Prestressing with Parafil tendons

The use of this new material is discussed by C J Burgoyne and J J Chambers, of Imperial College of Science and Technology

A new material has become available for prestressing tendons which will free the designer from some of the constraints which cause problems when using steel tendons. In particular, the tendons do not corrode, which obviates the necessity of providing cover to the tendons. The tendons may, therefore, be placed outside the concrete, or in environments where corrosion protection would be difficult to provide.

This article summarises the basic properties of this new material and describes some of the work in progress at Imperial College to furnish data relevant to prestressing. The material does not have properties identical to those of cold-drawn steel wire and if maximum benefit is to be gained from its use then its properties should be properly understood.

What is 'Parafil'

Parafil* (for PARAllel FILaments) is one of a number of 'Para' products manufactured by ICI. It consists of a closely packed, essentially parallel, core of high-strength continuous synthetic yarns, contained within a thermoplastic sheath. This sheath maintains the circular profile of the rope, and protects the core from ultra-violet radiation which could cause degradation. Otherwise, the sheath serves no structural purpose.

The core can be of a number of different materials, but those most commonly used are based on polyester yarns (Type A Parafil), or aramid, eg, Kevlar 29† (Type F) and Kevlar 49 (Type G).

Type A has a Young's modulus of about 12kN/mm^2, and an ultimate strength of about 620N/mm^2, which means that the ropes can sustain high strains (5–6 per cent). This makes them ideally suited for soil reinforcement. Paraweb‡, a related product, is widely used as the reinforcing material for this application[1].

The stiffer aramid materials are more suited to structural applications. Both Type F and Type G versions have similar strengths (1930N/mm^2), but differ in their Young's moduli. Type F (Kevlar 29) has a modulus of about 78kN/mm^2, while Type G (Kevlar 49) has a modulus of about 126kN/mm^2 (approximately 60 per cent that of steel). The higher modulus of Type G Parafil ropes means that they reach their peak stress at a strain (1.5 per cent) similar to that in cold-drawn steel wire at failure.

Kevlar achieves its high strength because it is a highly orientated, crystalline material, with high molecular weight. The basic molecule appears to be poly(p-phenylene terephthalamide) or PPT, and consists of long chain hydrocarbons as shown in Figure 1.

Kevlar, which is manufactured by Du Pont, has found many uses where high strength and low weight are important. It is used in epoxy composites in aircraft, and is used for personnel protection as mats in bullet-proof vests. When originally developed about 15 years ago, it was referred to as 'yellow gold', a reference to its colour and exceptional properties. Other aramids, with similar properties, are being developed by different manufacturers.

Properties of Type G Parafil

The high modulus of Kevlar 49 makes it the most suitable of the core yarns for use as prestressing tendons in concrete, so henceforward, we shall restrict the discussion to Type G Parafil ropes, with Kevlar 49 cores.

The stress-strain behaviour of the ropes is shown in Figure 2. Typical curves for cold-drawn prestressing steel and high yield reinforcing steel are shown for comparison. The Parafil clearly reaches a strength in excess of that of steel, but despite its lower modulus, is unable to sustain such high strains, due to the brittle nature of the failure mechanism.

The specific gravity of Kevlar is about 1.4, so that it just sinks in water. In the form of ropes, however, the specific gravity falls to about 0.98, due to the less dense sheath and the presence of air in the interstices between the filaments. These interstices are extremely small and it is very difficult to fill them with water, so the maximum theoretical specific gravity of the ropes of about 1.08 is rarely reached. The properties of the ropes are unaffected by immersion in water.

One of the problems associated with organic fibres is their tendency to lose strength under the action of long-term loads, a phenomenon known as stress-rupture. Long-term data are, naturally, scarce, but the best estimate that can be made for the load that will cause failure after 100 years, is about 50–60 per cent of the nominal breaking load (Figure 3). The theoretical lines on this plot are based on tests on Kevlar 49/epoxy composite strands[2] and Kevlar 49 yarns tested at high temperatures to accelerate failure[3].

Creep and relaxation might be expected to be significant with these ropes, but although the values are higher than for steel, they are not so high that they preclude the use of Parafil for prestressing. Relaxation losses of about 8 per cent after 1000 hours seem to be typical. However, when the lower modulus is taken into account, which reduces the losses due to the creep, shrinkage and elastic shortening of the concrete, total losses are similar to those in a beam prestressed with steel.

Kevlar 49 is resistant to most forms of corrosion, with two exceptions. It degrades in the presence of ultra-violet radiation and loses strength in the presence of strongly alkaline solutions. Thus, if the Kevlar yarns were used as reinforcement in intimate contact with concrete, degradation could be expected, given the high pH of concrete. However, the outer thermoplastic sheath of Parafil ropes serves to protect the core yarn from this source of attack, as well as

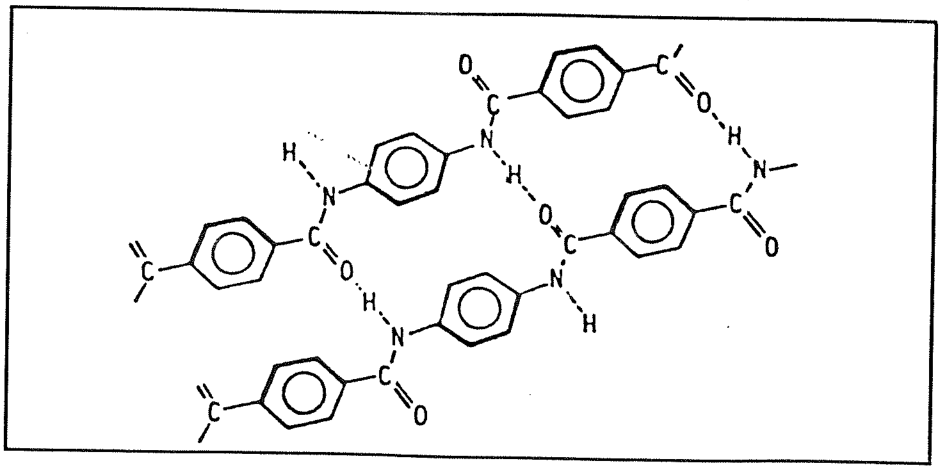

Figure 1: Chemical structure of Kevlar 49 (poly(p-phenylene terephthalamide))

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*Parafil is a trade mark of Imperial Chemical Industries.
†Kevlar is a registered trade mark of Du Pont.
‡Paraweb is a trade mark of Imperial Chemical Industries.

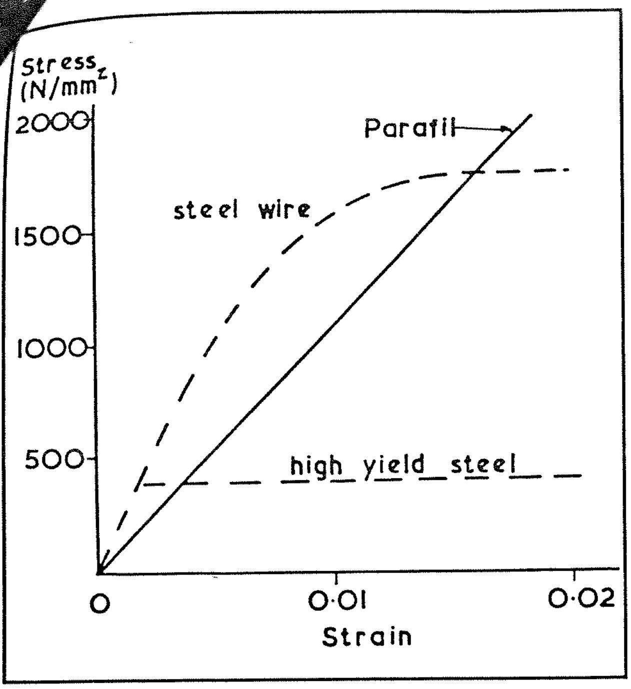


Figure 2: Stress-strain behaviour of Type G Parafil and steel

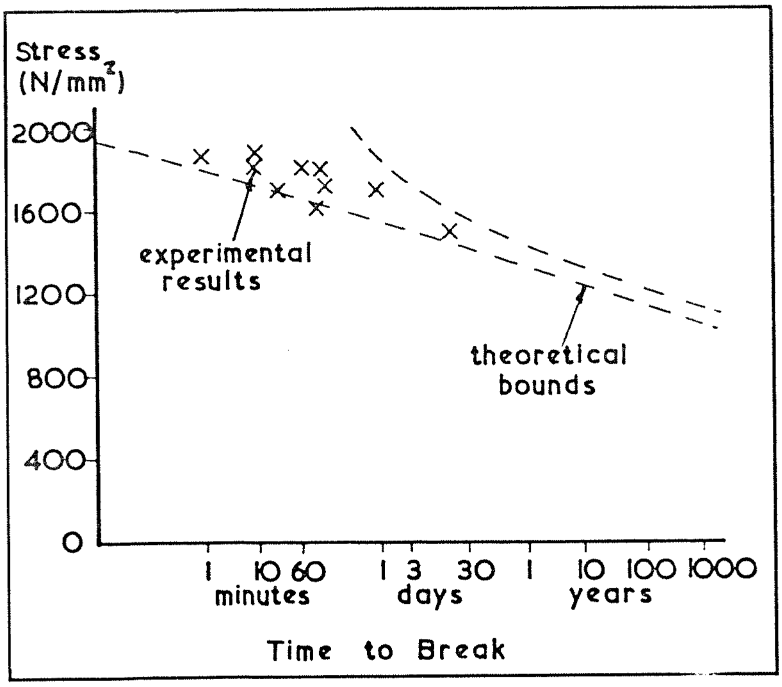


Figure 3: Stress-rupture behaviour of Type G Parafil

shielding the rope from ultra-violet light.

The fatigue properties of Parafil ropes are excellent, tests having been carried out under both tension-tension and tension-bending conditions.

Parafil ropes, as presently made, do not bond to concrete. Our tests show that slip occurs between the core and the sheath, and also between the sheath and the concrete. The criteria associated with unbonded tendons would have to be employed, therefore, when considering the ultimate flexural strength of prestressed concrete members incorporating Parafil. The lack of bond is not disadvantageous, as it will limit the additional strain in the Parafil under 'overload' conditions. This is especially important given the brittle mode of failure of Kevlar.

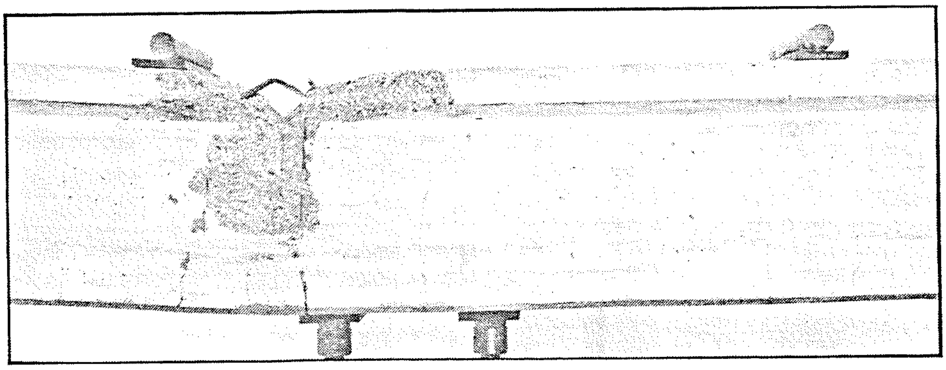
Work at Imperial College

A variety of test programmes are under way at Imperial College to determine in greater detail the properties of the ropes which are relevant for prestressing. This work, jointly sponsored by ICI and the SERC, includes work on stress-rupture, creep, stress-relaxation and thermal effects.

Stress-rupture tests have until now been carried out using electrically operated hydraulic jacks, but it is unrealistic to use this system for tests lasting longer than about three months. A rig will shortly be built so that a number of samples can be loaded with dead weight to give failure over periods of one to five years. This will extend the knowledge of 'times to break' into realistic time scales.

Bond tests on alternative rope constructions and tests to measure the tensile strength when the rope is deflected, (as would occur in a prestressed beam — Figure 4) are also being undertaken.

There are very little data regarding the thermal expansion of Kevlar. It is known to have a negative thermal coefficient at zero load while at room temperature, but the behaviour under load is unknown. If the coefficient of thermal expansion remains negative, then the fluctuation of prestress due to temperature effects would have to be considered in design. Work is being initiated which will establish the coefficient of expansion over a range of loads and temperatures.



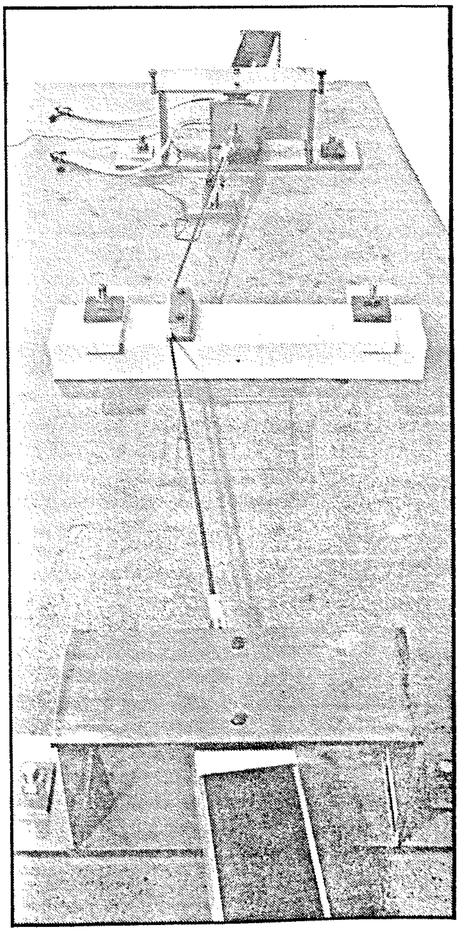


Figure 4 (right): A 6-tonne rope under tension round a point of deflection
Figure 5 (above): Failure zone of 5m beam

A 5m-span beam has been built and tested. It was prestressed with a single 60-tonne rope, tensioned to 42 tonnes. The beam was loaded by point loads to give a central region subject to pure flexure. Failure occurred, as expected, by crushing of the compression flange (Figure 5); this is the usual mode of failure for a beam possessing an unbonded tendon. Even so, the beam exhibited a considerable degree of ductility prior to failure, due to cracking in the tension zone of the concrete. The load-deflection curve (Figure 6) indicated considerable curvature and it was possible to unload the beam from the heavily cracked condition, with almost complete recovery. At first sight it may seem strange that a composite can be made which has considerable ductility, when the two components, Parafil and concrete, are both brittle.

Termination system

The ropes are anchored using a single internal spike, as illustrated in Figure 7. This presses the core yarn (not the sheath) against the sides of a conical hole in the main terminal body. The terminal can be threaded to take a variety of attachments.

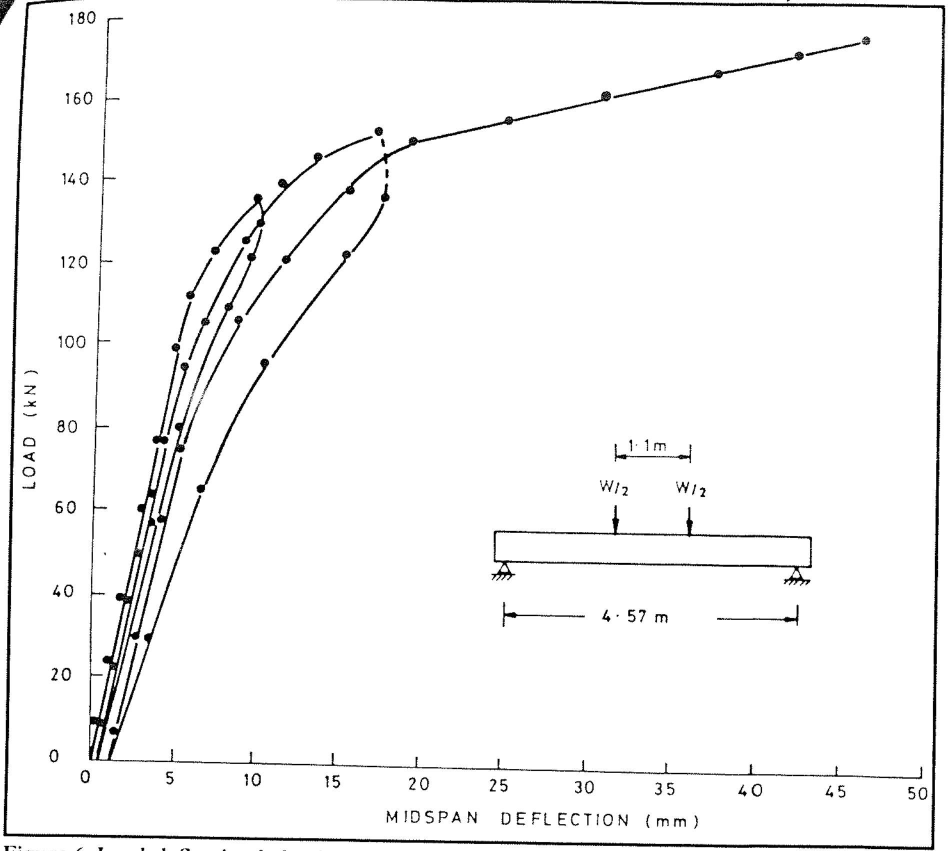


Figure 6: Load-deflection behaviour of 5m beam

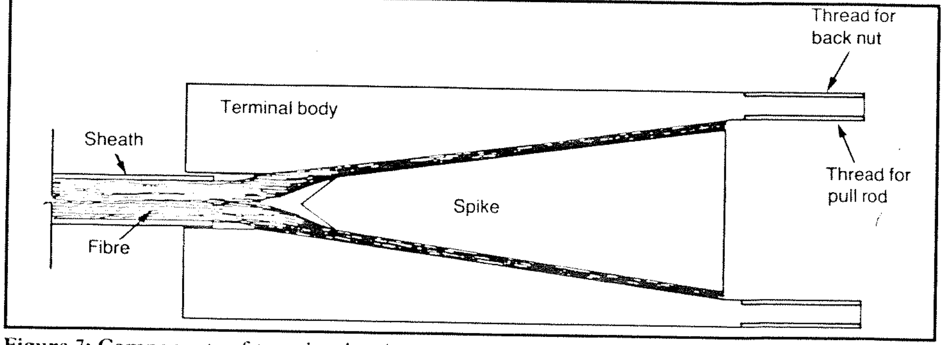


Figure 7: Components of termination (not to scale)

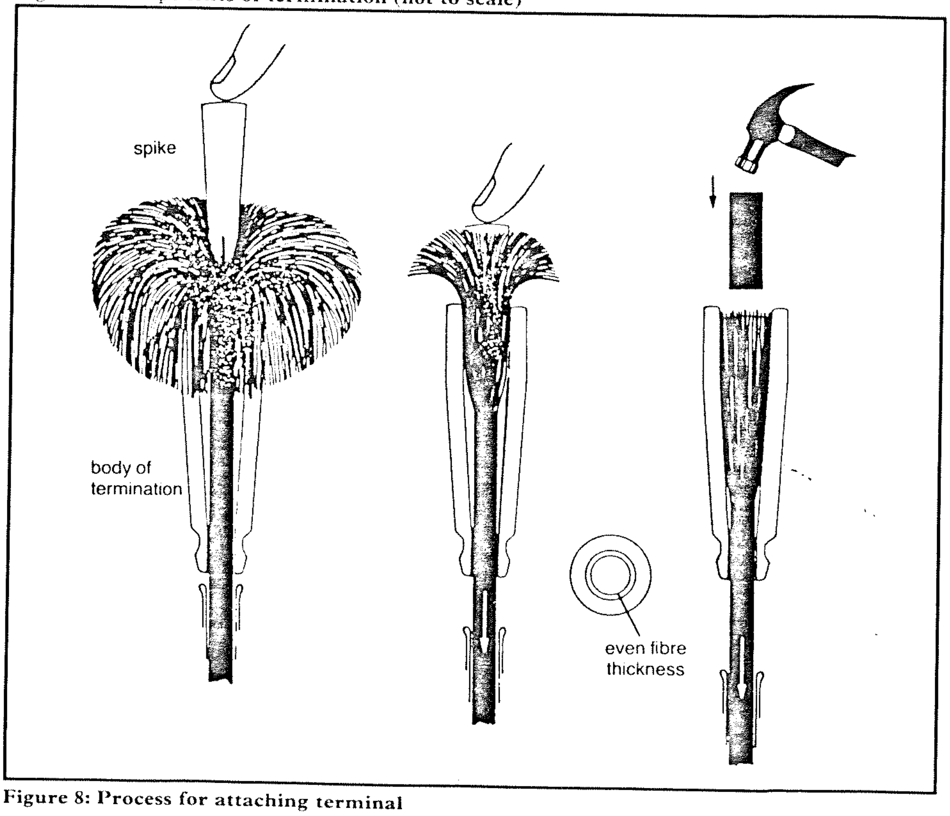


Figure 8: Process for attaching terminal

For prestressing applications, an internal thread is incorporated so that a pull-rod can be attached for the stressing operation, while a back-nut can be located on an external thread to form a permanent anchorage.

The terminals are fitted to the rope by passing the rope through the terminal, removing part of the sheath, and then drawing the rope back into the terminal so that the fibres grip the central spike (Figure 8). For small ropes, the process can be done by hand, but for ropes rated at several hundred tonnes, this would be impracticable. Mechanical systems have been used for the larger ropes, in which the yarns are held in a symmetrical pattern around the spike. The terminal body, which is mounted horizontally on rollers, is then drawn over the spike.

After fixing the terminals, the ropes can be pre-tensioned to a load in excess of the normal working load of the rope. This ensures that the spike is fully drawn in to the terminal, and helps to ensure that the loads are equally shared between individual elements. The spike has a relatively shallow angle, so the 'pull-in' is quite high; 24mm at each end of a 60-tonne rope is typical.

This termination system has performed well in the tests at Imperial College. The only failures within the terminal itself have occurred when the spike was not centrally located in the terminal, leading to inadequate load-sharing between yarns. Otherwise, the failures have all occurred in the rope away from the terminal.

The probable need to pre-load the ropes for prestressing applications, and the difficulty of fixing the terminals in situ, may mean that the ropes would normally be supplied cut-to-length with the terminals fitted, and with the pre-loading having been carried out already. If the tendons were to lie wholly within the concrete, they would normally be placed in ducts before the concrete were cast. In the case of external tendons, however, it would be sufficient to provide box-outs in the anchoring and deflection diaphragms for the rope to be installed after concreting.

The tensioning sequence would be as shown in Figure 9.

Since the ropes would be unbonded and the terminals are quite heavy, it would be good practice to provide a cap, anchored back by tie bars to the concrete to capture the terminal in the unlikely event of the rope failing.

Use in prestressed concrete

Parafil ropes have a number of attractive properties (high strength, high modulus and good corrosion resistance, amongst others), which make them clearly suitable for use as prestressing tendons.

It will be possible to use prestressed concrete in applications where the tendency of steel to corrode means that prestressing would be inappropriate, or possible only if expensive measures were taken to protect the steel. Thus, uses in or near the ground, such as foundation beams and slabs, ground anchors and piles, all seem logical candidates. Similarly, uses in marine environments, such as piers and jetties, oil platforms and pontoons, are also possible.

It is also likely that Parafil would be used for external tendons in bridge structures. It is already clear that significant savings in concrete, and hence cost, can be achieved by placing the tendons outside the concrete[4]. Even so, relatively few major structures have been built this way, due to the difficulties of providing long-term corrosion protection to the steel. Exe Viaduct (Figure 10) in the UK (designed by Freeman Fox and Partners) and Long Key Bridge in Florida, have external tendons within a box. Bubiyon Bridge (Figure 11) in Kuwait, on the other hand, has a concrete truss with the cables passing through it. Time will tell whether it was wise to have exposed steel cables in a very hot, humid environment, such as the Persian Gulf. Parafil tendons, however, would be very suitable for such applications.

Another probable use for the tendons is in the repair of structures. Many structures with inadequate prestress or reinforcement could be repaired by the application of prestress. The difficulty in existing structures has been the provision of a suitable duct to protect the steel tendon. If Parafil were to be employed it would only be necessary to provide anchor blocks and deflection diaphragms.

Alternative uses

Other applications are also possible. Clearly, the ropes are suitable as stay cables for both roof structures and bridges; these are areas in which steel cables are already being used. However, there are two other areas where steel is precluded by reason of its weight: offshore tension leg platforms in deep water, and very long span suspension bridges.

The tension leg platform (TLP) installed by Conoco in the Hutton Field in the North Sea, uses steel tubes for the tie-down tension members. It is clear that the TLP principle is only suitable for use in deeper water, if high-strength, lightweight tension materials are used for the ties. Kevlar, in the form of Parafil ropes, satisfies the required criteria, and is being considered for the next generation of TLP platforms[5]. With a density for the ropes close to unity, they become effectively weightless in water.

Perhaps the most exciting possibility for the ropes is as the main suspension cables for a Channel bridge. As the span of suspension bridges increases, so the weight of the main cables increases as a proportion of the total load on the structure. The largest span considered feasible for steel cables is about 3km (eg, for the Straits of Messina)[6]. However, Eurobridge are proposing a design for a Channel crossing with seven 5km spans, with the main cables made from Parafil[7]. With a specific strength (strength/density) approximately five times greater than steel, Parafil ropes open up completely new possibilities.

There is thus available a new and potentially exciting material which will eliminate the constraints of concrete members whose dimensions are governed by cover requirements. It is now time for designers to consider the implications for their work.

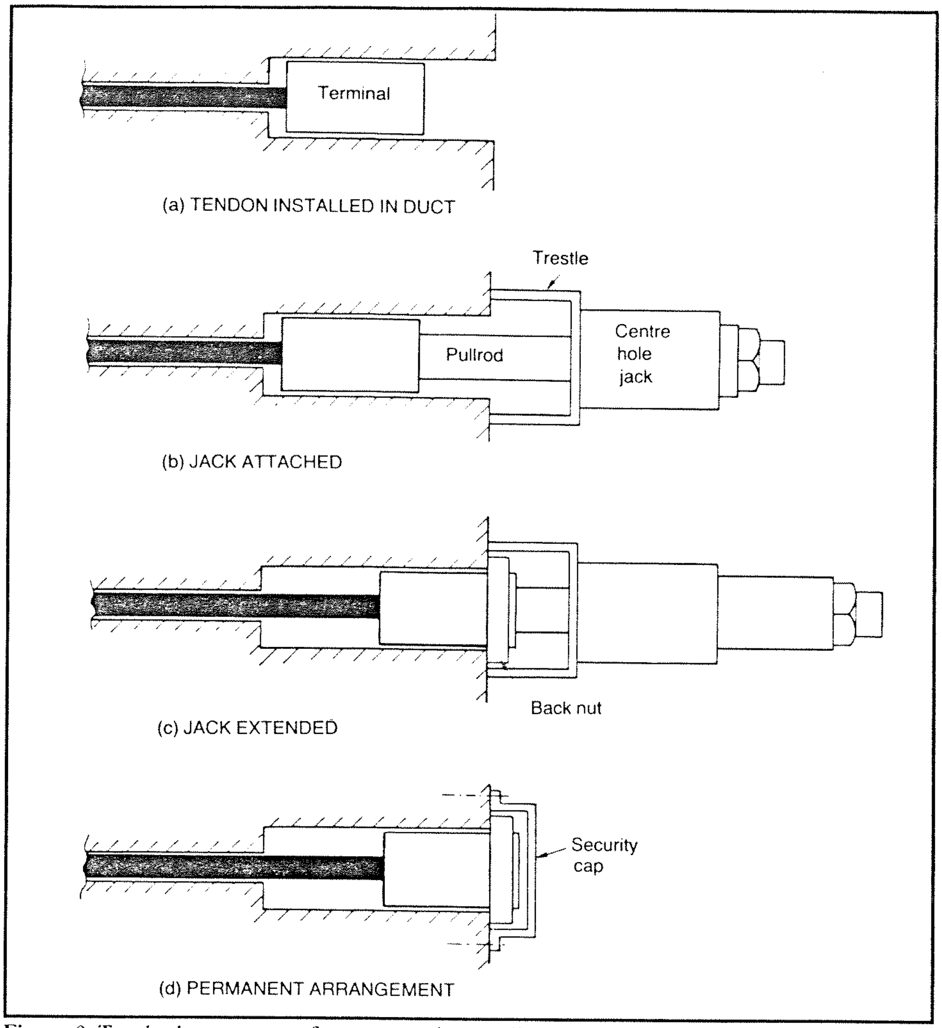


Figure 9: Tensioning sequence for prestressing application

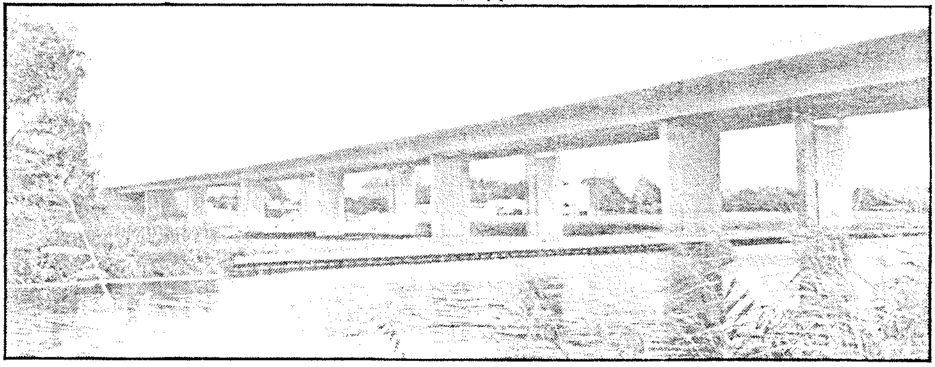


Figure 10: Exe Viaduct (photo Freeman Fox and Partners)

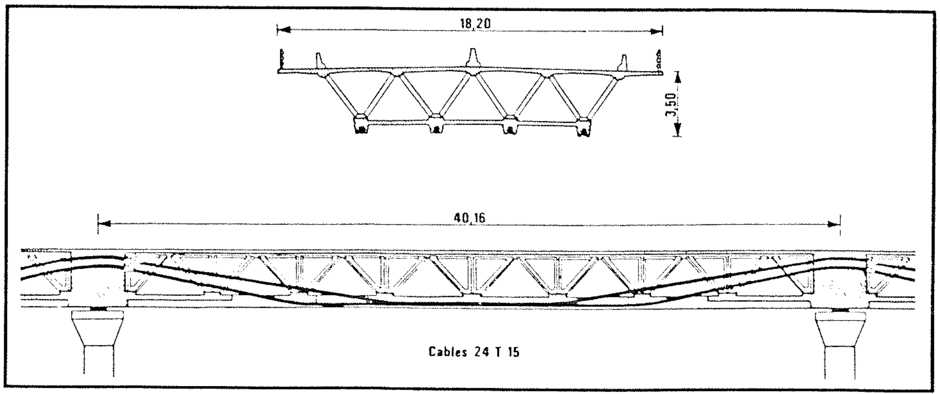


Figure 11: Typical arrangement of Bubiyon Bridge (from reference 4)

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