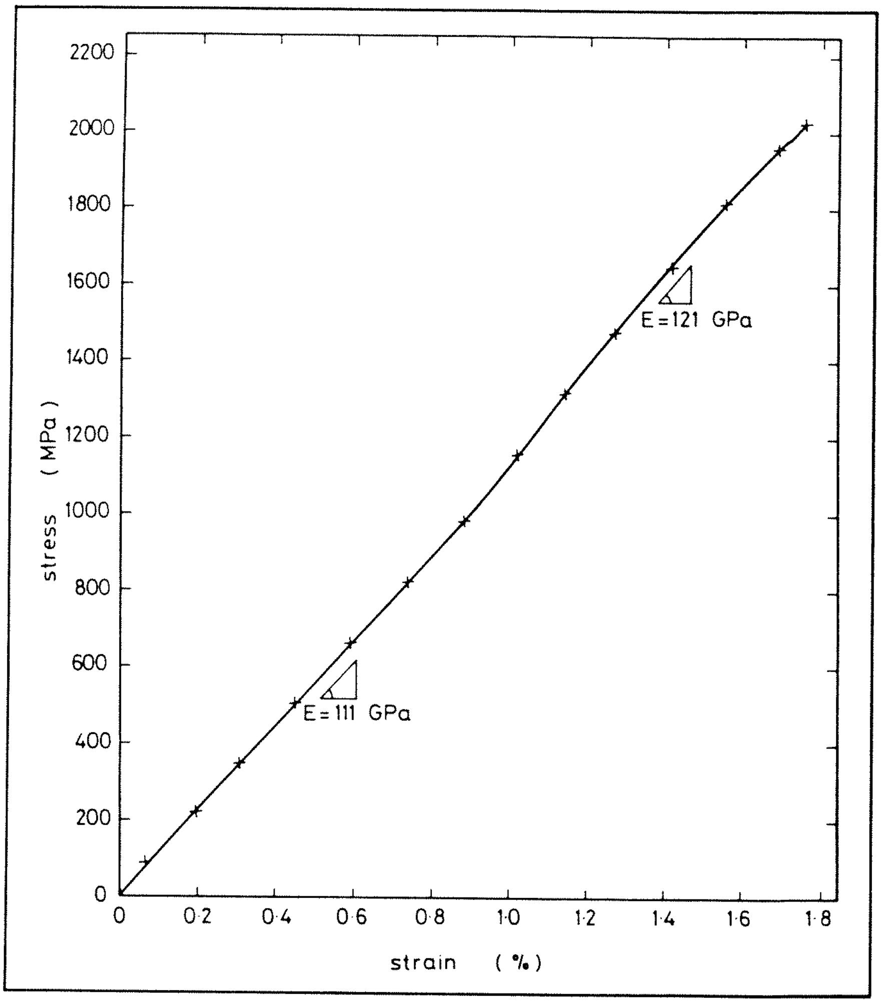

*Fig 3 Typical stress-strain curve for Type G Parafil*

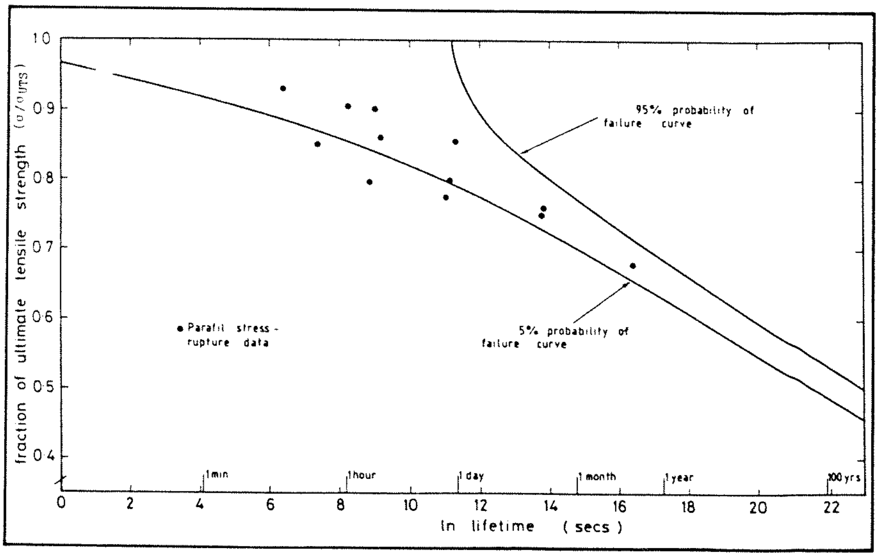

*Fig 4 Parafil stress-rupture predictions*

The behaviour of Kevlar in fire conditions is clearly important in some structural applications. Kevlar does not burn, but decomposes at about 450°C. The temperature at which Kevlar has about 50% of its short-term strength is about 300°C, which compares with the 550°C normally quoted for steel and on which most fire protection criteria are based. The thermoplastic sheath may melt at lower temperatues, but a fire retardent formulation could be used and this should not affect the load carrying capacity of the core.

## Test programme at Imperial College

A variety of test programmes are being carried out at Imperial College, sponsored by Imperial Chemical Industries, the SERC, the Marine Technology Directorate and industrial firms associated with marine and oil applications.

Tests have concentrated on three main areas:

1) to determine the long term properties of Parafil for use as prestressing tendons for concrete
2) to determine the thermal properties of Kevlar 49 when subjected to thermal cycles while under stress
3) to study the fatigue properties of Parafil when subjected to Tension-bending and Sheave Bending.

The long-term tests have concentrated on stress-rupture tests (from which creep data can also be obtained), and stress relaxation tests.

Two phases of stress rupture tests have been carried out, the first involving tests on 60 tonne NBL ropes, loaded by an electrically powered hydraulic jack, with loads in excess of 70% of the NBL which cause failure in periods ranging from a few minutes to a few months.

For longer lifetimes, powered application of load is not practical, so tests are now being carried out on smaller ropes (1.5 tonnes and 3 tonnes), loaded by dead load through a lever arrangement.

Detailed results for the first tests are given elsewhere(1), but a summary of the results is shown in *Figure 4*. These are in good agreement with the theoretical predictions, especially for the longer lifetimes. The first results from the tests on smaller ropes confirm these trends.

A typical creep result from one of these tests is shown in *Figure 5* which relates to one of the stress rupture tests carried out on 60 tonne ropes. This particular rope was loaded to 45 tonnes.

The response can be divided into four phases:

(i) an initial elastic response
(ii) a primary creep phase over the first few hours
(iii) a secondary creep phase, where the rate of creep on a log time scale is virtually constant
(iv) a tertiary creep phase, in which the rate of creep increases until

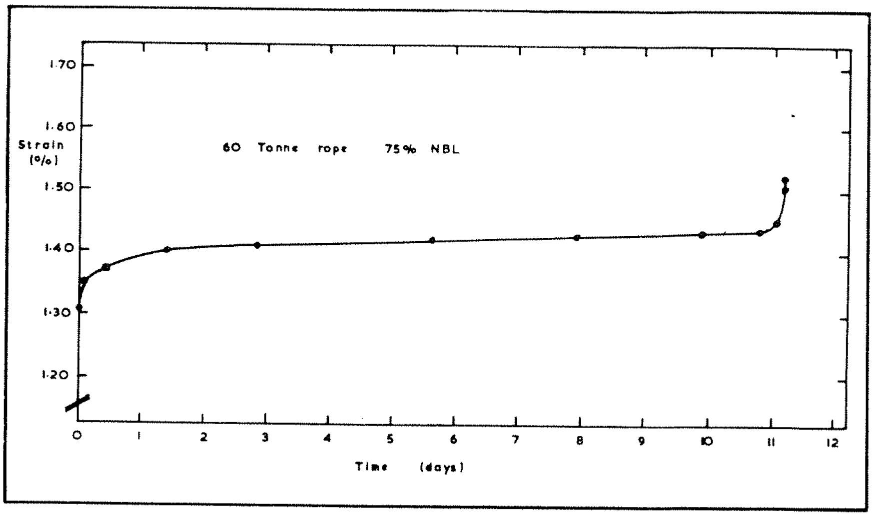

*Fig 5 Typical creep response*

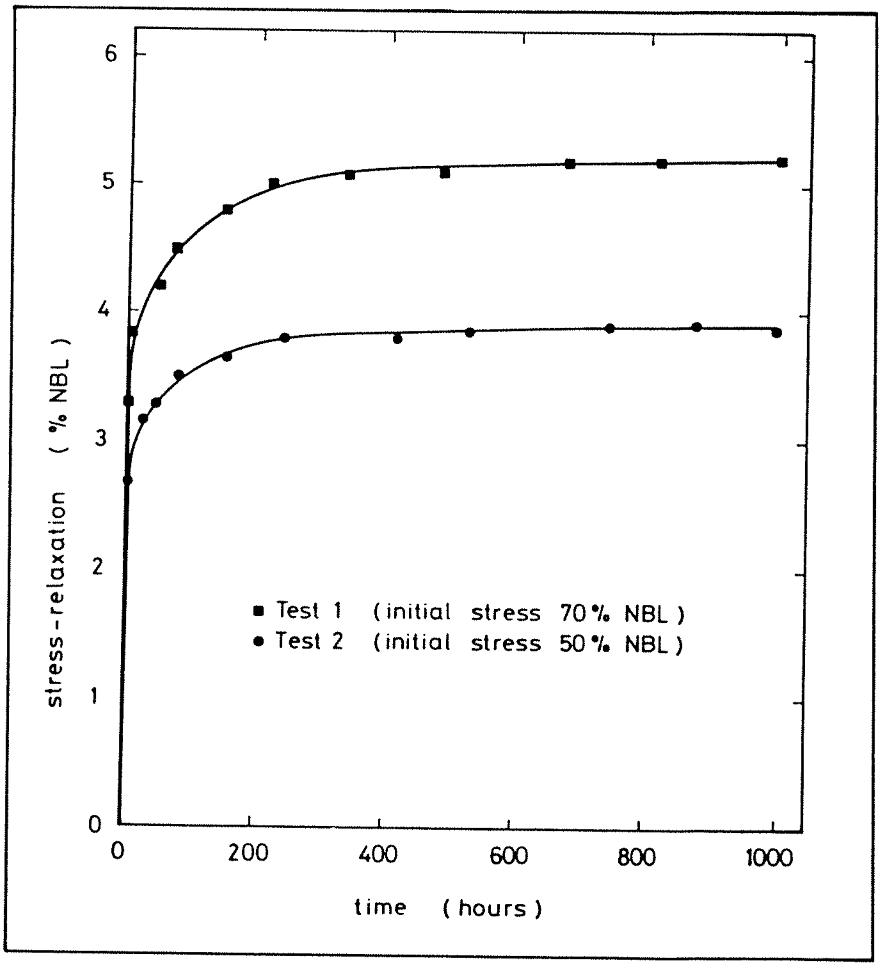

*Fig 6 Stress-relaxation behaviour*

failure occurs

The current stress rupture tests will be used to obtain additional data regarding the rate of creep at low stress levels to test the theory that stress rupture behaviour can be related to creep strain.

Stress relaxation tests have been carried out on 60 tonne ropes, by loading them against a reaction frame and then locking the terminals in position. The rate of relaxation becomes quite small after about 100 hours, as is shown by the test results given in *Figure 6*.

The thermal tests are concentrating on measurements of the coefficients of linear thermal expansion of Kevlar 49 yarns when under load. Initial results indicate that the manufacturer's quoted figure of $-2.10^{-6}$ is reasonable at low stress levels, but a higher value (perhaps as high as $6.10^{-6}$) would apply at about 50% of the breaking load. *Figure 7* shows a temperature strain curve for one complete cycle.

These tests are performed in a bath of water which can be quickly heated and cooled to eliminate creep effects. Additional tests are now underway, with the yarns held in a fine plastic tube, to ensure that the results are not affected by the intimate contact of the fibres with the water.

The fatigue tests relate to possible uses of the ropes for mooring offshore structures. In these applications, there may well be significant lateral cyclic movements of the rope. While Parafil is excellent in axial fatigue (since the rope construction does not provide any stress raisers), the behaviour in bending fatigue may not be so good.

Thus, tests are now in progress to determine the behaviour of the ropes when subjected to constant axial tension and a cyclic bending load. The most significant bending effects would appear to be at the terminal, but the ropes have behaved better than steel wire ropes of equivalent capacity.

Parallel-lay ropes will not be good at bending round tight radii such as winch drums and pulleys, since the construction will ensure that the outer fibres carry most of the bending stress. Tests on ropes bent round sheaves are now in progress, but detailed results are not yet available. However, it is clear that the loads induced in mooring ropes during intermittent handling are unlikely to cause fatigue problems.

## Potential uses

A material with such remarkable properties as Parafil is not going to be short of applications for long. In many of the applications considered to date, Parafil is not used to replace existing materials, but to extend the use of a technique to areas where traditional materials have been found wanting. Parafil has strength and stiffness properties not unlike those of cold drawn steel wire, so it is not surprising that it is in fields where this material is widely used that the first applications are to be found. Most of the applications to be considered rely

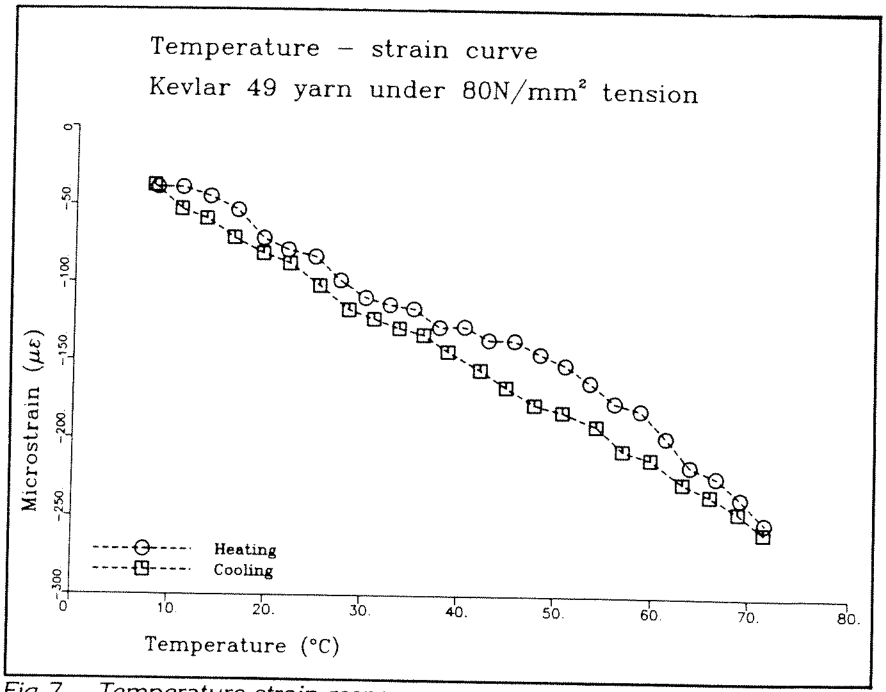

*Fig 7 Temperature strain response*

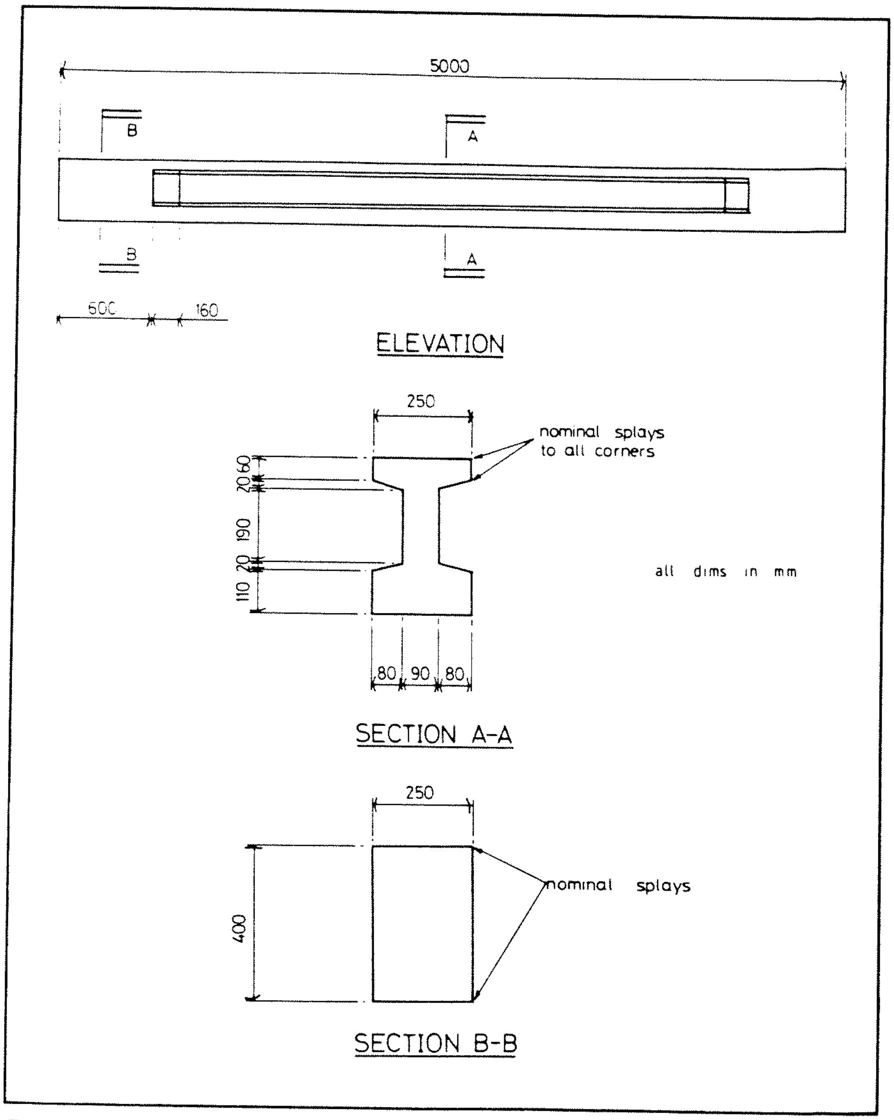

*Fig 8 Test beam, general arrangement*

on either the light weight of Parafil, or its resistance to corrosion, to extend the usefulness of a particular technique.

**For prestressing concrete**

Concrete is readily available, relatively cheap, and can be cast into many shapes. With reasonable care in design and on site, it can be a durable material lasting for centuries. It has one major defect: its lack of tensile strength. This can be overcome by using steel reinforcement or by applying an external compressive force to produce prestressed concrete.

The forces involved are extremely high. In a typical bridge beam, the prestressing force may be ten times the lateral load to be resisted by the beam. Consequently, even relatively minor bridges may have several thousand tonnes of prestress force in them. The force in the tendon does not change significantly under load. The tendon places the concrete in such a state that the concrete can resist the load, rather than by changes in stress in the tendon. Thus, prestressing tendons are tensioned to the highest stress possible, with due regard to safety. Stresses of 70% or even 80% of the ultimate strength of the tendon are commonly used, which far exceeds stresses used in any other structural application.

To protect the steel against corrosion over the lifetime of the structure, the tendons are usually embedded in the concrete. The high alkalinity of concrete (normally around pH12) ensures that the steel is passivated, and so does not corrode. But there is a penalty to be paid for this. Parts of the structure containing the tendons are frequently larger than needed for other reasons, simply to provide the corrosion protection for the steel. Cover to the steel of 50mm is quite common, to prevent a reduction of the alkalinity in the concrete next to the steel caused by carbonation due to the ingress of atmospheric carbon dioxide. This would have the effect of removing the passivation of the steel, allowing it to corrode. The additional concrete adds to the weight of the structure, which increases the bending moments, which in turn increases the size of structure required. This problem has been recognised for many years, and attempts have been made to resolve it.

One approach was to leave the tendons outside the concrete, except where they change direction, and to provide corrosion protection by coating the tendons in grease and wrapping them in a plastic sheath. A number of bridges have been built in this way over the last thirty years, but fears about the durability of the tendons (many of them justified) have restricted adoption of the technique.

Parafil tendons would be suitable alternatives to steel for these structures. The working stress would be about 900 N/mm$^2$, even after allowing for stress rupture, which compares with the normal working stress in a steel tendon of about 1000 N/mm$^2$. The slightly lower modulus of Parafil would mean a larger extension of the cable when prestressing, which would mean a lower loss of prestress due to creep and shrinkage of the concrete.

The ability of Parafil to resist corrosion means that the tendons can be safely left outside the concrete. In practice, they would usually be placed in the central void of box girder bridges.

To demonstrate the effectiveness of the prestress, a beam (*Figure 8*) was cast at Imperial College, and tested in flexure to failure. The 5 m beam was prestressed with a single 60 tonne Parafil rope which passed through a straight plastic sleeve on the centre-line of the beam. Although the tendon was inside the concrete, the only connections between the tendon and the concrete were at the anchorages.

The beam was loaded in two point bending, with the load deflection curve shown in *Figure 9*. The response of the beam was ductile, which at first sight is surprising for a beam made from two brittle materials, but if the cracking of the concrete is taken into account, the behaviour is predictable. The beam finally failed, as expected, by crushing the concrete in the compression zone (*Figure 10*). Relatively small stress changes took place in the tendon during the test, which was still carrying about 80% of the initial prestress after the beam had failed.

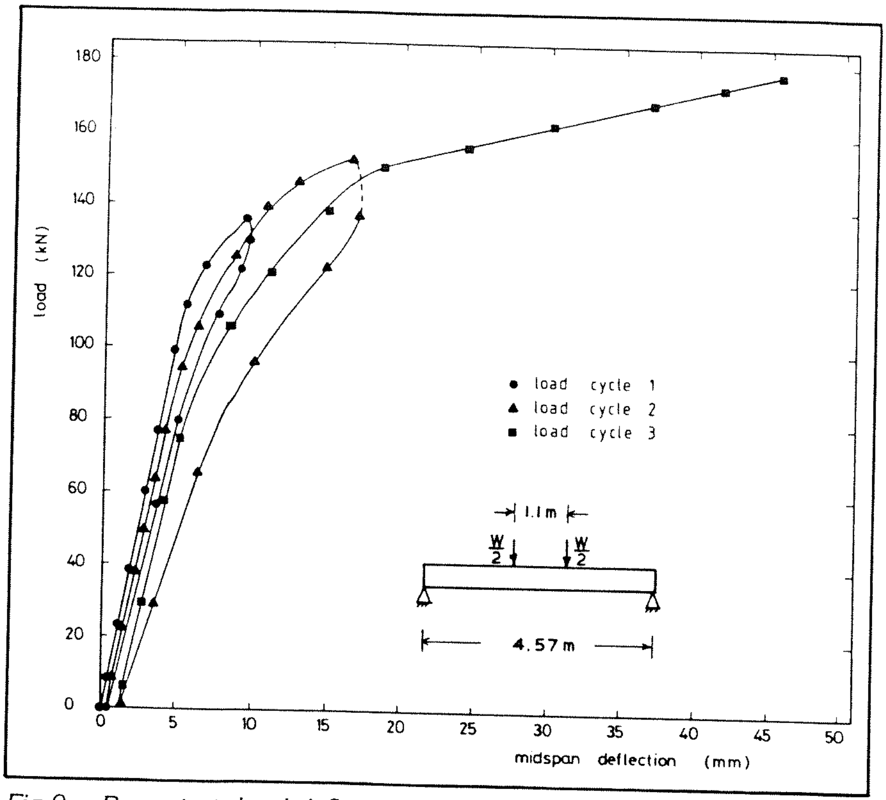

*Fig 9 Beam test, load-deflection curve*

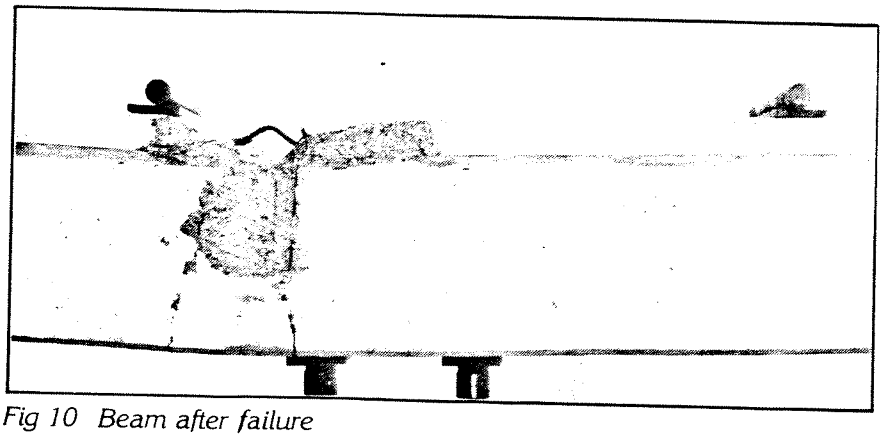

*Fig 10 Beam after failure*

## Use for repair of structures

Repair of structures by applying an external prestress is not new, with practical examples using steel tendons being reported. This can be for reasons of strength, or to limit deflections caused by creep. The general philosophy of repairing structures by prestressing has been described by Fargeot(2), in which external prestressing cables change the state of stress within the structure. The cables must be external, since no ducts exist for the tendons, but anchor blocks and deflection points have to be attached to the structure, either by bolting steel fittings to the structure, or by using short prestressing bars to connect in situ concrete to the original structure. Detailed examples have also been given by Safier(10), who describes a small office block, suffering from creep deflections of cantilever overhangs, which was repaired by external prestress, and domestic housing, cracking due to differential settlement, treated by prestressing the foundations.

Proposals have been made to repair a major bridge in the Far East(12). This structure was built by the balanced cantilever method, and is now suffering significant creep deflections which threaten to make the structure unusable. It has been proposed to repair the structure by providing additional prestressing tendons within the box girder but immediately below the top slab soffit.

The major problem with all these techniques is that it is difficult to provide corrosion protection to the additional tendons. By definition, they cannot be inside the concrete, and since any in situ concrete applied after stressing would itself not be stressed, the corrosion protection it provides would be suspect at best. Parafil ropes, with their inherent resistance to corrosion, would be ideal for these applications.

Parafil has recently been used for a repair contract on three large cooling towers at Thorpe Marsh power station. The site has six towers, three being of a similar shape to the ill-fated towers at Ferrybridge. The towers are 104 m high, with a diameter of 51 m at the top; the walls were originally 125 mm thick with a single layer of reinforcement but were thickened by the addition of 50 mm gunite on the outside after the collapse of the Ferrybridge towers. Recently, large vertical cracks were observed in the towers, the worst being about 12m long and 60 mm wide, with the reinforcement across the crack absent due to either corrosion or snapping (*Figure 11*).

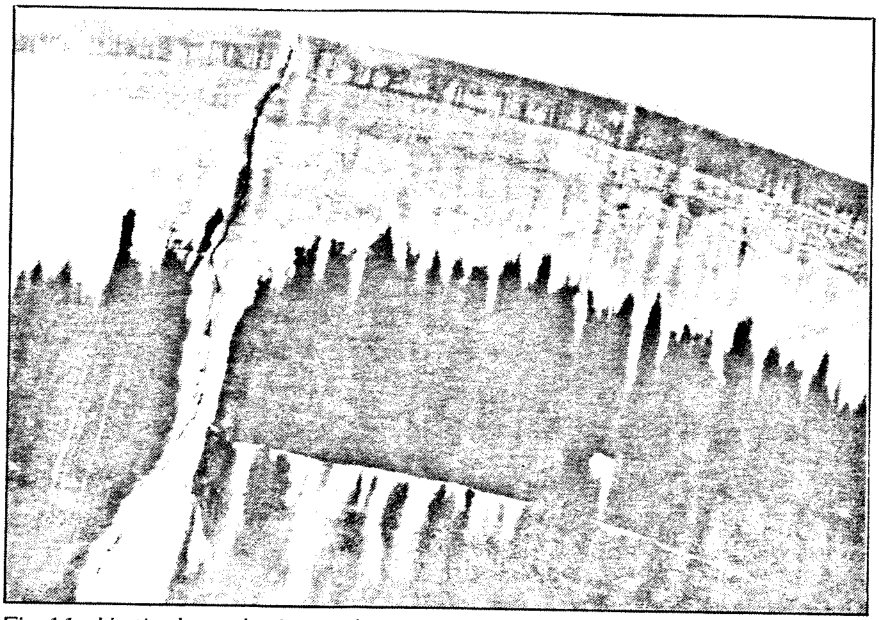

*Fig 11 Vertical cracks in cooling towers at Thorpe Marsh power station*

The towers were repaired under a £500,000 contract by resin injection into the cracks, followed by circumferential prestressing with Parafil tendons. Stainless steel hangers are bolted to the tower to support the Parafil ropes (*Figure 12*) which are stressed together at three or four points around the circumference using short lengths of stainless steel prestressing steel and Stronghold stressing fittings.

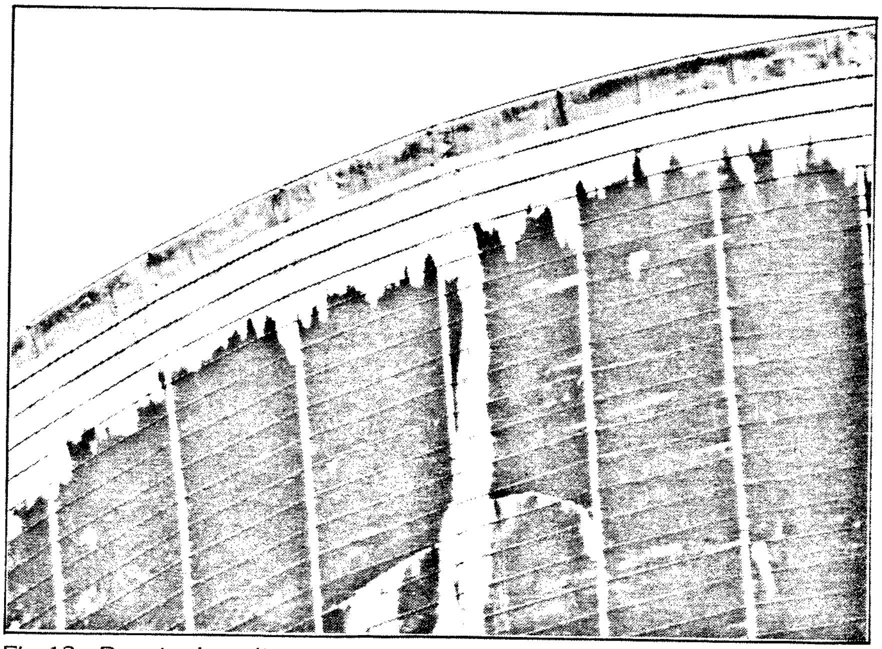

*Fig 12 Repaired cooling towers prestressed using Parafil tendons*

The ropes used were 10.5 tonne Type F Parafil (using the lower modulus Kevlar 29 as the core yarn), stressed to 3 tonnes initially. The lower than usual figure allows not only for stress rupture, but also for the considerable thermal strains which occur in cooling towers. There were some difficulties encountered in achieving equal loads at the three jacking points on each cable, but when the stresses were checked three months later when the cables were restressed to take out initial creep losses, the forces were found to have equalised. Presumably the movements associated with thermal cycles were sufficient to overcome local friction effects, which then allowed the cable to take up a state of uniform stress.

Parafil offered a number of advantages over alternative materials. No corrosion protection was required, and the lightness of the material allowed a coil of rope, complete with end fittings, to be manhandled by a steeple-jack. The coil could be hung from the stainless steel hangers, while the working cage was moved to a new position, without overstressing the hanger fixings.

## Use as soil reinforcement

Applications in which soil is reinforced by embedding a variety of materials range from ground anchors and ties, which are usually steel bars, through reinforced earth retaining walls, which use steel strips, to grids of plastic to stabilise embankments.

*Paraweb(*)*, which is essentially a flat form of Parafil, has been widely used for soil reinforcement[7]. A continuous roll of the flat strip is looped alternately round a bar at the back of the block of soil and through toggle bars on the back of the facing panels. *Figure 13* shows a detail of a wall built by this method in Jersey. Type A Paraweb is normally used for this purpose, since the lower modulus of the polyester core is quite acceptable in these applications.

For ground anchor and tie bar applications, the requirement is to

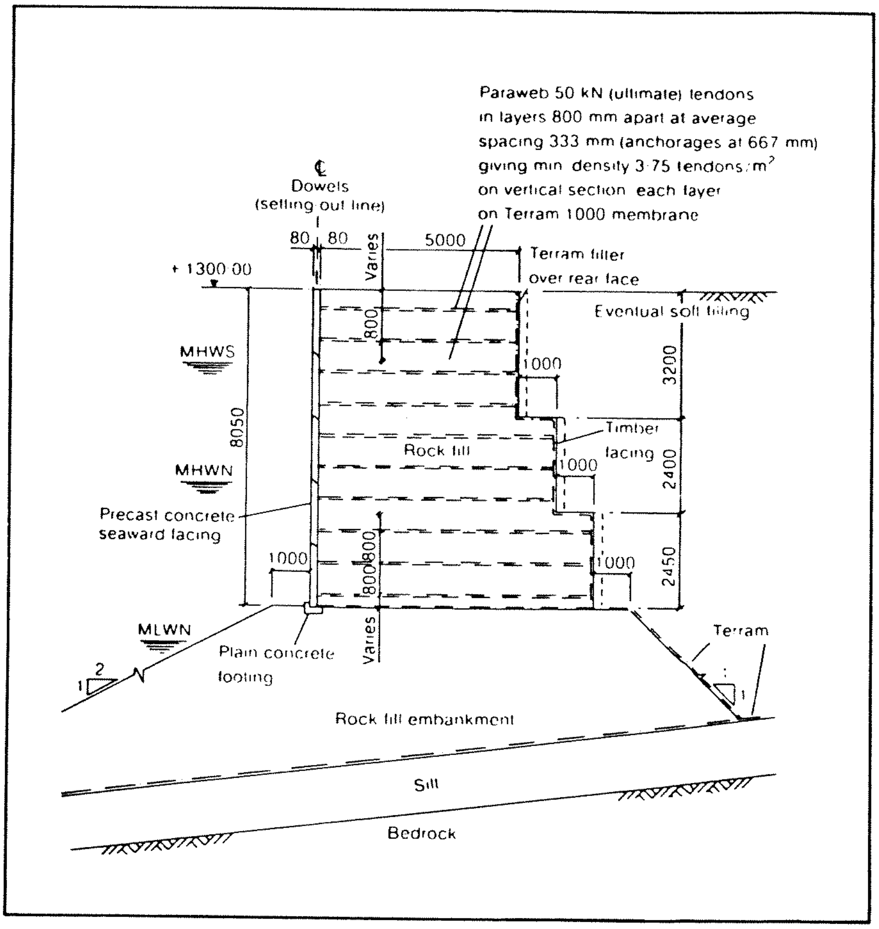

Fig 13 *Type A Paraweb used for soil reinforcement*

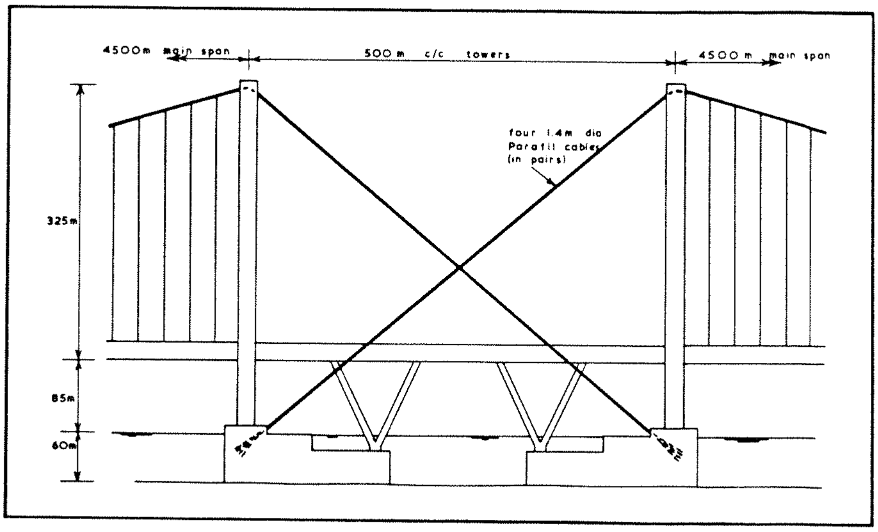

Fig 14 *Pier arrangement for the proposed Eurobridge*

carry a concentrated force between two points without significant deflection, so higher modulus versions of Parafil are more suitable. Because it is impossible to inspect the ties after installation, and because groundwater is normally present, the steel bars are normally much larger than required by stress considerations to allow some steel corrosion before the structure is weakened. Typically, the bar will be twice the diameter actually required, which means an overprovision of strength initially by a factor of 4. There would be no need to provide this waste material with a Parafil tie.

## Use for suspension bridges

Examples considered so far have made use of the resistance to corrosion of Parafil, but we now come to two applications which make use of the light weight of Parafil.

For long spans, the suspension bridge remains supreme, with Humber Bridge holding the record with 1,410 m main span. Even larger bridges have been suggested, with designs for a structure with a 3 km main span for the Straits of Messina between Italy and Sicily well advanced. This probably represents the longest span that can be built using steel cables(3), since the weight of the cables themselves becomes significant. Above this size, the proportion of the cable's strength utilised in carrying its own weight becomes so large that there is insufficient strength remaining to carry any live load.

Parafil ropes are about one sixth of the weight of a steel cable of the same strength, so there is an equivalent reduction in the stresses in the cable due to the dead weight of the cables, and the upper limit on the span of the bridge is raised.

One of the recent proposals for the crossing of the English Channel between Dover and Calais made use of this idea. The Eurobridge consortium proposed a design consisting of seven 4.5 km spans, with towers built on caissons floated into position to form artificial islands (*Figure 14*). The structure would have carried 12 lanes of road traffic, and would have been suspended from four Parafil cables each of 1.4 m diameter. The hangers would also have been of Parafil and various other lightweight materials were proposed for the deck of the bridge.

That the proposal was not accepted is unsurprising. It would have taken an engineer of vision to recommend such a novel solution and a bold politician to approve it. Nevertheless, the idea should not be regarded as dead. To make financial sense, the crossing has to have a high capacity for road traffic. That is difficult to provide in a rail tunnel carrying shuttle trains, as is now proposed, and the ventilation problems in a road tunnel are virtually insurmountable(9). Thus a road bridge is required, but minimising the risk to shipping means reducing the number of piers to a number that can be adequately protected against collision, so the span must be as high as possible.

Sufficient information on Parafil is

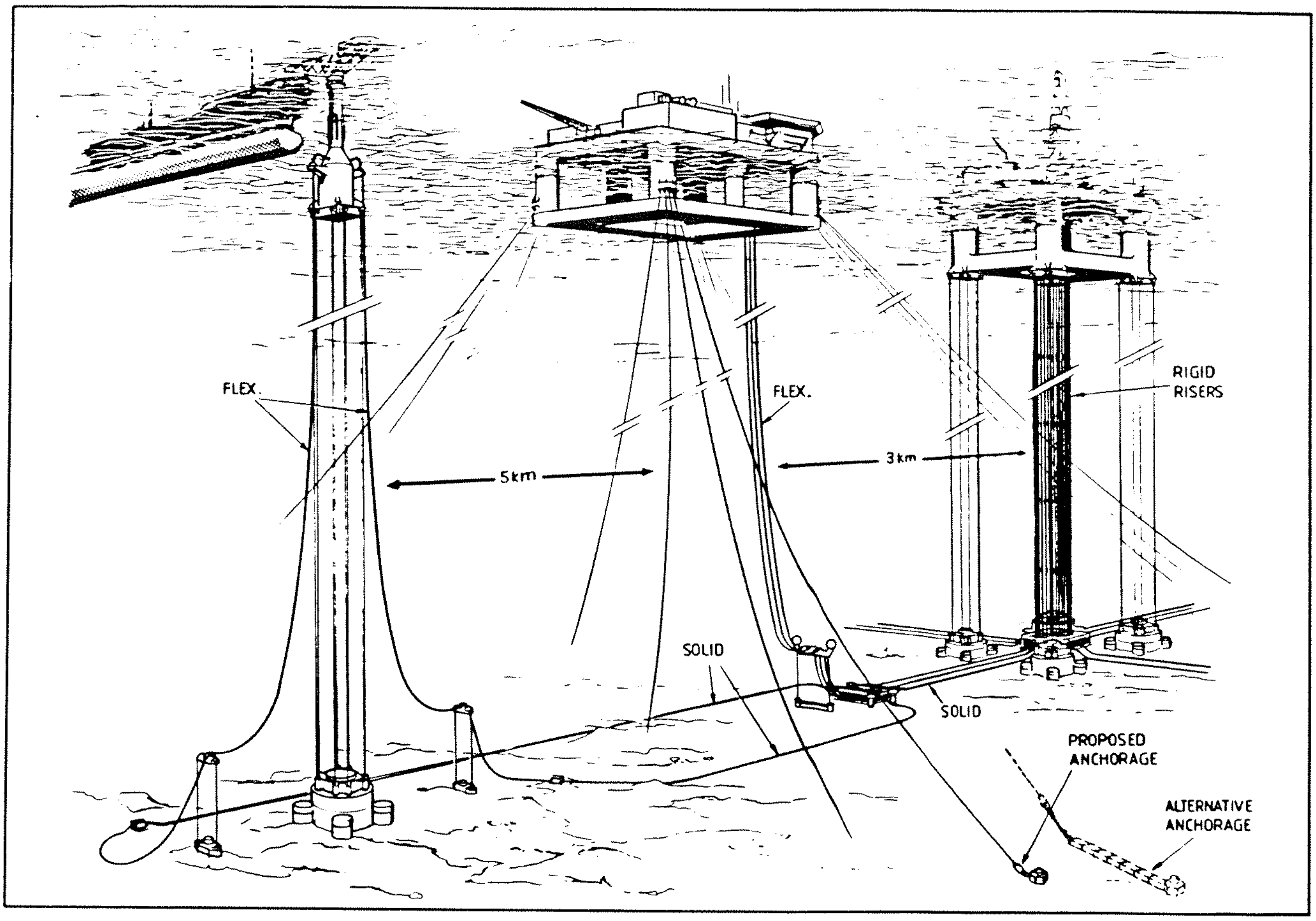

*Fig 15 Typical configuration for lightweight Parafil mooring systems*

becoming available to realise that a scheme similar to that proposed is certainly technically feasible.

### Mooring offshore structures

As the search for oil moves into areas of deeper water, it becomes less viable to produce structures for exploration and production in which the working area above water is rigidly connected to the seabed. There is an increasing tendency to have a floating structure on the surface moored above a seabed facility.

A variety of mooring systems can be employed:

1) The Tensioned Leg Platform installed for Conoco in the Hutton field, relies on tension piles in the seabed and the lateral component of the tension force in the tethers to prevent any sideways movement of the platform
2) Catenary systems use more or less conventional anchors some distance away from the rig and longer mooring ropes. These are arranged in a pattern around the rig so that horizontal movements are resisted by changes in the tension in at least one of the mooring lines.

   These systems can use clump weights or buoyancy devices to improve their dynamic characteristics.

The Hutton TLP, although a major production facility in its own right, is primarily a 'shallow' water (300 m) prototype for structures designed to exploit areas off the continental shelf (where water depths up to 3,000 m may be encountered).

As the water depth rises, the weight of the tethers becomes a primary concern since they represent a loss in buoyancy to the floating structure. Oil companies have therefore been looking at the possibilities of lightweight mooring systems. Salama(11) concluded that Parafil was a prime candidate for study and a major investigation is now underway into the possibilities of using it in a variety of mooring configurations. This study, organised by Advanced Production Technology Ltd, and sponsored by ICI, the EEC and a number of oil industry companies will be reporting soon on the details of its findings, including the fatigue tests at Imperial College described earlier. *Figure 15* shows some typical configurations for Parafil mooring systems that are being considered.

### Non-magnetic applications

There are a few structures where magnetic and electrical properties are important. These include radio antennae, where guy ropes must be insulators, and supports for electrical conductors, which must be similarly insulating. Some structures must be built with a minimum of magnetic materials to eliminate interference with communications signals. The electrical properties of Parafil make it ideal for these applications.

### Conclusions

Structural engineers now have a new material which can be used to carry tensile forces. It has light weight, high strength, high stiffness and does not corrode. It is used in, or being considered for, projects which are extending the range of application of conventional techniques.

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## Trade Names

(*) *Parafil and Paraweb are trade names of Imperial Chemical Industries.*

(+) *Kevlar, Kevlar 29 and Kevlar 49 are trade names of Du Pont.*

(**) *Twaron is a trade name of Enka.*

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