5 Parafil ropes for prestressing tendons

C.J. BURGOYNE

5.1 Introduction

Parafil ropes have several features which distinguish them from most other prestressing systems; they cannot be bonded to concrete; they contain no resin, and they were not initially developed for prestressing. Nevertheless, they have been used for prestressing concrete on a number of occasions, and have recently been adopted by one of the largest manufacturers of prestressing systems (VSL) as an alternative to steel tendons when corrosion is likely to be a problem.

Unbonded tendons are already widely used in floor slabs in buildings, but have not been widely used in bridge construction in the past. This has been due to worries about corrosion of the steel. However, the UK Department of Transport has recently imposed a moratorium on the use of grouted tendons in bridges, because of concern that grouting is rarely fully effective, leading to potential for steel corrosion in the voids. They propose that tendons should be unbonded, which although it makes the steel more susceptible to corrosion, allows them to be removed and replaced. Parafil, however, offers the same inspectability and replaceability, but in an inherently non-corroding material. There are also technical reasons why materials that do not yield should be unbonded; these are discussed later.

5.2 Description

Parafil ropes are manufactured by Linear Composites Ltd in Yorkshire, England. They contain a core of parallel filaments of a high strength yarn within a polymeric sheath. A variety of core yarns are used, the most common being polyester (known as Type A), Kevlar 29 (Type F) and Kevlar 49 (Type G). Kevlar was the first of the aramid fibres to be developed, by EI DuPont de Nemours, in 1973. The basic properties of ropes manufactured with these yarns are shown in Table 5.1. Those of primary interest to prestressing engineers are the Type G ropes, which have the highest stiffness and lowest creep properties, although the lower modulus versions could be used in applications where the prestressed structure itself tended to creep under the influence of the prestress. In this case, the lower modulus of the fibres would require larger jack extensions at the time of prestressing, but would mean less loss of prestress due to creep.

Table 5.1 Tensile properties of Parafil ropes (data from Linear Composites Ltd)

Designation	Material	Strength (N/mm^2)	Stiffness (kN/mm^2)
Parafil Type A	Polyester	617	12.0
Parafil Type F	Kevlar 29	1926	77.7
Parafil Type G	Kevlar 49	1926	126.5

Other fibres could also be used, including the alternative aramid fibres such as Technora (made by Teijin), or possibly Vectran (made by Hoechst). Both claim to have certain properties better than Kevlar, and there is no reason why they could not be used in these ropes.

5.3 Termination system

The most important component of any system carrying tension is the anchorage, where the forces are transmitted to the rope. In Parafil, the ropes are anchored by means of a barrel and spike fitting, which grips the fibres in an annulus between a central tapered spike and an external matching barrel (Figure 5.1).

To attach the termination, the end of the rope is passed through the terminal body, and the sheath is removed over the length of the spike; the yarns are then spread out evenly around the terminal body before the spike is introduced. The rope is drawn back into the terminal and the rope pretensioned to a load in excess of that to be applied in practice. During pretensioning, the spike is drawn fully into the termination, applying an outward force on the fibre pad and gripping the yarns. Subsequent changes in force cause only tiny movements in the spike and can be ignored for practical purposes. For prestressing operations, where the largest load applied to the rope is the act of prestressing, the pretensioning of the rope can take place at the same time as the prestress. Allowance then has to be made for the bed-down of the spike to ensure that the rope is the correct length, but this is easily done.

This system has a number of advantages over wedge systems which grip the outside of a tension member.

1. The gripping force between the spike and the barrel has to pass through every fibre (Figure 5.2), which means that each fibre can develop an equal friction force against its neighbours or the fitting. Thus, there is no tendency for some of the fibres to carry a dis-

Figure 5.1 Barrel and spike termination for Parafil.

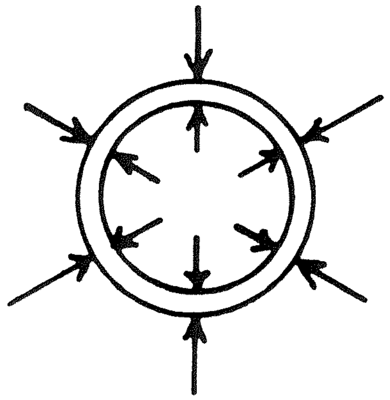

Figure 5.2 Gripping forces within termination.

proportionate amount of the load, which would cause early failure of those fibres, and hence the rope. Systems which rely on external wedges have a tendency to develop hoop compression around the outside of the tension member, leaving the inner fibres less well gripped.

2. There is no resin in the system, which means that the effectiveness of the termination is not affected by temperature or creep.
3. The system is easy to fit, on site if necessary, simply by removing the sheath and splaying out the fibres. If possible, a pretension in excess of that expected in the service life of the ropes should be applied.
4. There are no size effects; terminations for large ropes are linearly scaled versions of the terminations for small ropes. The mechanics of operation remain the same.
5. The terminations can develop the full strength of the parent rope; when used for tension tests, the rope breaks away from the termination.

There appears to be no degradation of termination efficiency, or of creep within the termination, with time.

5.4 Development of ropes

The ropes were first developed in the early 1960s to meet a requirement for mooring navigation platforms in the North Atlantic. These would have required mooring lines several kilometres long and the weight of steel ropes would have been prohibitive. At the same time, accuracy of position of these platforms meant that the lines had to be stiff and to have good axial fatigue performance. Conventional structured ropes, where the individual fibres follow tortuous paths along the rope, could not be used since they lose a significant proportion of the fibre's inherent stiffness. The large number of points where fibres cross also causes a loss of fatigue strength.

Linear Composites Ltd (then part of Imperial Chemical Industries) developed the idea of keeping the fibres straight and giving the rope some structure (normally provided by braiding or twisting) by enclosing the fibres in an extruded sheath. The fibres used at that time were polyester, the aramids not yet being available.

In the event, the requirement for aircraft navigation systems was met by satellites, so the North Atlantic platforms were never needed, but methods of producing the ropes and their properties were well established, and this led to their adoption in a variety of applications. The earliest of these were as guys for radio antennae where the non-conducting nature of the ropes did away with the need for conventional insulators. The first installations used polyester ropes, but since the development of aramid fibres, and with the communications industry using arrays of masts which have to be placed accurately in relation to one another, the stiffer aramid ropes are now being used more extensively.

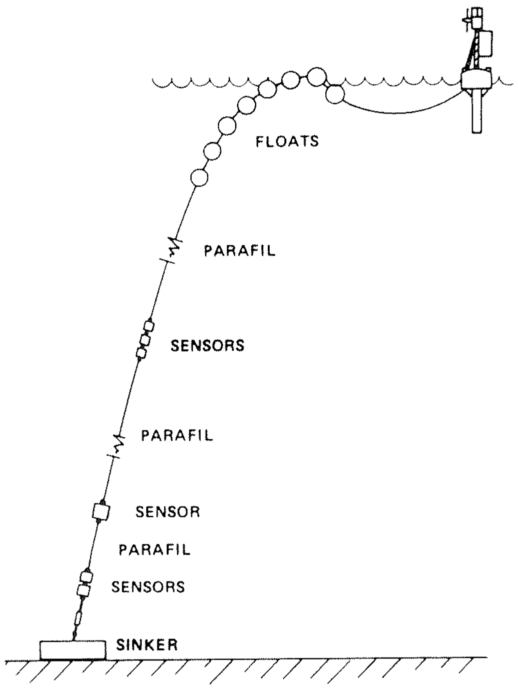

Figure 5.3 Typical mooring application, in 6000 m water depth, showing Parafil combined with floats and other equipment.

Moorings for floating systems, such as buoys, are used extensively (Figure 5.3). These often have floats, weights, and other equipment attached at the top and bottom, with the bulk of the length of the mooring being provided by Parafil.

Other early uses of Parafil as replacements for steel wire followed. Such uses have included standing rigging in ships, where the smooth sheath has been found to provide the added advantage that ice can easily be shaken free, supports for overhead wires in trolley-bus systems (again making use of the electrical insulation), and in safety rails around the deck of ships. Many of these systems are in use by military authorities around the world.

In the 1970s, Kevlar, the first of the aramid fibres, became available. Experiments showed that the techniques used for making ropes from polyester could easily be adopted for aramids, resulting in a stronger and stiffer rope. The strength of the rope is about 20% higher than a normal prestressing steel, while the stiffness is about two-thirds that of steel. These properties make the ropes very attractive as structural elements in their own right, and a programme of research was undertaken to give practising engineers confidence in both the short- and long-term properties of the ropes.

Prestressing tendons for concrete were soon identified as a very suitable application. These tendons are the most heavily stressed elements in normal use; no other structural component is regularly loaded to a permanent force of 70% of its break load. For this use, there are clear advantages in using the stiffer Type G Parafil, incorporating Kevlar 49, and in all that follows, it is this type of Parafil that is being considered, unless otherwise stated.

5.5 Testing

Much of the early testing on Kevlar concentrated on the short-term properties of the fibre, but for structural engineering applications, the long-term properties are just as important. A lot of testing has thus been done on the ropes rather than the fibres, to establish their properties.

5.5.1 *Strength and size effects*

The stress–strain curve of the ropes (Figure 5.4) matches quite closely that of the constituent fibres. The Young's modulus is about 120 kN/mm^2 and the strength is about 1930 N/mm^2. There is a slight stiffening at about 1000 N/mm^2; that is a property of the fibre and is not significant in most cases. Once the rope has been fitted with terminals and these have been bedded down properly in accordance with the manufacturer's instructions, the ropes have their full stiffness from zero load.

When a number of fibres are used together, it is not possible to use the full strength of all the fibres, or even to achieve the average strength of the fibres. This is because the weaker fibres fail at a lower load than the stronger ones, leaving the total load-carrying capacity reduced. This process has to be applied twice in Parafil ropes; they are made as a bundle of parallel yarns, which are in turn made from about 1000 individual filaments. The filaments themselves have strengths of about 3500 N/mm^2; the yarns have a strength of about 2900 N/mm^2, and the ropes have a minimum strength of about 1930 N/mm^2.

These effects are described by bundle theory, which accounts for these size effects. It is also possible to account for length effects in a similar way, by using weakest link theory. Both theories rely on the variability of strength of yarns and fibres and predict that the strength will reach an asymptotic value as the rope size gets bigger, and also as it gets longer. Figure 5.5 shows the variation in strength with rope size as measured in Type G Parafil ropes. Other tests have been carried out on much larger ropes (up to 1500 tonnes break load) and these lie very close to the

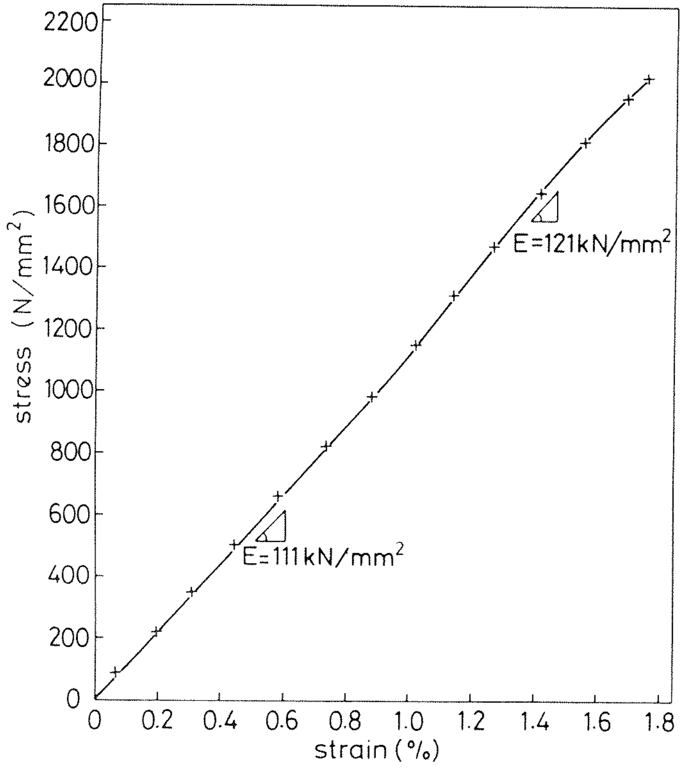

Figure 5.4 Typical stress–strain curve from tests on 60 tonne Type G Parafil ropes.

asymptotic value. Thus, for all practical rope sizes and lengths used in prestressing, the strength of the ropes can be taken as 1930 N/mm^2, measured over the cross-sectional area of the yarns.

5.5.2 *Creep, relaxation and loss of prestress*

Aramid fibres offer significantly lower creep than most other fibres used in rope making; indeed, for many rope applications, the creep is negligible. However, when used for prestressing concrete, engineers are interested in the creep as a proportion of the initial extension, since this governs the amount of prestressing force lost.

Total creep strains are of the order of 0.13%, which can be compared with a rope extension (when stressed to about 50% of its initial break load), of about 0.8%. Thus, we can expect to lose something like 16% of the initial prestress force in a Parafil tendon.

Figure 5.6 shows predicted stress relaxation figures for different ages

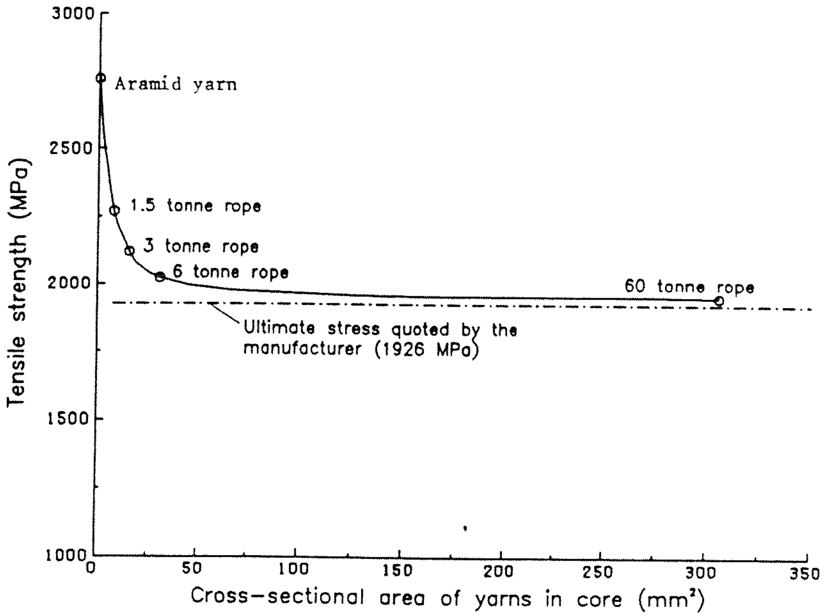

Figure 5.5 Measured strengths of ropes of different sizes, showing asymptotic strength for large ropes.

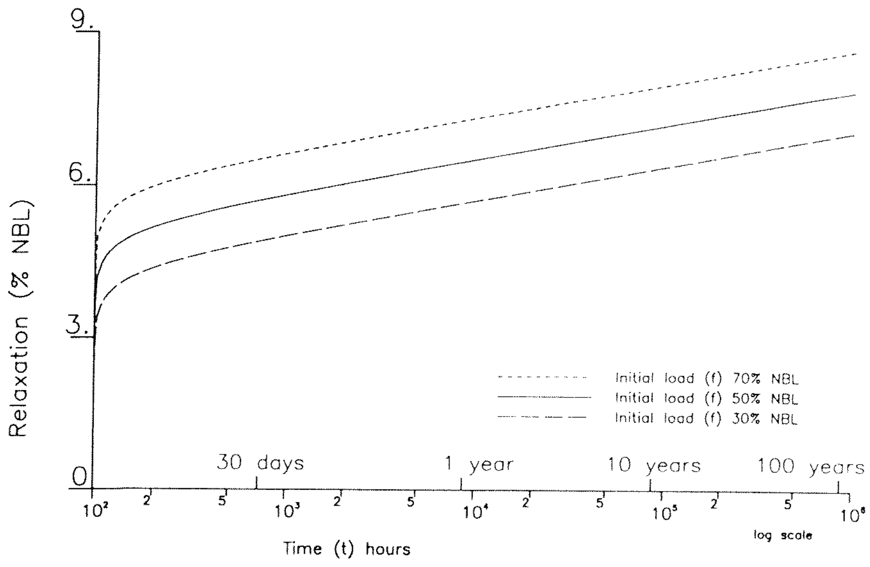

Figure 5.6 Stress relaxation predictions for Type G Parafil, from different levels of initial prestress, expressed as a percentage of the nominal break load (NBL) (Chambers data).

and for different initial stresses (expressed as percentages of the nominal break load, NBL), based on a series of rope tests. It can be seen that they agree quite closely with the limiting value given above.

The total loss of prestress force in a member prestressed with Parafil is very similar to that in a beam prestressed with steel. The losses due to the relaxation of the tendon are higher, as explained above, but this is compensated by reduced losses due to the shortening of the concrete. Kevlar yarns have a lower elastic modulus than steel (approx. 2/3), so that the loss of force in the tendon caused by a reduction in length of the concrete is about two-thirds of that in steel tendons. This will be true for losses caused by elastic shortening of the concrete and also for losses due to creep of the concrete. Friction losses are of a similar order to those with steel tendons but, especially when using external tendons, where friction losses occur at discrete points where the tendon is deflected, it is probably worth wrapping the tendon in PTFE or using a lubricant to reduce the friction further.

As with all loss calculations, the total losses depend on details of the design, which will differ for structures designed with steel or Parafil tendons, but for most cases the various effects cancel one another fairly closely.

5.5.3 *Stress rupture*

Stress rupture, or creep rupture as it is sometimes known, is the name associated with failure caused by a material creeping until it breaks. This is not normally a problem in steels, except at high stresses or high temperatures, but it is likely to be a governing criterion for the long-term use of most systems that rely on new materials.

Stress rupture is clearly related to creep and relaxation. At higher stresses, materials creep more and fail in a shorter period of time than at low stresses. There are strong theoretical arguments, related to the activation energy of the creep process, why there should be a linear relationship between the applied stress and the logarithm of the lifetime of the material. This is indeed observed in tests on both Parafil ropes and on Kevlar yarns. Figure 5.7 shows values of lifetimes as measured in tests on Parafil ropes and compares them with theoretical predictions based on tests performed on Kevlar 49 and epoxy bars. The results have been normalised with respect to the short-term strength, because of the bundle theory effects described above.

Statistical analyses have been carried out on these data and it is predicated that a rope loaded to 50% of its short-term strength will have a 1.4% chance of failing if the load is maintained continuously for a period of 100 years. This prediction is based on extrapolation of tests carried out at ambient temperature for periods of about 4 years, and from consideration of tests carried out for shorter periods at elevated temperatures (which can be related to those at ambient temperature via the activation energy). At the moment, tests are underway with ropes loaded by dead weights to produce failures in ropes after periods in the 5–10 year range. These will give engineers more confidence in the extrapolation up to structural lifetimes.

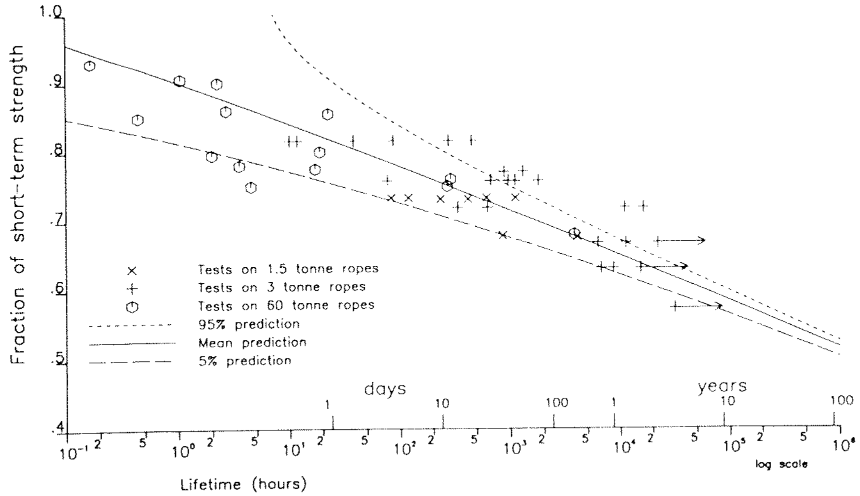

Figure 5.7 Stress rupture test results and predicted lifetimes, based on tests by Guimaraes and Chambers.

Work is currently underway identifying the cumulative damage rule that must be applied if a rope is subject to varying loads. The most likely rule appears to be one where the rope sustains stress rupture damage as a linear proportion of the lifetime that it spends at each load. This allows the stress rupture lifetime to be calculated where the load is reducing as the prestress force drops off because of concrete creep and tendon relaxation.

One point needs to be made about these results. The stress rupture lifetime relates to loads applied continuously; it does not mean that the short-term strength is reduced by the same extent. The strength retention observed in a rope that has been subjected to a load for half of its stress rupture lifetime would be virtually unchanged from the short-term strength. This has important implications for prestressing concrete. The initial prestressing force can be chosen on the basis of the long-term stress rupture of the tendon, taking due account of the relatively short period of time the rope spends at a higher force before creep and relaxation have occurred. But the force in the tendon then changes very little due to live load effects, other than very occasional excursions when the structure is

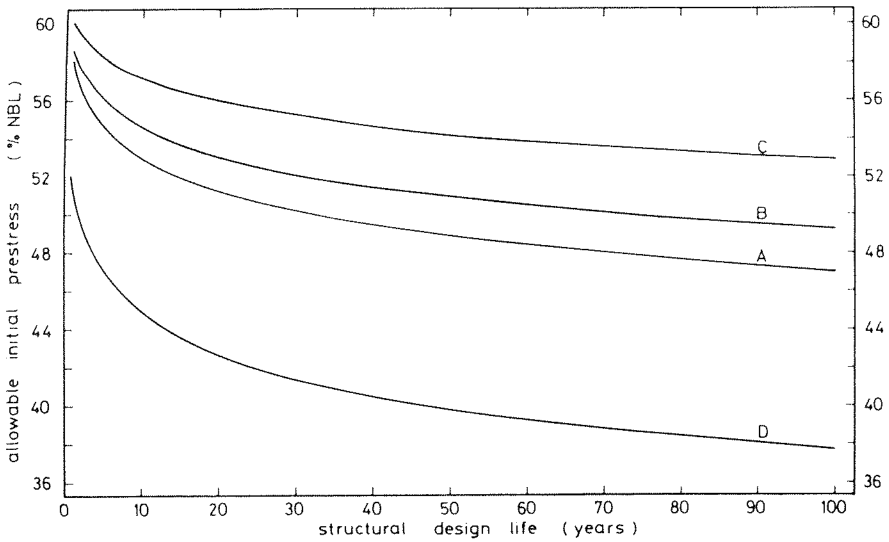

Figure 5.8 Suggested initial prestress, based on assumed losses of force due to stress relaxation and creep of concrete, to give a 10^{-6} probability of failure due to stress rupture (based on Chambers test results). For definition of curves A–D see text.

overloaded. On these occasions, the tendon will still have virtually its full strength.

These ideas can all be combined. Figure 5.8 shows allowable initial prestressing forces in a beam to give a 10^{-6} chance of failure due to stress rupture for a given design life. Curve D shows the maximum allowable force for a constant load, but curves A, B and C show the situation for minimum, typical and maximum prestress losses, respectively. For the case of typical losses, an initial prestressing force that is about 10% higher can be allowed, since the force will subsequently reduce, thus reducing the stress rupture damage that is taking place.

5.5.4 *Durability*

The tendons can be expected to have high durability in normal environments. Kevlar is degraded by ultraviolet light, but this is shielded by the sheath and is not a problem. Kevlar fibres also suffer hydrolytic attack by strong acids and alkalis, but the tendons would not be bonded to the concrete, so the fibres will not come into contact with the alkaline concrete. In any event, the sheath will act as a barrier to ingress of chemicals. DuPont have reported that Kevlar is not degraded by either fresh or salt water at normal pH levels.

There are potential concerns about fire and vandalism with these materials. Kevlar does not burn; it has very similar fire resistance properties to Nomex, which is chemically very similar and is widely used for protective clothing by firemen and racing drivers. It decomposes at a temperature of about 450°C, and loses about half of its strength at about 250°C. It has very low thermal conductivity, so in large ropes, the central core of fibres will not lose strength as quickly as the outer fibres. Nevertheless, it is likely that some attention should be paid to protecting Parafil from fire, especially when used as external tendons.

There is also the potential problem of mechanical damage, especially due to vandalism. Prestressing tendons are not normally accessible to the general public, but in cases where they can be reached, consideration should be given to putting the tendon inside a casing of some sort.

5.5.5 *Fatigue*

The fatigue characteristics of aramid fibres are very good. The resistance of Kevlar to tension-tension fatigue is better than that of steel, and is probably due to cumulative damage due to stress rupture, rather than simply the number of cycles. When 'fatigue' failures of Kevlar do occur, they are normally due to fretting of fibres over one another. This can only occur at the terminations, or at loading points, and the variation in force in prestressing tendons, especially when unbonded, is extremely low. Thus, it is not believed that fatigue is a problem in prestressing applications.

5.6 Structural applications other than prestressing

Because the ropes can be made in almost any size and with efficient terminals at the ends, it is possible to use them in a variety of ways. Several novel applications have been made, where the various properties of Parafil have contributed significantly to the success of the scheme.

5.6.1 *Bicentennial tent*

During the Australian Bicentennial celebrations in 1988, a touring exhibition was mounted, which consisted of a series of tented exhibition stands mounted on trucks (Figure 5.9). These were moved around the country and erected many times at different locations. Parafil ropes were used as the main supporting cables for the tents, and also as the tensioning elements around the edges of the tents. They were lighter than the equivalent steel cables and stood up well to the rigours of repeated assembly and disassembly.

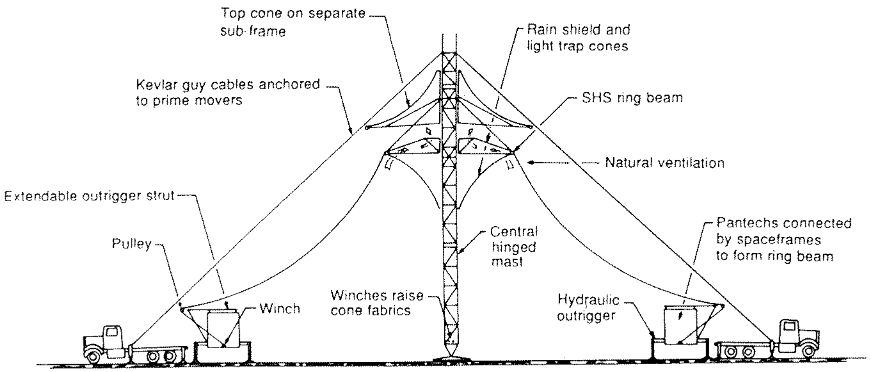

Figure 5.9 Tent for Australian bicentennial touring exhibition.

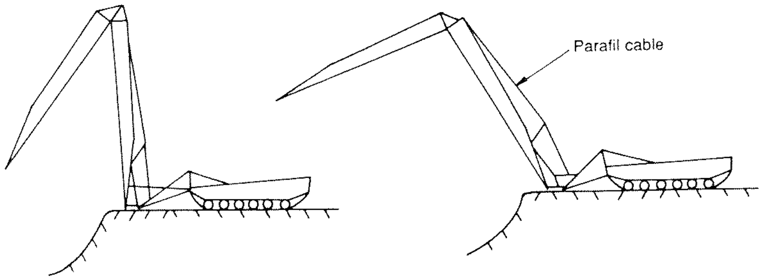

Figure 5.10 Scissoring action of tank-launched bridge, controlled by Type G Parafil (Defence Research Agency).

5.6.2 *Tank bridge*

The British Army uses an armoured deployable bridge system mounted on a tank chassis. This uses a rope to deploy the bridge in a scissoring action (Figure 5.10); the available lever arm is small, so the forces that have to be carried are high. The rope must be stiff as well as strong, as it controls the accuracy with which the bridge can be placed. Conventional steel rope is very heavy and is awkward to both carry and stow. To overcome these problems, the Defence Research Agency carried out tests using Parafil ropes. They are much easier to handle and are just as effective in operating the bridge; future versions of the bridge are likely to incorporate Parafil scissoring ropes.

5.6.3 *Bus station roof, Cambridge*

A small bus station was completed in Cambridge in 1991; this has a roof supported by Parafil ropes with a 7 m cantilever (Figure 5.11). There are four masts, each supporting a pair of forestays and a pair of backstays. Although designed primarily to resist snow loading, the stays are permanently stressed to ensure that the roof remains stiff even when wind loads cause uplift. The structure was designed by Cambridgeshire County Council and the ropes were fitted with terminals and preloaded in the Engineering Laboratories at the University of Cambridge.

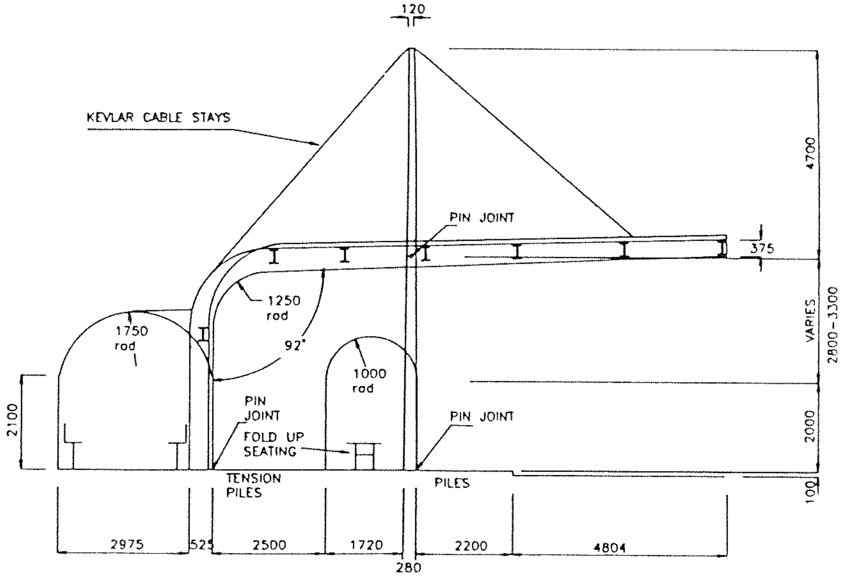

Figure 5.11 Cable-stayed roof on bus station at Cambridge (Cambridgeshire County Council).

5.6.4 *Aberfeldy bridge, Scotland*

The western world's first all-plastic bridge has just been completed at Aberfeldy in Scotland. It combines a deck and towers made from lightweight glass-reinforced plastic pultrusions (developed by Maunsell Structural Plastics Ltd and manufactured by GEC Reinforced Plastics) with stay cables made from Parafil. The bridge carries a footpath linking two halves of a golf course across the River Tay, with a clear span of 64 m (Figure 5.12). The only non-plastic components are concrete in the foundation and some connecting pieces between the deck and the cable terminations to distribute the concentrated load.

The bridge was built by students from Dundee University; the pultrusions were assembled on scaffolding on shore and then launched across the river, supported on a cats-cradle of cables made up from the per-

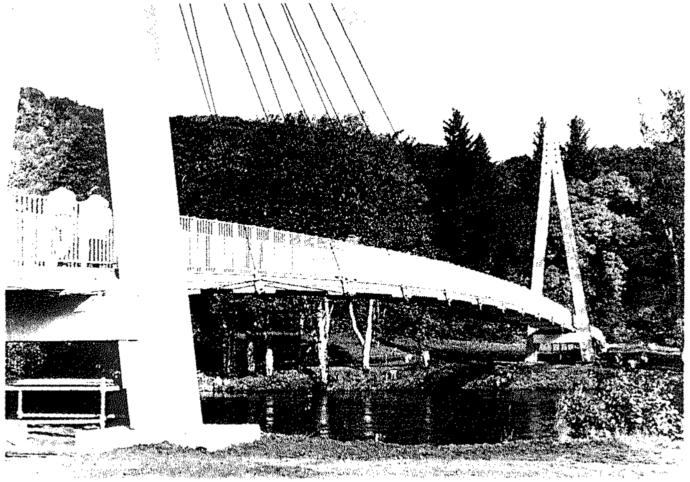

Figure 5.12 Aberfeldy bridge, Scotland. The deck and towers are glass-reinforced plastic; the cables are Type G Parafil ropes (reproduced by kind permission of Maunsell Structural Plastics).

manent Parafil stay cables and some temporary cables. The lightness of all the components meant that no cranes were needed during the erection.

5.7 Prestressing applications

5.7.1 Thorpe Marsh Power Station

Thorpe Marsh electricity generating station in the north of England was one of a series built in the 1960s to use coal mined locally. It has six large cooling towers, of which three were recently found to have large cracks at the top; this left them in a very unstable condition. Demolition would have kept the station out of service for a considerable period, but it was decided that the towers could be repaired by circumferential prestressing after injecting the cracks with resin; Parafil ropes were used for this application (Figure 5.13). The prime benefits were the resistance to corrosion and the light weight, which meant that the prestressing could be carried out by steeplejacks carrying coils of cable up the towers. They could work their way round the towers, installing the cables as they went, before stressing the cables one-by-one. The alternative, using steel cables, would have meant assembling a net at ground level, and lifting it up by means of cranes and then adjusting the lengths of all the elements; a much more complex operation. After several years in operation, the Parafil ropes are performing well.

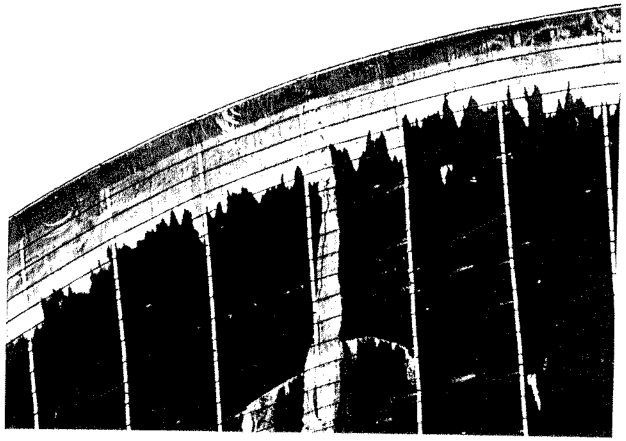

Figure 5.13 Cooling towers at Thorpe Marsh electricity generating station, Doncaster, circumferentially prestressed with Parafil ropes.

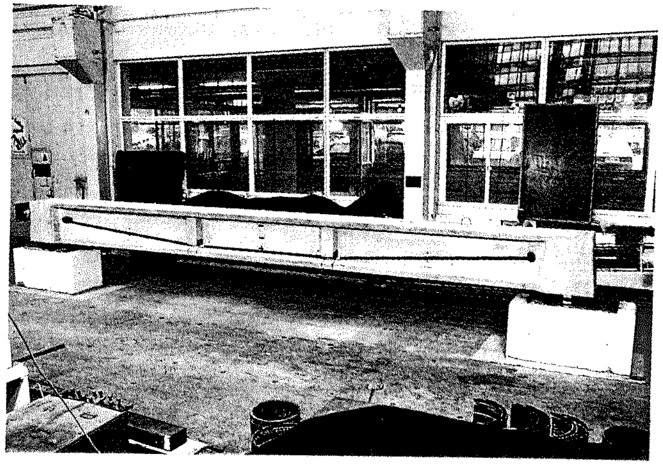

Figure 5.14 Beam (8 m long) prestressed externally with two 60 tonne Type G Parafil ropes.

5.7.2 Beam tests at Imperial College

Tests have been carried out on two beams prestressed with Parafil to demonstrate the feasibility of producing structural elements in this way. Two designs were produced; the first had a single, straight unbonded tendon, contained within a duct on the centreline of a simple I-beam, while the second had two external deflected tendons, one on each side of a T-shaped cross-section (Figure 5.14). In each case, the tendons were

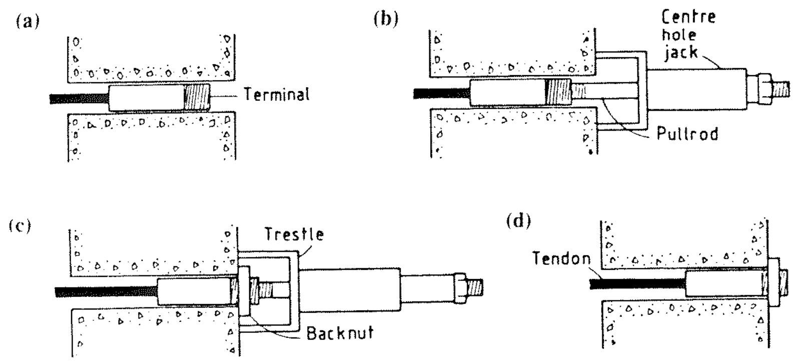

Figure 5.15 Stressing procedure for Parafil ropes: (a) tendon installation; (b) jack attachment; (c) prestressing force application; (d) final arrangement.

Type G Parafil with a nominal break load of 60 tonnes, prestressed to about 50% of their short-term strength.

For an internal tendon, the terminals have to be fitted before the rope is placed in position in the beam; since the terminals are too large to pass through the duct, this is built up around the tendons. In the second beam, the tendons were to be placed outside the concrete, so there was no need to assemble the rope in a duct prior to casting. Holes were formed in the thickened end blocks to receive the rope terminations, by casting-in plastic pipes.

The principles of the stressing procedure are shown in Figure 5.15. The tendon is placed in the structure and a pull-rod fitted to the internal thread of the termination. The pull-rod is then passed through the centre hole of a hydraulic jack and secured by means of a nut. The jack is held away from the beam by means of a trestle, which allows access to the terminal to secure the back-nut. Force is applied by the jack, which brings the terminal just outside the face of the concrete; the back-nut can then be fitted to lock the tendon in position in its stressed state. The jack, trestle and pull-rod are removed, and a security cap fitted to prevent dirt and debris getting into the termination. This would also serve to contain the anchorage in the unlikely event of a rope failure.

Measurements of the forces in the second beam showed that the coefficient of friction was about 0.32, which is slightly higher than would be expected with steel tendons, but could be brought down by a better selection of sheath and deflector material. Measurement of the force in the tendons, after the force had been transferred from the jack to the permanent back-nut, indicated that no loss of prestress occurred at this stage.

5.7.3 *Load–deflection behaviour*

Both beams were tested in four point bending rigs, with loads applied by hydraulic jacks. The beams were taken through several elastic loading cycles; the second beam was kept under sustained load for 42 days to monitor the effects of creep and relaxation.

The relationship between the applied load and the deflection at the centre of the second beam is shown in Figure 5.16. On the application of the load, the response is almost linear, with the portions of the curves corresponding to loading and unloading being parallel. The instantaneous camber produced by the prestressing is indicated by the horizontal part of the curve at zero load. The increase of deflection due to the effects of shrinkage and creep of concrete after 42 days was 59% of the instantaneous deflection caused by the applied load. This figure is not affected by relaxation of the tendon, the increased deflection being due to loss of stiffness of the concrete.

The total loss of prestress in both tendons of the second beam, due to shrinkage and creep of concrete and due to stress relaxation in the tendons, is shown in Figure 5.17. The tendons were tensioned initially to approximately 22% of their tensile strength, when the age of concrete was 10 days. Losses of 13% and 14% of the initial force were observed in the two tendons after 23 days, when the full prestressing force was applied. Over this period of time, the beam was subjected only to its own

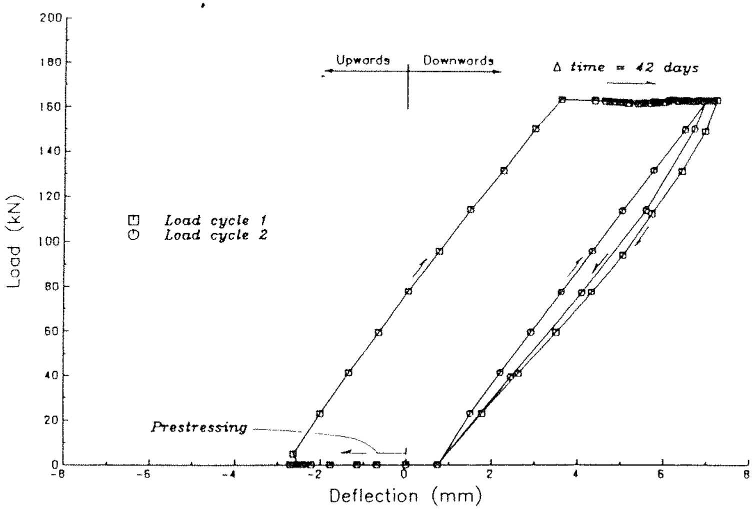

Figure 5.16 Applied load versus mid-span deflection for the second (8 m) beam, showing camber due to prestress, elastic response due to load and extra deflection due to creep of concrete.

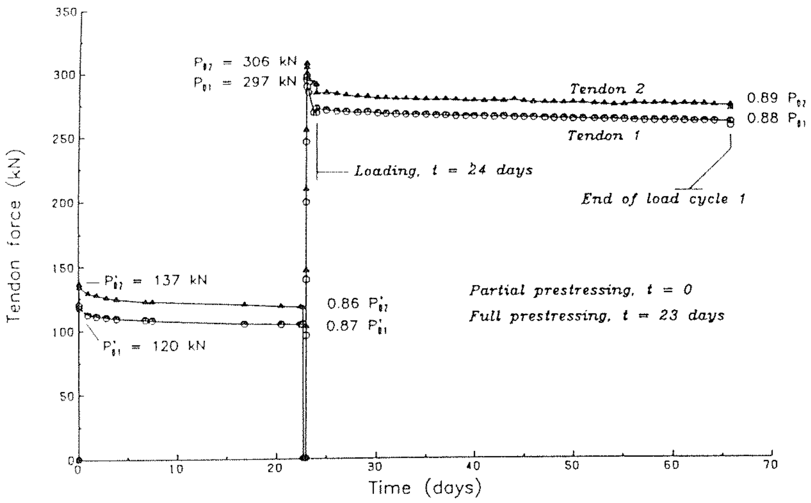

Figure 5.17 Variation of prestressing force with time in an 8-m beam.

weight. Forty-three days after the application of the full prestressing, the losses of prestress under service load were 12% in tendon 1 and 11% in tendon 2. It can be seen in the figure that most of the losses occurred within the first day after prestressing. From then on the curves show a very low rate of loss. These figures are very similar to losses to be expected in steel tendons, in accordance with the comments made earlier.

Ultimate load tests were carried out on both beams, which responded as expected. After passing the cracking load, the stiffness reduced considerably; when unloaded from the cracked (but still elastic) state, the stiffness remained lower until the cracks had closed up but the full elastic stiffness was recovered and there was virtually no permanent set.

When loaded until failure, both beams showed considerable curvature at virtually constant load, with large cracks forming in the bottom of the beam. Failure occurred in both beams by crushing of the top flange. Figure 5.18 shows the load–deflection curves for the second beam; the results for the first are similar. Even though failure of the top flange concrete precipitated the final failure, there was a lot of warning of failure as the cracks opened up.

There were slight differences in the final failure mode of the two beams which cast important light on the behaviour of unbonded and external tendons. In both cases, the top flange failed by crushing, but in the first beam, as the tendon was constrained in the bottom flange, the beam did not completely collapse. The compression zone passed down through the web and into the top of the bottom flange, with a consequent reduction in

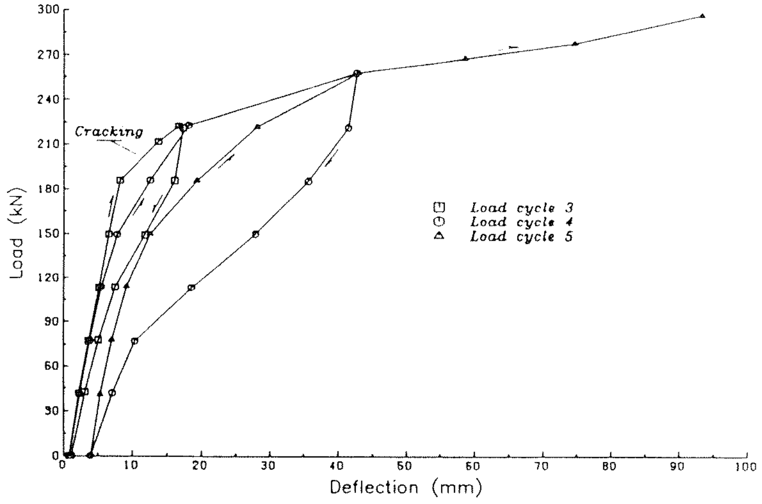

Figure 5.18 Load–deflection curve for an 8-m beam when loaded to failure. Note the plateau corresponding to crack opening.

load. However, the bottom flange did not fail, remaining axially prestressed. After the test, the tendon was found still to be carrying a significant force.

In the second beam, the tendon was outside the bottom flange, which could thus deflect while leaving the tendon in its original position relative to the ends of the beam. The beam thus failed suddenly and completely, with a total loss of prestress.

The results obtained in these tests were very similar to those that would have been expected with unbonded steel tendons. There would be slight differences due to the different Young's modulus of the Kevlar, but the overall behaviour of the beam and tendon together, as a composite system, is not affected by the different material. Ductility and rotation capacity of such beams should not be a problem, as the concrete can crack and slide relative to the tendon, without causing significant problems. The new design rules for unbonded tendons in bridges are awaited from the Department of Transport with interest; the principles (at least) should be applicable to Parafil as well as to steel tendons.

5.7.4 *Reasons for not bonding to concrete*

Aramids, like carbon fibres and glasses, exhibit brittle behaviour when tensile loads are applied to them, which means that they are very sensitive to applied strains which exceed the design values. This is in contrast to steel, where the plateau on the stress–strain curve means that the tendon

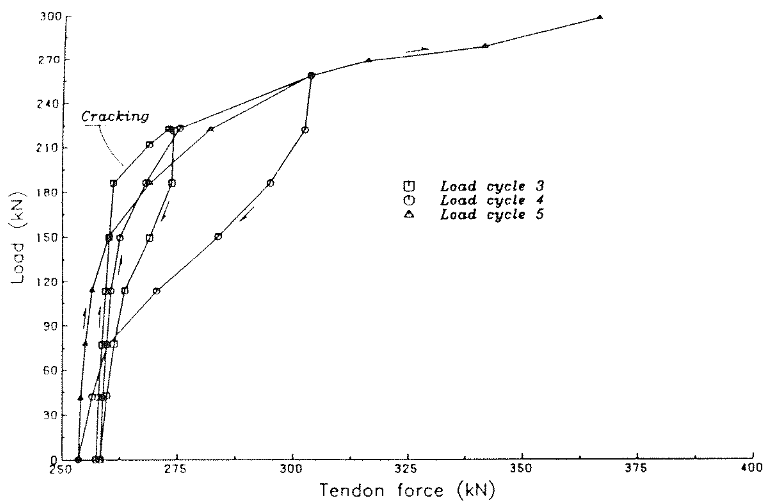

Figure 5.19 Change in tendon force in an 8-m beam when loaded to failure. Note the relatively small change in force as the tendon was unbonded.

can absorb high strains locally with no significant problems other than a permanent set.

We must therefore be very careful when deciding whether to bond these materials to concrete. In the vicinity of cracks, the local strains are very high; indeed, if we have perfect bond between steel and concrete, they are infinite. Thus we might expect that beams prestressed with any of these materials, if they are bonded to the concrete, will fail by local snapping of the tendon, with no possibility of redistribution of load, or of plastic deformation to accommodate the strain. There may be some redistribution of load due to bond failure, but this will not significantly alter the problem.

Thus, beams prestressed with new materials should be designed with unbonded tendons. This has some implications for design procedures, as there will be relatively little increase in tendon force as the beam is loaded.

This effect was observed in the beam tests; Figure 5.19 shows the tendon force during the ultimate load cycles on the second beam, from which it can be seen that fairly small changes in tendon force occurred, even though the concrete was significantly cracked, because the tendon could slide relative to the concrete. There is thus very little chance of snapping the tendon. The change in resistance to external bending moment is almost exclusively due to an increase of the lever arm between the internal compression and tension forces whose magnitudes remain relatively unchanged.

Table 5.2 Indicative sizes of Parafil ropes (data from VSL International)

Nominal break load (kN)	Rope diameter (mm)	Rope weight (kg/m)	Termination	
			Length (mm)	Diameter (mm)
1000	40	0.42	520	130
2000	55	0.72	650	180
3000	67	1.03	950	220

Parafil ropes, with their polyethylene sheath, cannot be bonded to concrete. Even if they are cast in place, there will be slip between the tendon and the sheath and creep of the sheath itself.

5.8 Link with VSL International

Parafil ropes have now moved from the development and prototype stage to fully fledged prestressing tendons with an agreement between Linear Composites Ltd and the VSL International group, who are one of the world's leading suppliers of prestressing systems. Engineers will now be able to design structures with Parafil prestressing, in the knowledge that jacking systems and specialist assistance will be available at the time of installation. The jacking system used will follow the principles described above with special fittings to allow the use of existing VSL jacks. Typical sizes of prestressing tendons are shown in Table 5.2. VSL have recently introduced polyethylene duct systems for conventional prestressing tendons; combining these with Parafil will completely remove the danger of corrosion of the prestressing system.

5.9 Predictions for future prestressing systems

It is expected that beams, both in bridges and buildings, will be prestressed with Parafil. The tendons will either lie outside the concrete, or unbonded in ducts within the concrete. No account will be taken of increased forces in the tendon due to live load.

The results of the Imperial College tests show that basic design principles for prestressed concrete do not need altering radically; the following are points which a designer should take into account when designing a beam with Parafil tendons:

1. The tendon should be pretensioned, with the terminals in place, to a load level in excess of that expected during both the initial

stressing operation and the service life of the structure. This will have the effect of ensuring that the terminal spike is properly bedded and will also give a check on the tendon length before being placed in the structure. It is normal practice, according to the manufacturer's instructions, to pretension ropes to 60% of the nominal breaking load prior to use, whenever possible. These ropes, when used in conventional rigging arrangements, are normally stressed to much lower load levels than those in use in prestressing tendons; in these cases, 60% is perfectly adequate as a pretensioning load. However, in prestressing tendons, where high force levels are normal, a higher pretensioning level may be needed to ensure adequate bedding of the termination.

2. Any deflector points should be properly flared to ensure no damage to the sheath during stressing operations; this should not be difficult to arrange if taken into account at the design stage.
3. The coefficient of friction between the tendon and the duct (or the deflector) should be reduced wherever possible. This may mean undertaking some studies of friction coefficients between various possible sheathing materials and alternative duct materials. Alternatively, coating materials, such as PTFE or nylon tapes, might be considered.
4. The working load design of prestressed concrete beams should be based on allowable stress limits taking account of the design prestressing force, after allowing for losses, and the ultimate strength of the section should be based on the assumption that only minimal increases of force take place due to geometry changes as the beam deflects.
5. The compression zone of the concrete should be provided with confining reinforcement to increase the ductility of the concrete in that area.
6. If the tendons are external to the concrete, they should pass through loose rings so that, in the event of failure, the tendons are forced to deflect with the beam. This will ensure that failure occurs in the more controlled manner of the first beam.

5.10 Conclusion

It is clear that Parafil will start to find more widespread use as a non-corroding prestressing tendon. Repair of structures by the use of external tendons is already taking place and will become more common; the use of unbonded, replaceable tendons is likely to become the norm for all structures in the near future. Structures, such as water towers, which often have poorly protected steel prestressing and a high incidence of corrosion, are currently being studied with a view to their repair with external Parafil tendons. A number of bridges with suspect prestressing tendons are also being identified by the current bridge assessment programmes; these would make useful demonstration sites for new materials as the new tendons would be adding an extra margin of safety, rather than providing the primary stressing.

Offshore, as exploration for oil and other minerals moves into ever deeper water, the arguments for using mooring lines with almost neutral buoyancy become more persuasive. Structures can be moored in 300 m of water using steel, but not in 3000 m. Virtually all the major oil companies have conducted studies into the use of lightweight mooring lines; when economics dictate that such structures be built, Parafil ropes, or similar systems, will undoubtedly be used.

Similarly, as bridge spans increase, the use of lightweight stiff materials becomes more economic. The excellent fatigue behaviour will also be seen to be important. The Eurobridge proposal to cross the English Channel with seven spans of 4.5 km was probably 20 years ahead of its time, and had some conceptual flaws. Nevertheless, such large spans are only going to be possible if new materials are used.

Other applications will make use of the non-magnetic nature of the material; applications such as de-Gaussing facilities for ships, or as strength elements in members carrying important communications (such as railway signalling and control equipment), can also be envisaged.

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