Structural applications of Type G Parafil

C. J. Burgoyne, PhD, MA, CEng, MICE

Imperial College

When considering the potential applications for a new material, it is tempting to find the existing material with the most comparable properties, and think of the new material as a direct replacement for it. On this basis, Type G Parafil, with a core of the high modulus aramid fibre Kevlar 49, looks a suitable candidate to replace cold drawn steel wire.

Such comparisons are at best simplistic, and usually do not make the most of the new material. It is often better to think of the new materials in their own right, and to consider which applications take most advantage of the improved properties.

In this paper a brief comparison will be made between the properties of Parafil and steel wire; we will then consider what applications will make the best use of the enhanced properties, and which applications are excluded for various reasons.

Properties similar to those of steel

The most obvious properties to consider in this context are strength and stiffness. With a short term strength of 1925 N/mm^2 (1), Type G Parafil has a strength which exceeds that of most cold drawn steel wire, at least in the diameters most commonly used in structural applications. Even when we allow for a reduction of that strength by 50% to eliminate the possibility of stress rupture during the lifetime of the structure, and apply an additional material factor of 1.5, we are still considering a material which can be used at permanent working stress levels in excess of 640 N/mm^2, with higher stresses allowable for occasional short term loadings.

The stiffness of Type G Parafil ropes at about 120 kN/mm^2, is also comparable with that of spiral steel strand (approx 160-195 kN/mm^2, depending on construction), and about 2/3 that of structural steel, where there are no reductions in stiffness due to the spiral lay of the strand.

In this context, we may also consider the creep and relaxation properties to be broadly similar to those of steel wire ropes. Although slightly larger, and not negligible, the creep of aramid based Parafil ropes is much lower than those made from other organic or glass fibres, and is much closer to that of metals.

Properties better than those of steel

In a number of respects, Type G Parafil has properties that are better than those of steel.

The resistance of aramid fibres to corrosion is very good. Only extremely strong alkalis are known to cause deleterious effects; the fibres are not affected by water, either fresh or sea, nor by aqueous chemicals present in groundwater, such as sulphates and chlorides.

The core fibres themselves are adversely affected by strong ultra-violet light, which is present in sunlight, but the thick sheath on the ropes themselves prevents such attack and need not concern us here.

Another benefit of the ropes is their low weight. With a specific gravity of the ropes at 0.98 (dry) or 1.09 (saturated), the ropes offer a significant weight saving over steel equivalents by a factor of seven in air. When in water, the ropes are virtually weightless, which is a significant benefit in offshore construction (2).

The electro-magnetic properties, although not often of significance to structural engineers, can be important in a few special applications. The ropes are both highly efficient insulators and non-magnetic.

The tension-tension fatigue properties of Parafil are excellent (3), and are primarily limited by fretting in the terminations, rather than axial fatigue in the fibres. Refinements to the termination design can be expected which are likely to further enhance the performance. As parallel-lay ropes, the bending fatigue response will not be as good as that of braided or twisted ropes (4), but we are not concerned here with applications where significant flexural loads are to be applied to the ropes themselves.

The production process, which in essence consists of extruding a thermoplastic sheath over the parallel core fibres, is relatively easy to scale up to deal with very large ropes. Schemes have been prepared for the production of large ropes on site; thus, only reels of the constituent yarns would need to be transported, and complete ropes could be prepared on site in one operation, rather than spinning or assembly as is required for very large steel ropes. The length of rope is not likely to cause a limitation, since fibre is produced in lengths measured in kilometres.

Properties less good than those of steel

The use of a material in a situation where it is not suitable, and consequently does not perform well, is likely to lead to it being ignored in other applications where it would be ideal. The use of cast iron for tension members in bridges was a classic example of this misuse, and led to the material being ignored for structural applications, even though it has some remarkably beneficial properties.

Thus, it is sensible to highlight those properties which may limit the use of the material, or which should be taken into account in design.

The fire resistance of Parafil is not as good as that of steel. The core yarn itself does not burn or melt, but decomposes at a temperature of about 450 deg C. The strength decreases with increasing temperature, and has about half of its ambient temperature strength at about 250 deg C (as compared to 550 deg C for steel). The sheath is a thermoplastic, and although fire retardants can be included in the formulation, the sheath will melt at temperatures in excess of about 150 deg C.

The resistance of the ropes to damage is not as high as that of steel, whether the damage is caused by accidental abrasion or vandalism. The sheath itself is relatively weak, and the strength of an individual filament to cutting or high lateral loads is not high. However, a non-structural abrasion resistant sleeve (such as a thin metal tube) would normally be sufficient to protect the rope in regions susceptible to damage.

The cost of the ropes must also be acknowledged as a disadvantage, although not necessarily an overwhelming one. On a 'cost per Tonne force' basis, Parafil is between 5 and 6 times as expensive as cold drawn steel wire; this will not be enough to outweigh the savings when advantage can be taken of the material's enhanced properties.

The final disadvantage lies not with the material, but with the potential users. Unfamiliarity with a material is, in itself, enough to dissuade some engineers from using it, and unwillingness to be innovative prevents others from being the first to adopt a new material.

Ideal applications for Parafil

We can now consider potential applications for Parafil, bearing in mind the properties discussed above.

The material will be useful where a tension member is required in situations in which it is difficult or expensive to protect steel from corrosion. It will also be useful where steel is excluded by virtue of its weight, or by its electro-magnetic properties.

With these factors in mind, we can look at specific examples. We shall not present here detailed calculations for each application, since these would need to be derived from assumptions about particular structures: rather, we shall concentrate on general principles.

Prestressed concrete

Prestressed concrete is an obvious use for a high strength, high stiffness material like Parafil. The prestressing tendon is very highly stressed, but the tension is virtually constant. This allows maximum use to be made of the strength of the tendon, since only a small allowance has to be made for variations in the force, and the maximum force is applied in a controlled and measurable way by a jack.

External prestressing

'Conventional' prestressing places the tendon inside the concrete, in order to provide maximum corrosion protection to the tendon. In prestressing terms, the use of external cables is quite acceptable, and leads to significant savings in weight, since the thicknesses of the webs, and to a certain extent the flanges, do not have to be artificially increased to provide cover to the tendon.

Various attempts have been made to prestress concrete externally, principally in France (5), but also elsewhere. Exe Viaduct (Figure 1), on the M5 in Devon, has such tendons outside the concrete, but inside the central box. Bubiyon Bridge, in the Arabian Gulf (Figure 2), takes the idea to its 'logical' conclusion, with the concrete elements reduced to a lattice truss,

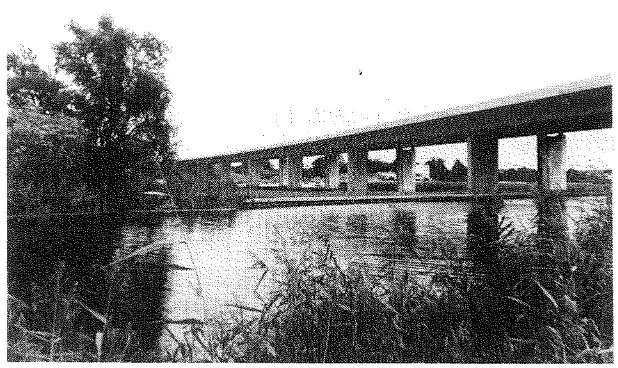

Figure 1. Exe viaduct. Externally prestressed.

and the tendons completely outside the structure. Although such structures show significant economic advantages, widespread adoption of the ideas has not taken place because of worries about corrosion of the tendon.

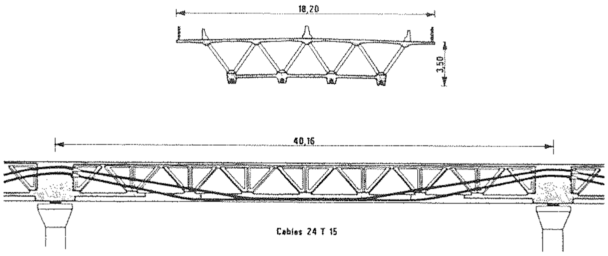

Figure 2. Bubiyon Bridge. Prestressed lattice.

To prevent such corrosion, common practice is to grease the tendon, and then coat it in a plastic sheath, but in France, where problems occured with some early examples of external prestressing, it is normal to weld a thin sheet steel tube around the tendons, and fill this with hot bitumen; such expensive exercises virtually negate the cost benefit of steel over Parafil, for which there would be no need to provide such protection. Both the examples given above would benefit from the new material, which has been used to construct a beam with external tendons at Imperial College (Figure 3).

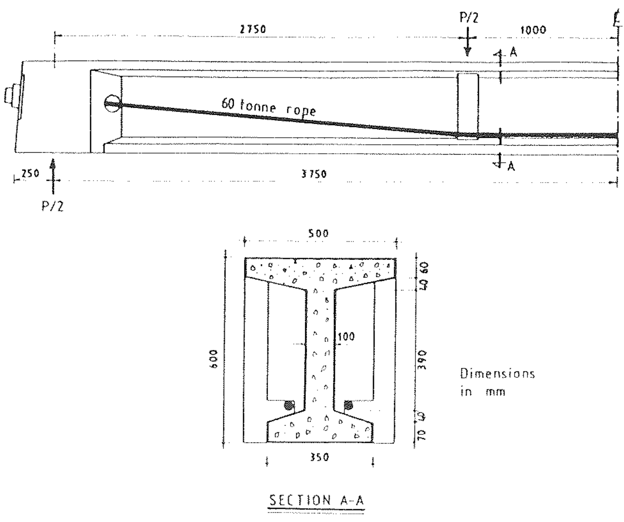

Figure 3. Beam externally prestressed with Parafil

Prestressing for repair

The use of external prestressing in new construction requires a change in thinking by designers, to take advantage of a new material. One field where engineers are being forced to look at new materials is in the field of repair of existing structures.

Many existing structures are in need of repair for a variety of reasons. They may have been inadequately prestressed or reinforced to begin with, or there may have been corrosion of the steel subsequently. Some structures have to be reinforced to cope with larger loads, or because of settlement of foundations. Repairs have been carried out to some structures by gluing steel plates to the concrete, but recently doubts have been expressed about this method because of doubts about the creep and thermal properties of the adhesive (6,7).

Many of these structures can best be repaired by prestressing, since this usually enhances the integrity of the existing structure, without adding to the weight. In most structures, unless deliberately built with a view to the provision of additional prestress, spare ducts are not available and the structure must be externally prestressed. As with new construction, these cables have to be protected from corrosion if made from steel. Such protection would be unnecessary if the tendons were made from Parafil.

One such set of structures that have been repaired in this way are three large cooling towers at Thorpe Marsh Power Station near Doncaster (Figure 4). These towers had been coated with gunite after the collapse of similar towers at Ferrybridge, but were recently found to have large vertical cracks at the top. They were repaired by wrapping the towers with Parafil ropes, which were supported off stainless steel brackets, and subsequently tensioned. In this case, not only did the Parafil offer benefits of freedom from corrosion, but also in the light weight, which allowed the ropes to be manhandled from light gantries during erection.

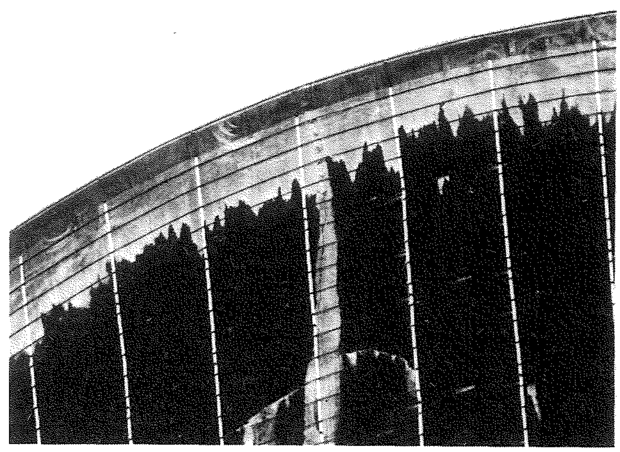

Figure 4. Thorpe Marsh Power Station Towers repaired with Parafil

For bridges, various alternative repair strategies can be contemplated; many of these have been suggested for use with steel tendons, but are more suitable for use with Parafil tendons (8). These include the addition of prestressing cables inside the central void of box girders, either just below the soffit of the top flange, as has been considered for structures built by the balanced cantilever method, or by placing cables adjacent to the webs in more conventional construction systems (Figure 5). The only modifications required to the existing structure would be the addition of anchor blocks and deflection points, which can be provided relatively easily by bolting stainless steel brackets to the structure, or by exposing existing reinforcement and casting in-situ deflecting blocks onto the structure (Figure 6).

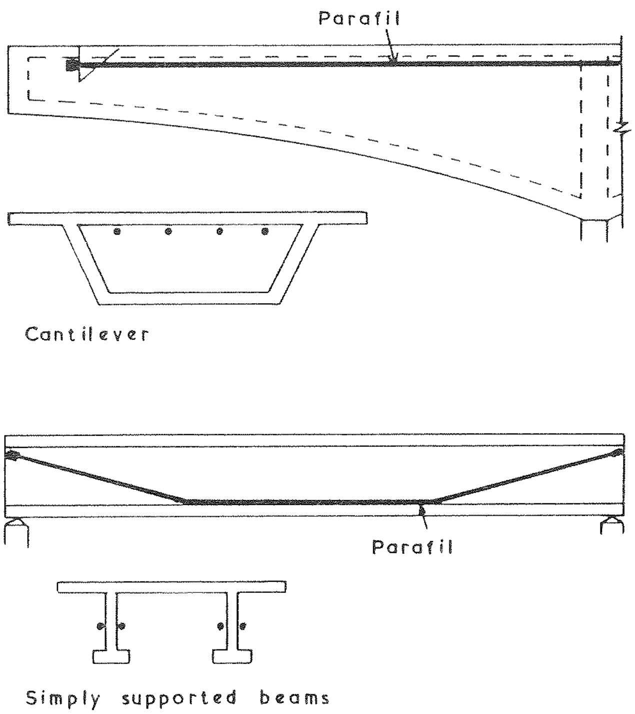

Figure 5. External cables for repair.

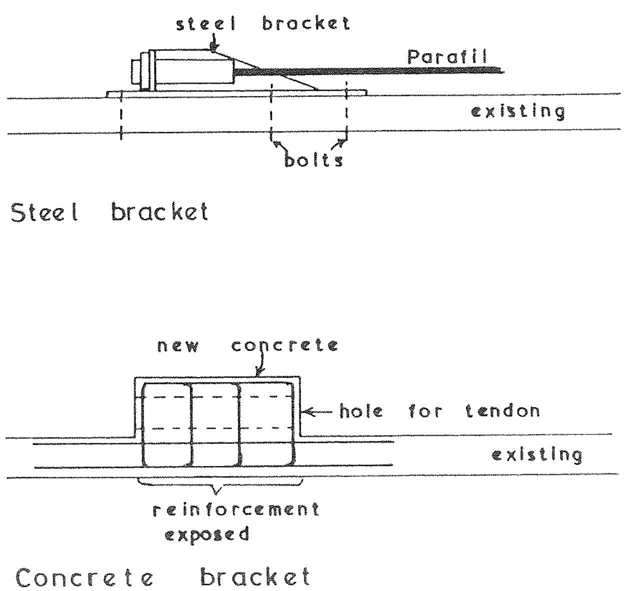

Figure 6. Anchor blocks for repair systems.

In the context of repair of structures by prestressing with Parafil, it is also possible to consider repair of indeterminate steel structures by utilising the parasitic moments that can be induced in a structure by prestressing. These allow the redistribution of moments between the mid-span and pier regions; a facility which is well understood and utilised by the designers of prestressed concrete bridges, but which is not normally available to designers in steel.

Internal prestressing

Parafil tendons can be used internally within the concrete in the same way as steel ones, although this mechanism does not take full advantage of the material's properties. This mode of use would be particularly suited to situations where an external tendon would be exposed to abrasion or vandalism, and where there was no central void that could be used. It must be accepted that the tendon cannot be bonded to the concrete; even if the sheath could be bonded to the concrete, the individual fibres are not locally bonded to one another, or to the sheath. Indeed, with a material which fails in a brittle manner, bond between concrete and tendon would be a disadvantage, since high local strains in the concrete (such as occur in regions failing in flexure) will not cause high local strains in the tendon.

When contemplating the procedure for using internal tendons in prestressed concrete, consideration must be given to the procedure to be adopted on site. The terminals are larger than the ropes themselves, and so cannot be threaded through ducts designed only for the ropes; the terminals also have to be fitted by drawing the rope back into the terminal body, so some alternative provision must be made.

This can be done by using a two part duct (Figure 7), and placing the cable in the duct, complete with terminals, before the concrete is cast, or by detailing the duct to expose one end of the rope over a suitable length, so that one terminal can be fitted in-situ. Neither procedure should cause problems if taken into account at the design stage, and indeed the first has been successfully employed when building test beams with internal tendons (Figure 8).

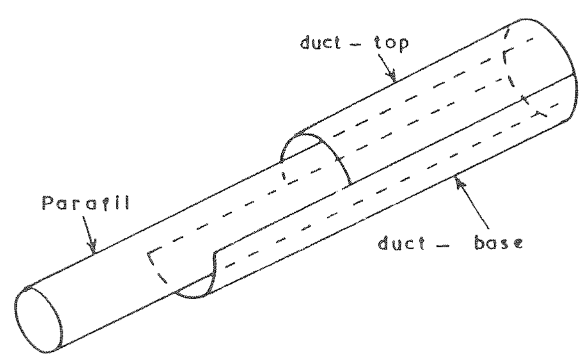

Figure 7. Two-part duct.

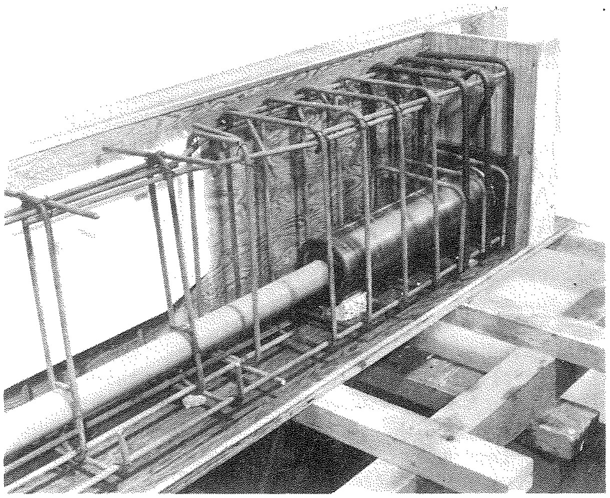

Figure 8. Test beam before casting. Parafil rope already installed in duct.

Properties of Parafil prestressed concrete

At first sight it would appear that using Parafil to prestress concrete, both of which are brittle materials, will yield a brittle composite, but this is not the case. Figure 9 shows the load deflection curve for a beam prestressed with an unbonded Parafil tendon. The response is ductile, with considerable deflection, and hence energy absorption, after the first cracking of the concrete. The cracks lengthen, but the composite continues to carry load, until the final failure of the beam occurs when the concrete fails in compression.

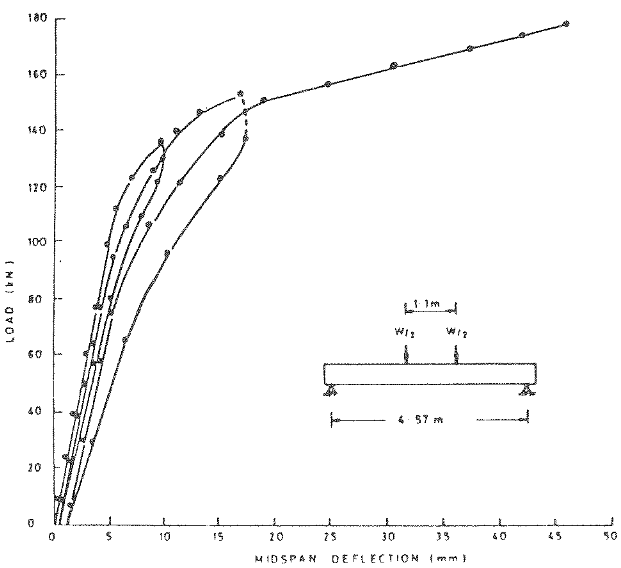

Figure 9. Load deflection curve for Parafil prestressed beam.

One consideration that is important for designers of prestressed concrete is the ability to estimate losses of prestressing force. Parafil creeps slightly, and so relaxation losses are higher than for steel, but because the Young's modulus is lower than steel, the effects of elastic shortening and creep of the concrete are reduced. Comparisons (9) show that the total losses are approximately the same as those that can be expected in beams prestressed with steel.

The termination system required for prestressing concrete only needs slight modification from the standard form. The terminal body needs two fixings, one to connect to the jack and the other for the permanent anchor. A simple arrangement is to provide the first by means of an internal thread on the terminal body to connect to a pull-rod, while the second is provided by an external thread for a permanent back-nut.

The stressing operation is shown in Figure 10; since the final anchorage is provided by a back-nut, there is no loss of force from draw-in of the wedges, and considerable adjustment is possible within the length of the external thread.

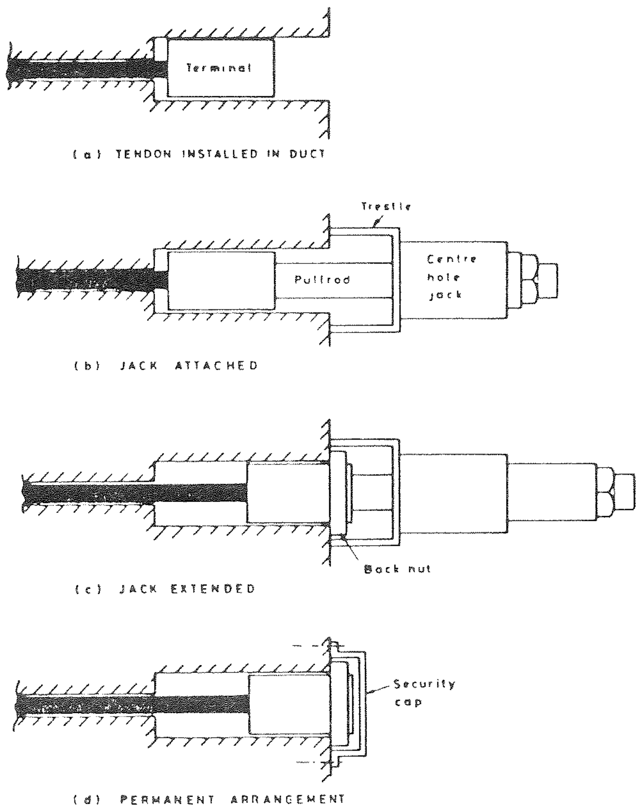

Figure 10. Stressing sequence for prestressed concrete

Types of structure

We can identify various types of structure that would benefit from the use of Parafil prestressing tendons. Bridges are one example, since the weight of the structure can be kept down by the use of external tendons in new construction and many existing bridges are in need of repair or strengthening.

Marine structures, such as piers and jetties, would also benefit, since the tendons do not need to be protected from the aggressive corrosion that can occur, especially in the splash or tidal zones. We can contemplate a whole range of novel marine structures, in which the tendons pass through voids in thin-walled hollow structures, rather than being constrained to pass through concrete (Figure 11).

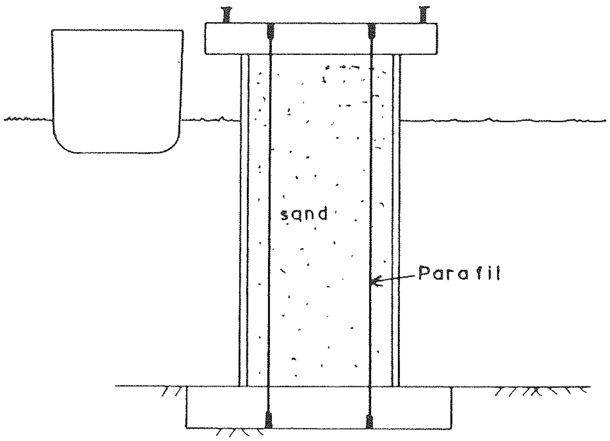

Figure 11. Prestressed mooring dolphin.

Structures in the ground would be other candidates for the use of Parafil prestressing, this time because of the resistance to ground water attack. Thus, the design of piles, foundation beams and floor slabs could all be reconsidered in the light of the new form of construction.

Reinforced Concrete

It is perhaps worth making some mention at this stage about the feasibilty of using Parafil or indeed other non-metallic materials for reinforcing concrete. This is not a practical proposition in most cases, since the strains that are needed before most polymers achieve high stresses are so large that the concrete would be badly cracked before the fibres were doing anything useful. Even Kevlar 49, which is the highest modulus fibre commercially available (apart from certain expensive Carbon fibres), would need strains of 0.5% before it achieved a reasonable working stress of 640 N/mm^2. Lower modulus materials, such as polyester and polypropylene would be even worse in this regard. The current vogue for the use of polymer filaments in concrete only serves to increase the strength of concrete while it is very fresh; as the concrete matures the effect on the strength is negligible. If someone can invent a cheap organic fibre, with a strength of 2000 N/mm^2 and a modulus of 800 kN/mm^2, then the picture might be very different.

Prestressed brickwork

One novel form of construction that has been developed recently, but which has not realised its full potential with steel tendons, is prestressed brickwork or masonry (10). The primary problem is creep of the brickwork, due mainly to creep in the mortar beds rather than in the bricks themselves. The lower modulus of Parafil means that tendon extensions will be higher than those of steel tendons, so less stress will be lost when the brickwork creeps. Indeed, the lower modulus Type F (Kevlar 29) ropes, or even Type A (polyester) ropes might be more suitable.

In addition, brickwork does not provide the passive environment which prevents corrosion of steel tendons, but with Parafil that is not a problem.

Prestressed brickwork diaphragm walls for building construction can be contemplated, in which the tendon is placed between the two leaves (Figure 12). A form of looped tendon could be incorporated, which passes over saddles at the top and bottom of the wall, reducing the number of relatively expensive terminals needed (Figure 13). Stressing could be by simple screw jacks at the top of the wall, with blocks subsequently inserted to hold the prestress.

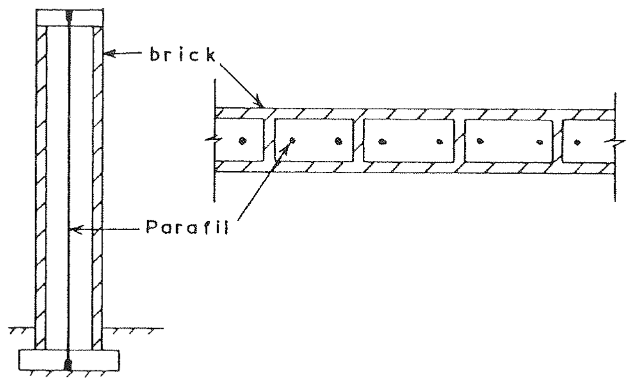

Figure 12. Prestressed diaphragm wall.

Prestressed brickwork retaining walls are also possible, with advantages of appearance and ease of construction over concrete alternatives. The prestressing would probably be between a capping beam at the top, and the foundation slab at the bottom, with the tendon behind the wall and inclined to resist the eccentric soil loadings (Figure 14). Occasional counterforts could be included to ensure stability during erection; the tendon would lie within the backfill material, and could, if required, be stressed in stages as backfilling progressed.

Cable stayed bridges

Cable stayed bridges clearly have a requirement for exposed structural tension members, and corrosion protection is obviously critical. Furthermore, such structures are often limited by the stiffness of the cables, so the higher the modulus the better. Thus, there is a logical case for replacing steel stays with Type G Parafil ones.

There are, however, other benefits that can be achieved by using Parafil. There has always

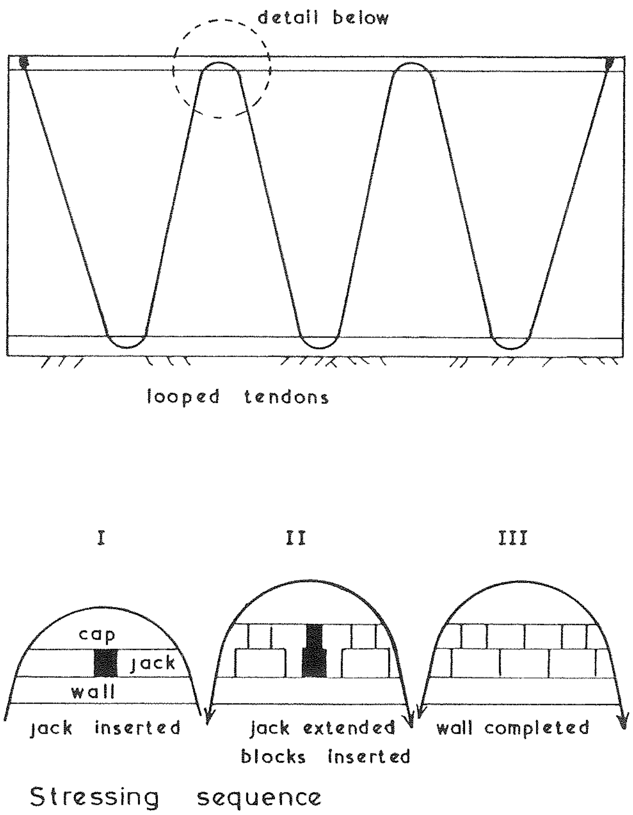

Figure 13. Stressing system for looped tendons.

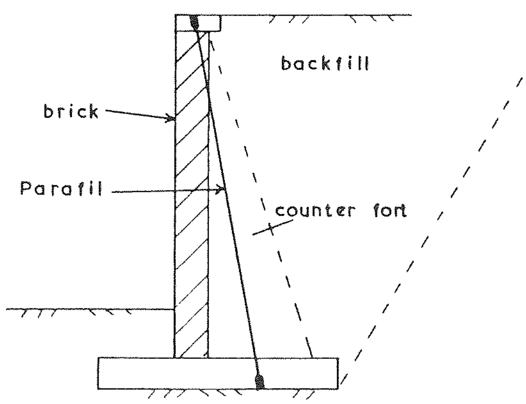

Figure 14. Prestressed retaining wall.

been a debate amongst designers of cable stayed bridges about the relative merits of providing a stiff deck with few cables, or a thin deck with many cables. Early bridges (e.g. Erskine, Wye etc.) tended to have few cables, which meant that the deck served a global structural purpose and carried significant bending moments. More recently, the tendency has been to move towards a thinner deck (e.g. Kessock, Barrios de Luna etc.); as the deck gets thinner, so the dead load reduces, and the live load becomes an increasing proportion of the total load (Figure 15). This causes an increased stress range in the supporting cables, which leads to the cables being limited by axial fatigue. The inherent absence of fretting due to the parallel lay nature of the ropes, and the ability to resist axial fatigue of the fibres themselves, means that Parafil will extend the range of structures that can be designed, rather than merely being used as a steel replacement.

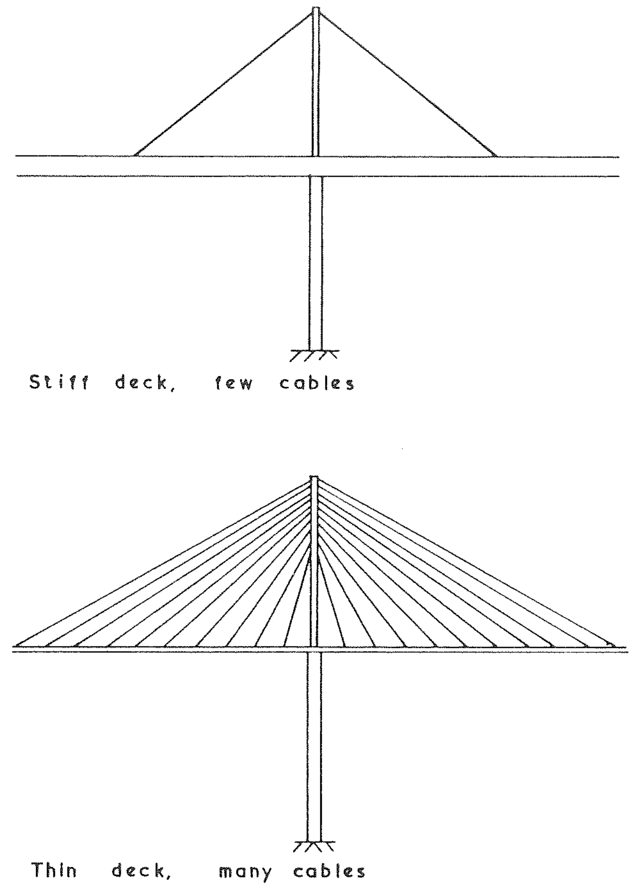

Figure 15. Forms of cable stayed bridges.

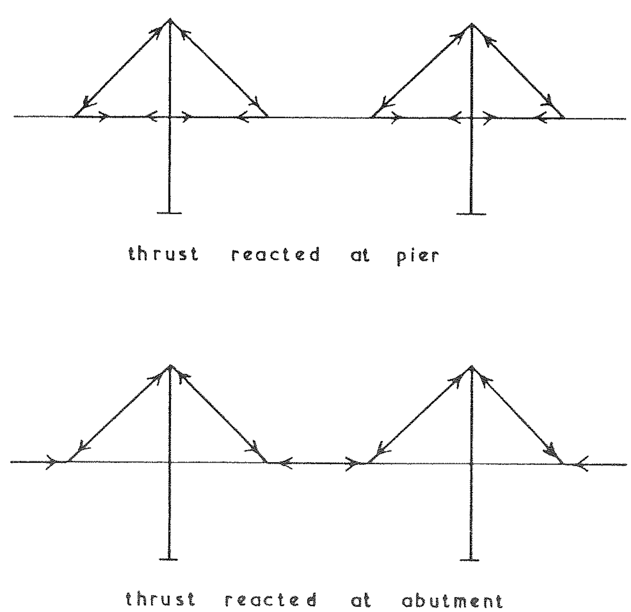

Figure 16. Different methods of resisting stay forces.

If these design consideration are taken to their logical conclusion, we can envisage structures in which the deck merely spans between the cables and reacts the horizontal component of the cable force. This could even be done by resisting these forces by tension at the mid-span (Figure 16), rather than compression at the support, which would serve to further improve the stability of the structure. The deck could consist solely of a thin, prestressed concrete slab, with little wind resistance; the overall stability would be provided by the stay cable layout, rather than the stiffness of the deck.

Roofs

The logical extension of cable stayed bridges is to cable supported roofs. The only stiffness of these roofs comes from the axial stiffness of the cables, with the flexural stiffness of the panels serving only to distribute local loads.

To mobilise the axial stiffness properly, the cables have to be tensioned. This can be done either by stressing the cable against the weight of the roof after installation, or more sensibly by building the roof with anticlastic curvature so that the cables can be stressed together before erection of the infill panels.

Calgary Saddledome is an example of this type of construction (Figure 17), with a span of approximately 130m, but with a roof thickness of only 50mm. Parafil cables would reduce the weight of the roof considerably, without reducing the stiffness of the resulting structure, and the light weight would considerably simplify erection.

Figure 17. Calgary Saddledome under construction

Suspension bridges

Potentially the most exciting use of Parafil will be in the construction of very long span suspension bridges. The longest existing bridge span is the Humber Bridge at 1.4km, with a proposed bridge in Japan of 1.8km span due for construction in the next few years. A structure across the Straits of Messina has been talked about for many years, with a main span of 3km. This is widely regarded as being on the limit for steel cables, since the weight of the cables themselves becomes a governing consideration, and no strength remains for carrying the live load.

At one stroke, replacement of the steel cables by Parafil would reduce the weight of the cables by a factor of seven, thus allowing much larger spans. One of the serious contenders to build the Channel crossing, between England and France, was for a bridge with seven 4.5km spans, each supported by four Parafil cables 1.4m in diameter (Figure 18). It would have taken an engineer of vision to recommend the acceptance of such a design when no major structures existed with Parafil supports. There is little doubt, however, that such a scheme could be made to work. Care would be needed to take account of the creep of the cables, however small, and the aerodynamics of such a structure would need careful consideration.

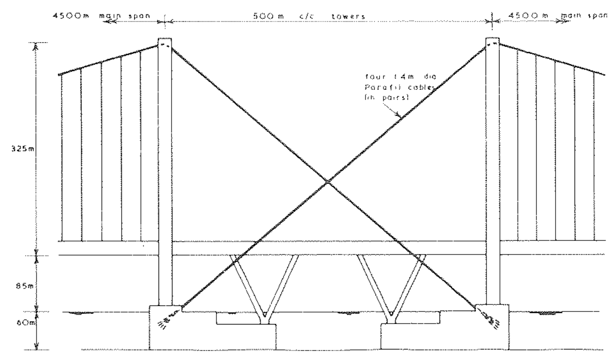

Figure 18. Proposed Channel Bridge.

Nevertheless, such a design offers significant advantages over conventional alternatives. The reduction in the number of piers reduces the risk of ship collision, and allows significant protection to be provided at each location. The ability to produce the main cables on-site in one operation obviates the need for extensive cable construction in-situ, and reduces significantly the overall construction time.

Perhaps one day we shall see such a structure built. When the railways on either side of the Channel realise the potential for long haul freight there will be little remaining capacity for shuttle trains of cars, and a bridge remains the only feasible solution for a fixed link to carry vehicles under their own power.

Benefits of electro-magnetic properties

Although the electro-magnetic properties of materials are not important in the design of most structures, there are a few applications where a non-magnetic and electrically insulating tension member would be useful. The insulating properties would be of benefit in power transmission systems (ropes have already been used to support trolley bus wires), and many structures supporting communication equipment would benefit from the non-magnetic properties.

There are also certain scientific and military applications where magnetic interference must be reduced to a minimum.

Conclusions

Type G Parafil offers the structural engineer a material with a new range of properties. In many forms of construction it offers advantages over existing materials that outweigh the additional expense. These will manifest themselves, not as Parafil replacing steel, but as Parafil extending the range of structural forms beyond those that are feasible today.

Thus, we can expect to see bridges with external Parafil cables, structures repaired with Parafil tendons, and foundations prestressed with Parafil. Prestressed brick walls, very thin cable stayed bridges and very long span suspension bridges are also possible. Man's ingenuity will produce other applications.

We do not know all the answers yet about this new material, but we know sufficient to predict that it will find widespread application. It is now up to the designers to consider how best the material should be used in their particular fields, and to determine which questions remain to be answered.

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