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Properties of Polyaramid Ropes and Implications for Their Use as External Prestressing Tendons

by C.J. Burgoyne

Synopsis: The paper describes the properties of parallel-lay ropes with a polyaramid (Kevlar 49) core, with particular reference to the long term properties which are of importance to the designers of prestressing systems. The anchorage and prestressing systems are described, and results are given for stress-strain, relaxation, creep, stress-rupture and fatigue behaviour.

Durability and thermal response are also considered, and it is inferred that the lack of corrosion, in addition to the high strength and high stiffness, makes these materials ideal for use as prestressing tendons where the concrete cannot be used to provide corrosion protection to steel.

Descriptions are given of tests on beams prestressed with external tendons, which show that a ductile response can be achieved in a beam made from two brittle materials.

It is concluded that these materials will extend the range of structures that can be built with prestressed concrete, and will at last allow the realisation of the full potential of externally prestressed concrete.

Keywords: beams (supports); corrosion resistance; creep properties; durability; fatigue (materials); modulus of elasticity; plastics, polymers, and resins; prestressed concrete; prestressing; strength; stress relaxation; thermal properties

Dr Chris Burgoyne is a lecturer at Cambridge University, and has been carrying out research into the properties of aramid ropes for a number of years. His other research interests include the application of expert systems to the design of prestressed concrete, and the general philosophy underlying structural design. He was formerly employed at Imperial College, London, where much of the work described here was carried out.

INTRODUCTION

The use of external tendons in prestressed concrete is an idea that has been tempting designers almost since the first use of prestressing. The biggest benefit is the saving of weight in the webs. They can be reduced to the thickness needed to carry the shear forces, without the necessity of providing cover for the tendons. In addition, the cables are accessible for inspection and, potentially, replacement.

The drawbacks lie in the absence of the corrosion protection that is normally provided by the concrete. Without the passivating environment provided by the highly alkaline cement matrix, the steel will corrode very rapidly unless extensive measures are taken to prevent corrosion from occurring.

In the United Kingdom, as elsewhere, there have been problems with corrosion in external tendons. At Braidley Road viaduct, the external tendons had to be replaced and provided with additional corrosion protection after some of the tendons failed after only 12 months (1).

Even internal tendons can corrode. A recent report on Ynys-y-Gwas bridge in Wales (2), which collapsed in 1985 under the action of dead load only, attributes failure to corrosion of the prestressing tendons. This is despite the fact that the tendons are internal, that most ducts were properly grouted and that the concrete was of adequate quality. Furthermore, the bridge was regularly inspected and there were no indications of anything awry before failure. The bridge was of segmental construction, with mortar joints between the segments and no in-situ topping. Water, almost certainly containing de-icing salts, penetrated these joints and caused severe localised corrosion, which eventually led to failure.

A recent report on a condition survey of the stays in cable supported bridges (3,4) has shown that many of these are visibly in a bad state, and other work has shown that many failures in multi-strand cables begin on the inner wires, rather than the outer ones (5). It must be presumed that many prestressing cables are deteriorating in a similar way.

The conclusion that can be drawn is that new and existing structures prestressed with external steel tendons are very susceptible to corrosion. Many existing structures prestressed with internal steel tendons must also be very suspect, but how their condition can determined, without causing the corrosion that we wish to prevent, is a separate problem that is being investigated.

Attempts have been made to realise some of the advantages of thinner webs, without resorting to external tendons, by keeping all the tendons in the flanges, but at the expense of more awkward tendon arrangements. Redheugh Bridge over the River Tyne at Newcastle uses this system (6), and the nearby bridge over the River Coquet extended the idea by using precast panel elements for the webs, with in-situ concrete flanges (7). These are only intermediate stages however.

There is thus a proven need for a non-corroding prestressing tendon, which can be used externally, either in new construction, or as additional prestressing in structures in need of repair. The remainder of this paper describes the properties of such a material.

PARALLEL LAY ARAMID ROPES.

Aramid fibres, with an elastic modulus (approx 124 kN/mm^2; 18,000,000 psi) approaching that of steel and a strength (2760 N/mm^2; 400,000 psi) exceeding that of prestressing steel, offer a combination of properties that are suitable for prestressing tendons. These fibres were developed under the name Kevlar (by Du Pont) in 1973, and similar, though not identical, materials are now produced by Akzo (under the name Twaron) and by Teijin (under the name Technora).

The fibres themselves are very fine, being supplied as a yarn consisting of 1000 individual filaments, each filament being of 2.13 denier (equivalent to a cross sectional area of 0.000163 mm^2; 2.53×10^{-7} sq.ins). The individual fibres must be aggregated to form tendons; conventional laid ropes, which maintain their integrity by twisting together many yarns, are not suitable, since the individual fibres follow helical paths along the rope. These would act like springs when stretched, and the axial stiffness of the rope would be very low by comparison with that of the constituent fibres (8). On the other hand, parallel-lay ropes allow virtually the full stiffness of the fibres to be realised without the need to introduce resin, but require an external sheath to maintain integrity.

This paper is concerned with one such parallel-lay rope, manufactured by ICI Linear Composites Ltd, under the name Parafil. Various fibres can be incorporated within the core, but all the results quoted here were obtained from Type G Parafil ropes, which have a core of Kevlar 49 fibres.

The ropes were originally developed for other purposes, most notably mooring buoys and offshore platforms in very deep water. The combination of properties, especially when using stiffer fibres like Kevlar, makes the ropes suitable for structural applications.

Anchorage

The ability of an element to carry significant tensile forces is only as good as the mechanism for getting the force into the member; a number of methods are possible, including external wedges, bond or cast resin cones. For a variety of reasons, however, including the desire to avoid resins because of creep and the poor response to high temperatures, one method is clearly preferable (9). This is the internal wedge (or spike) which provides a radial ripping force between the spike and the external body, so that all the fibres re anchored. The length of the spike can be chosen to ensure that the ransverse stresses are within the capacity of the fibres. As with the rope tself, there is no need to introduce resin anywhere in the termination.

igure 1 shows a typical termination for parallel lay aramid ropes. Once the oad has been transmitted from the fibres to the terminal body, further onnection to the structure can be made by fitting a variety of devices, such s clevis pins, anchorage plates, or whatever is required. The figure shows uch a terminal modified for use as a prestressing tendon. The terminal body as two threaded regions; the inner thread is used for connection to a pull od which is attached to the jack during stressing, while the outer thread is sed to provide a connection for a permanent back nut, which also allows ome adjustment to take account of slack. The anchorage is capable of chieving the full strength of the rope. Reasonable care must be taken to nsure that the spike is fitted centrally within the rope (to ensure even load-sharing between fibres), but otherwise no special skills are needed. Anchorages for parallel-lay aramid ropes with capacities between 1 and 1500 tonnes (2.2 to 3300 kips) have been provided using this system. All the results quoted here have been obtained on ropes fitted with anchorages in this way.

It is normal practice, where practicable, to preload the rope to ensure that the central spike is fully drawn into the termination. This makes sure that no subsequent movement occurs in the termination, either on loading or unloading.

Stressing procedure

The stressing procedure for tendons is straightforward (Figure 2). A pull-rod is connected to the internal thread on the terminal body, and passed through a centre-hole jack. This is loaded against the concrete by means of a trestle, and when the correct jack force is achieved, a back-nut is placed on the external thread to provide the permanent anchor.

ROPE PROPERTIES

The rope properties of most interest to prestressing engineers are the strength, elastic modulus, relaxation, creep & stress rupture, and durability. The response to temperature changes and the fatigue behaviour are also relevant, as is any bond between the ropes and concrete. There is no space here to go into full details of these properties, but a broad outline of the results, and the way they were obtained, will be given.

Strength and elastic modulus

Figure 3 shows a typical stress strain curve for a Type G Parafil rope with a nominal breaking load of 60 Tonnes (132 kips). The elastic modulus is about 118 kN/mm^2 (17,100,100 psi), while the strength is about 1950 N/mm^2 (283,000 psi). These values are lower than those observed in tests on individual fibres, but bundle theory, which relates the properties of an agglomeration of components to the properties and variability of the components themselves, adequately accounts for the majority of the difference (10,11). Figure 4 shows the effect of rope size on strength; as predicted by bundle theory, small ropes (below about 6 Tonnes capacity (13.2 kips)) are stronger than larger ropes, but there is very little decrease in strength above 6 Tonnes capacity. The largest rope tested to date (1500 Tonnes; 3300 kips) failed at virtually the same ***stress*** as the 60 Tonne ropes described here. Since all ropes used for prestressing tendons would be of at least 60 Tonnes capacity, this indicates that size effects can be ignored in practice.

The manufacturer's quoted nominal breaking loads (NBL) for all sizes of rope are based on an assumed stress at failure of 1926 N/mm^2 (279,000 psi), and this principle has been followed in this paper. As can be seen from Figure 4, this is conservative for all rope sizes.

Relaxation

The relaxation of tendons is clearly crucial to the behaviour of prestressed concrete. Aramid fibres are better in this respect than most organic materials. Figure 5 shows the relaxation of 60 Tonne ropes, loaded to various proportions of their breaking load. After about 100 hours, the stress reduction response becomes approximately linear with the logarithm of time, and the following formula for the reduction in stress in a tendon has been proposed (10).

$$r = 1.82 + 0.0403\times f + 0.67\times\log_{10}(t-100) \qquad (\text{for } t > 100),$$

where
r is the stress-relaxation expressed as % NBL
f is the initial stress expressed as % NBL
t is the time in hours

This formula relates to the properties of the rope itself. Movement within the termination has been allowed for in deriving these figures, and in practice is eliminated entirely by the normal preloading of the rope/terminal connection.

At working load stresses of about one third of the breaking load, this formula predicts relaxation losses of about 7% NBL, but most of this occurs within the first few days, and restressing would virtually eliminate relaxation losses.

An extensive test programme is underway to provide more data on the stress relaxation behaviour under sustained extension over long periods of time, and with various amounts of restressing after a few days.

Creep and stress-rupture

The creep response of a material is clearly related to its relaxation behaviour, although the two are often treated independently since they are usually important in different circumstances and are measured in different ways. A typical creep curve for a rope loaded to a high proportion of its breaking load is shown in Figure 6. Primary creep, immediately after loading, settles down to creep at virtually constant rate (on a logarithmic time basis). For loads which are a significant proportion of the breaking strength of the rope, there follows a tertiary creep phase which leads to failure.

An approximate correlation between stress relaxation and (secondary) creep has been published for pultrusions of the aramid fibre Twaron (12), and some consideration has been given to the subject for Parafil (13). A more detailed study is now underway at Cambridge University.

Creep to rupture, or stress-rupture as it is more commonly known, is undesirable and it is important to be able to predict the lifetime of ropes at different load levels. Tests have been carried out on 60 Tonne (132 kip) NBL ropes at high stress levels, under loading applied by hydraulic jacks, with 'times to break' of up to 5 months. This method of loading is unreliable and inconvenient for long term tests, so dead weight loads are used for lower stress levels. Such tests have been underway now for some time on 1.5 Tonne (3.3 kip) and 3 Tonne (6.6 kip) ropes, with the object of providing sufficient data for engineers to have confidence in the long-term properties of the material. Figure 7 shows the results obtained to date. Some ropes have been under load for nearly two years.

The most realistic theoretical model for the failure of such materials is one based on a reaction rate approach. This predicts a linear relationship between applied load and the logarithm of the 'time to break'. A large number of tests were performed at the Lawrence Livermore National Laboratory (LLNL) on Kevlar 49/epoxy composites (14), which confirmed this model, and also gave some indication of the scatter of the results. Certain empirical factors must still be determined; these have been found from the tests on 60 Tonne (132 kip) ropes, and the predictions of this work for the lifetime of the ropes are also shown Figure 7, represented as 5% and 95% confidence limits. The results obtained so far from the smaller rope tests indicate that these predictions could, if anything, be pessimistic, since many of these results lie above the 95% probability of failure line. It seems reasonable to predict that a Parafil rope would sustain a load equivalent to 50% of its short-term breaking strength for a period of 100 years.

Estimates, based on the scatter of the LLNL data, have been produced elsewhere (15) for the probability of failure at different load levels. These have been converted into load levels to give a 10^{-6} probability of failure at different lifetimes. A more recent estimate, based solely on tests on Parafil ropes (13), gives almost identical predictions for the lifetimes at typical working loads. A cumulative damage technique has been applied to estimate the effect of relaxation of the tendon and creep of the concrete in a prestressing application (10). The combined effect is that a prestressing cable, stressed initially to 49% of its breaking load, would have a 10^{-6} probability of failure after 100 years, whereas a rope loaded by a *constant* force of about 38% of its breaking load would have a similar probability of failure. This is because the high initial stress of 940 N/mm^2 (136,000 psi) reduces rapidly with creep of the concrete and relaxation of the Parafil to about 730 N/mm^2 (106,000 psi) in service. Analogous results can be produced for other loading regimes or desired lifetimes.

Durability

Kevlar is durable under most circumstances. It is affected by ultra-violet light, by a mechanism which involves breaking links within the polymer chains, thus reducing strength. In a Parafil rope, this will not cause *problems, since UV light* is excluded by the thick black sheath.

There is some data available on the hydrolysis of Kevlar in steam at elevated temperatures (>140°C), and also evidence of reduction in strength at ambient temperature in strong acids and alkalis. However, there is no evidence to indicate that there is any reduction in strength in fresh water, sea water or mildly acidic or alkali solutions at normal operating temperatures.

Nevertheless, a test programme has been initiated at Imperial College, which aims to determine what would be the first signs of deterioration. If these are absent in a normal environment, then there will be positive evidence for the durability of aramid fibres.

Fatigue

Work on aramid filaments themselves (16) has shown that fatigue failures due to direct tension-tension loading only occur at a large number of cycles, and then only at stress ranges well above those normally used in real applications. There is also work (17), mainly on other filaments such as Nylon, but also on Kevlar, which indicates that 'fatigue' failures are related to duration of loading, rather than the number of cycles. This would indicate that rope lifetimes are better estimated on a stress-rupture basis, rather than on a fatigue basis. For structures such as bridges, where there are many load cycles, but where each is of short duration, it is probable that failure of the ropes due to cyclic loading would be unlikely.

Tension-tension fatigue tests (18) and tension-bending fatigue tests (19) have been carried out on Parafil ropes. These indicate that failure is caused by inter-fibre fretting, either in the termination, or at the lateral loading point, and that this behaviour is far more significant than true fatigue of the fibre. Figure 8, taken from (18), shows that the tension-tension fatigue behaviour is better than that of conventional steel ropes.

Thermal response

The thermal properties of a material are important in two ways; the response to fire, and the response to normal temperature fluctuations.

Aramid fibres do not burn, but decompose at about 450°C. They retain about one half of their short term strength when heated to about 250°C (20). In the form of a Parafil rope, the sheath, which is thermo-plastic, will melt during a fire, but fire retardants can be incorporated in the formulation. The thermal conductivity of the fibres is extremely low, and this will enhance the material's ability to withstand a fire.

The coefficient of thermal expansion is negative, as determined by tests on bare yarns immersed in distilled water, and is a function of stress (13). At operating stresses of prestressing tendons (about 700 N/mm^2; 100,000 psi), the coefficient of thermal expansion is about -6×10^{-6}. This will have some effect on the design of structures prestressed with Parafil, since the Parafil and concrete will have different coefficients of expansion. However, because of the low conductivity, it is unlikely that daily temperature cycles will have a significant effect on the ropes. Only very slow temperature changes will need to be taken into account. Even when conducting the tests on Kevlar 49 yarns completely immersed in water, it was found that there was a very significant lag in the response of the yarn to temperature changes.

There is some evidence of absorption of water by aramids, which does not affect the strength, but which could have affected the values quoted here. These tests are to be repeated soon with the yarns dry, to separate the effects of temperature from those due to the water.

Bond

Various tests have been carried out to measure the bond between Parafil ropes and concrete (13). However, the bond strengths achieved were very low, (of the order of 0.15 N/mm^2; 22 psi), and for all practical purposes should be ignored. This is not particularly surprising, since the individual yarns are not linked in any way, either to themselves or to the sheath. The sheath itself is smooth, and so cannot be expected to bond significantly to the concrete. Furthermore, since the sheath is made from a thermoplastic, (usually polyethylene), any sustained shear load passing through the sheath would cause large creep strains over a period of time, and any bond that existed would effectively be lost. There is thus no real possibility of using the ropes for pretensioning cables, or as reinforcing bars, where load transfer must be by bond.

IMPLICATIONS FOR PRESTRESSED CONCRETE BEAM DESIGN

Now that the properties of the material are available, the implications for the design of prestressed concrete beams can be considered.

1. The materials are durable, so there is no need to embed them in concrete to provide corrosion protection.

2. Aramid fibres are brittle, so it is not desirable for the ropes to pick up additional strains due to live loads. It would thus be a disadvantage if the ropes bonded to the concrete, so the difficulty of achieving such bond is not a problem. This result may at first sight be surprising, and needs a little explanation.

   In the vicinity of a flexural failure in a beam, cracks will open in the concrete. If the tendon is bonded to the concrete, it is forced, locally, to have very high strains. If the material is ductile, these do not cause a problem; the tendon yields but does not fail. For a brittle material, however, the tendon would snap, thus losing all its tensile force.

3. The working stresses are likely to be determined by stress-rupture criteria, rather than short-term strengths. Initial prestress loads of about 49% of the nominal breaking load would give a probability of failure of about 10^{-6} in 100 years.

The conclusion is that the material is suitable for use as external prestressing tendons for concrete. Indeed, unlike steel, there are no benefits to be gained by embedding the tendons in concrete, either for pre-tensioning or grouted post-tensioning. The ropes are equally useful for the repair of existing structures, as well as for the building of new ones.

BEAM TESTS

As part of the development process for the materials and to check the systems for applying loads to the tendons in practical situations, two beams have been built at Imperial College using Parafil ropes as prestressing tendons.

The first beam, with a length of 5m (16ft 5ins), was prestressed with a single straight 60 Tonne (132 kip) tendon which passed through a plastic duct on the centreline of the beam as shown in Figure 9 (10). There was, however, no attempt made to bond the tendon to the duct, and indeed the rope was wrapped in PTFE tape to reduce further the friction between duct and sheath. The terminals are obviously larger than the rope, and it is difficult to terminate the ropes in-situ, so the tendon was cut to length, fitted with terminals and installed in the duct, before the concrete was cast.

The second beam, on the other hand, was more representative of a practical application, with two 60 Tonne (132 kip) ropes mounted externally to the concrete, and deflected at saddles close to the loading points. This beam was 8m (26ft 3ins) long overall (13). In this case, larger holes were left for the anchors in the end block, so the tendons could be fitted after the beam had been cast. Figure 10 shows the overall beam layout. Full details of the beams and their geometry will be given elsewhere (21), but a summary of the procedures and results is given here.

The beams were simply supported close to their ends, and loaded by two point loads applied through a spreader beam. In both cases, a number of load cycles were applied, each at successively higher loads, until the beam failed. The maximum load on the first cycle was fixed when the first visible cracks were observed.

Beam test results

Figure 11 shows the load deflection curve from the first beam (10); the results from the second beam are similar. After the initial loading, the beam returned to its initial shape, as would be expected, under the action of the restoring force provided by the prestressing cable. Even after unloading from higher loads, when severe cracks were appearing in the beam, most of the deflection was recovered.

The final failure in both beams was characterised by large cracks opening in the tension face, with considerable deflection at virtually constant load. In both cases, final failure occurred by crushing of the top flange, followed by compressive failure in the concrete down the web as the beam tried to carry its own dead weight on a steadily reducing section. In the case of the first beam, the failure stopped when the beam came into contact with support trestles under the beam, with the bottom flange intact. For the second beam, failure continued right through the beam.

In both cases, the Parafil tendons did not appear to be affected by the failure of the concrete. In the first beam, the single tendon was found to be carrying a load of 33 Tonnes (72.6 kips) after failure (*cf* initial prestress of 42 Tonnes; 92.4 kips); this had to be destressed before the beam was dismantled. Unfortunately, the tendon had to be cut to remove it from the beam so it was not possible to test the tendon itself subsequently. In the second beam, however, the tendons could be removed and were subsequently tested to failure in tension. They both failed at loads (69.9 and 68.1 Tonnes; 154 and 150 kips) in excess of the short term breaking load of the tendons (60 Tonnes nominal, normal mean figure about 61.5 Tonnes (135 kip)). Similar increases in strength have been observed after relaxation tests on Parafil (10) and other polymeric ropes. The reason for this increase in strength is not immediately clear, but it is possible that a sustained load (approx 50% of the nominal strength) applied to a rope for a significant period (in this case, about 2 months) will tend to even out the load sharing between filaments (due to differential creep), and thus lead to the bundle having a higher overall efficiency. The possible interaction of bundle theory and visco-elastic behaviour is currently under investigation.

CONCLUSIONS

Parallel-lay aramid ropes, such as Parafil, offer a new material for the designer of prestressed concrete. For the first time, they allow designers to make use of the inherent advantages of externally prestressed concrete without the need to worry about corrosion. Structures will become feasible that, hitherto, could not be built because of the dangers associated with corrosion of steel prestressing tendons.

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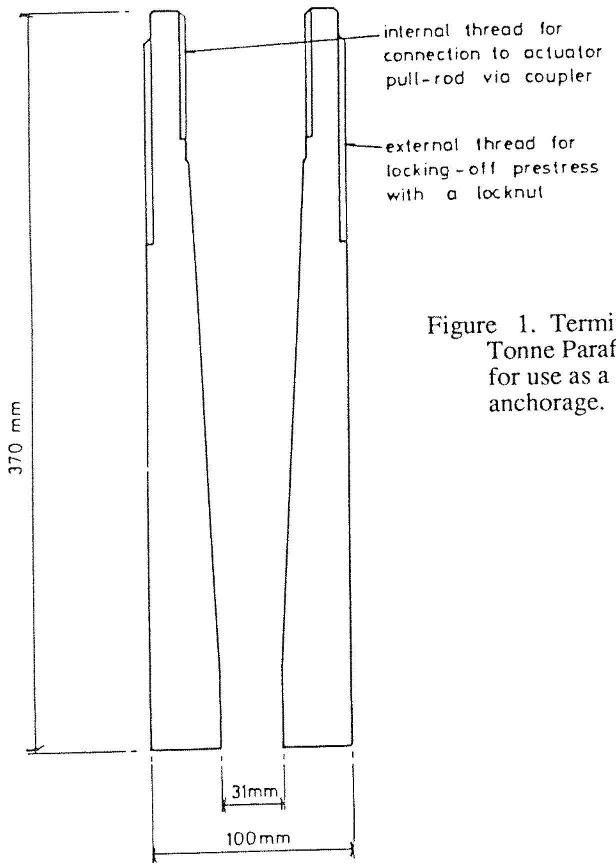
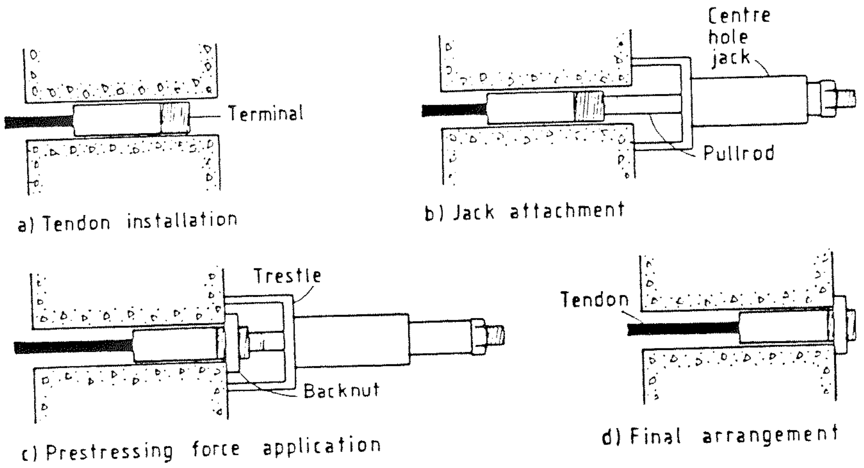


Figure 1. Terminal for a 60 Tonne Parafil rope, modified for use as a prestressing anchorage.



a) Tendon installation

b) Jack attachment

c) Prestressing force application

d) Final arrangement

Figure 2. Stressing sequence for Parafil prestressing tendons.

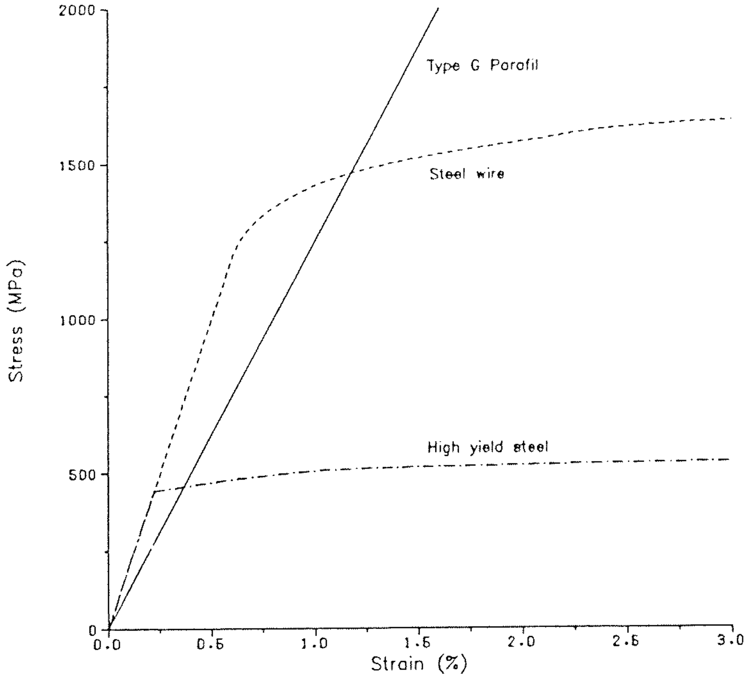


Figure 3. Stress-strain curves for Type G Parafil and steel.

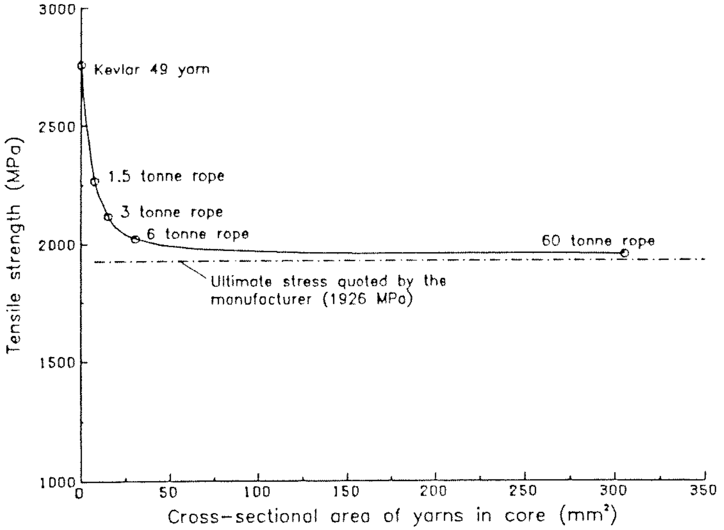


Figure 4. Effect of rope size on strength for Type G Parafil.

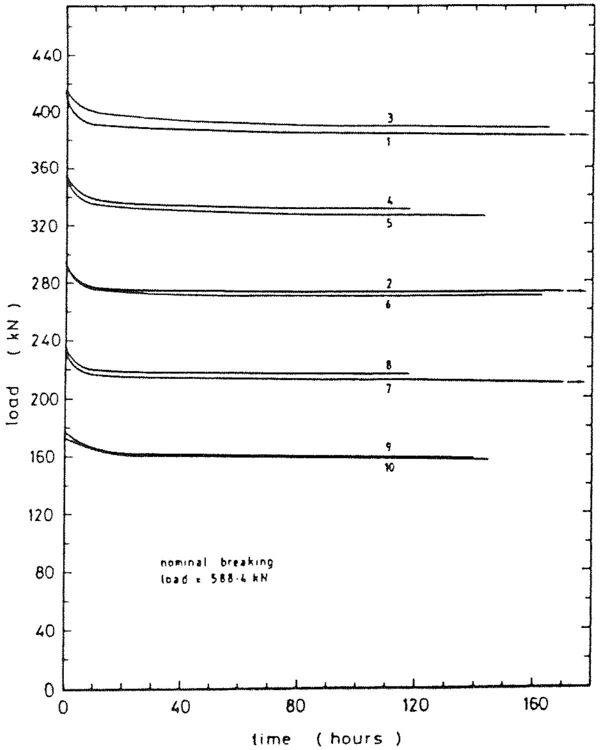


Figure 5. Relaxation behaviour of Type G Parafil ropes.

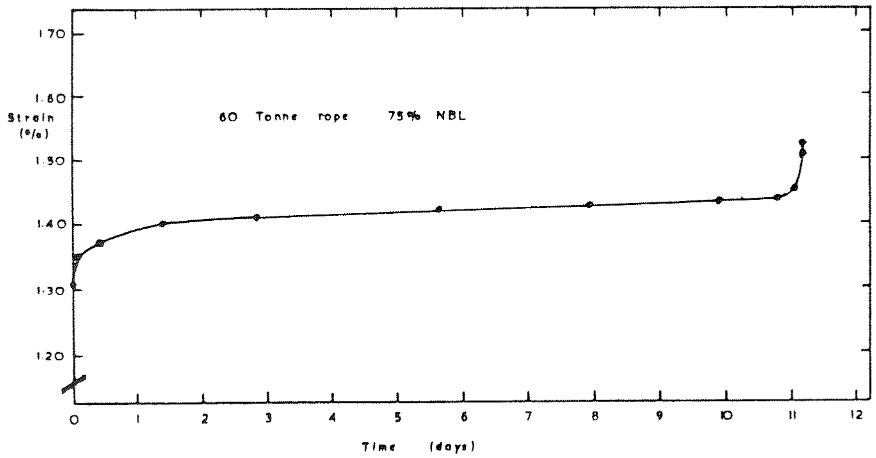


Figure 6. Typical creep behaviour at high load levels.

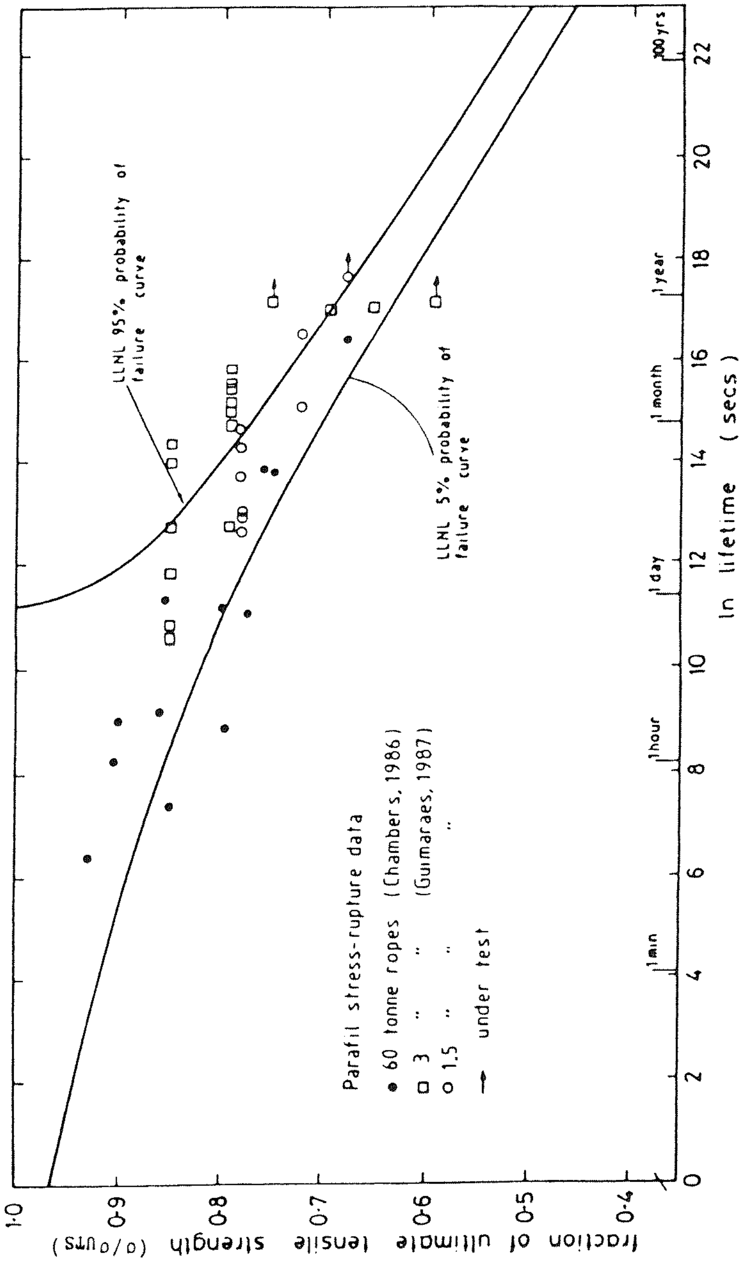


Figure 7. Stress rupture behaviour of Type G Parafil ropes.

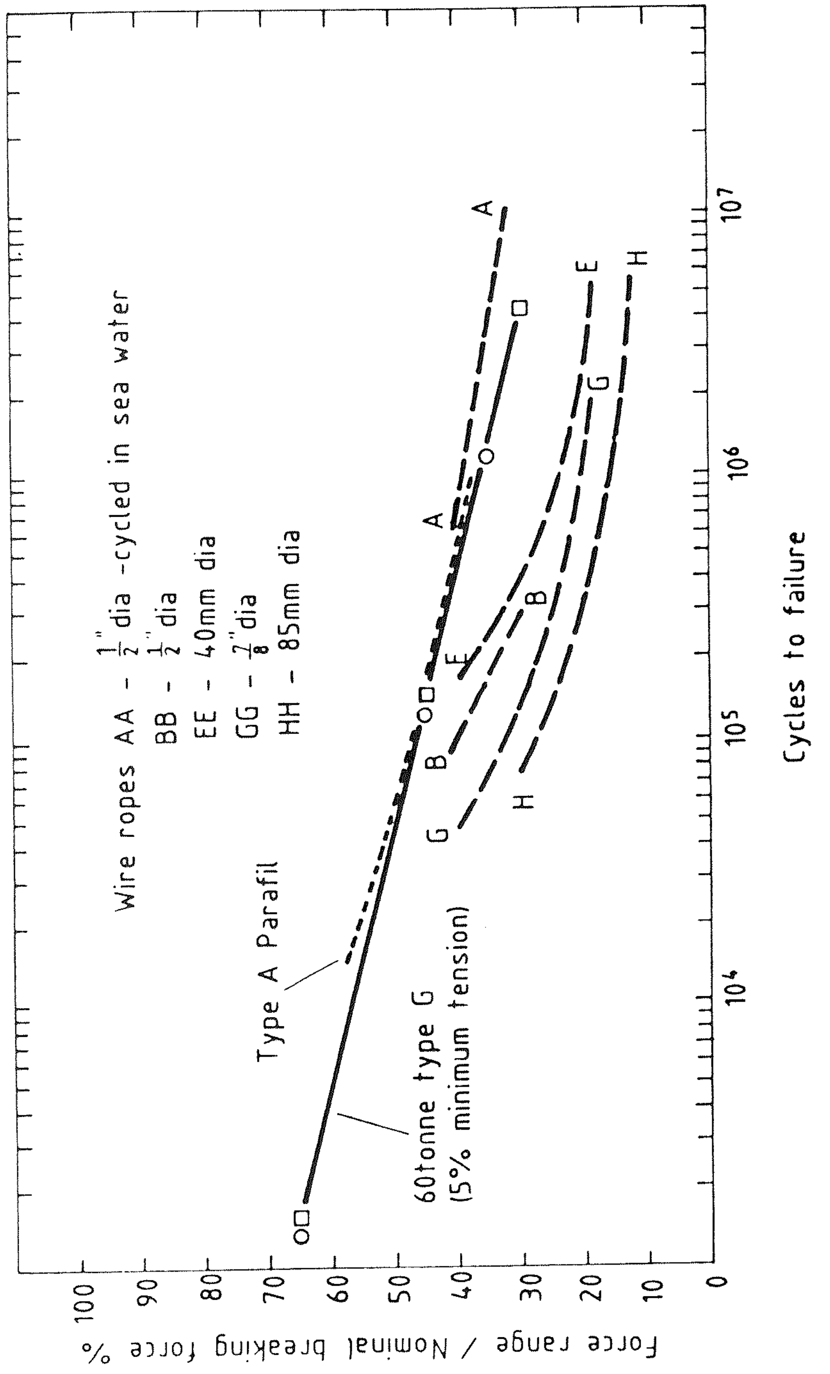


Figure 8. Fatigue response of Parafil and wire ropes.
(from reference 18.)

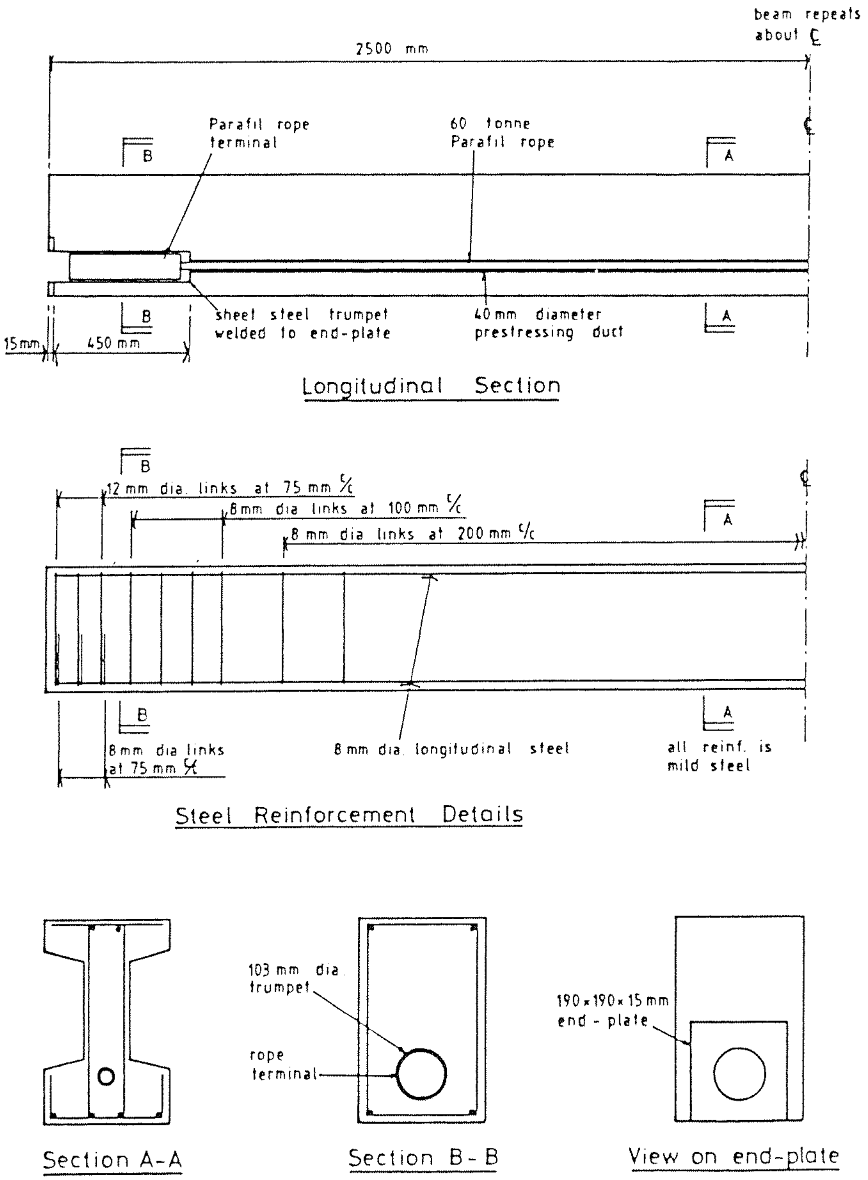


Figure 9. Details of 5m Parafil prestressed beam.

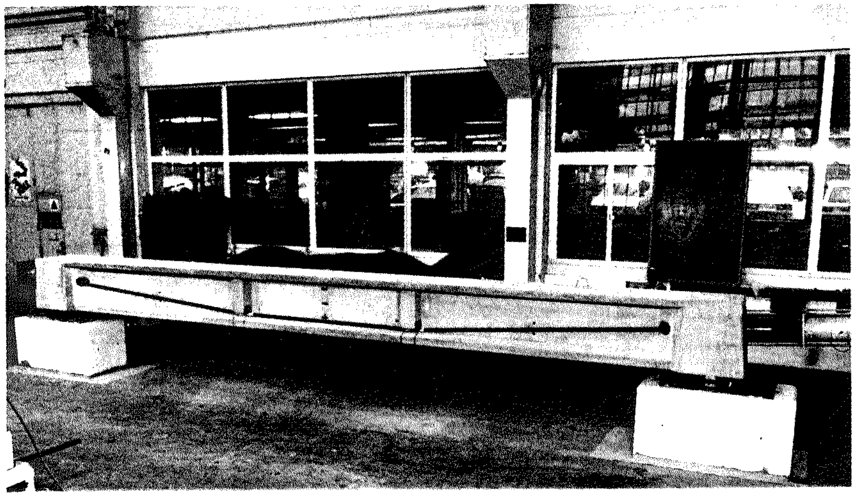


Figure 10. 8m beam prestressed with two 60 Tonne Parafil tendons.

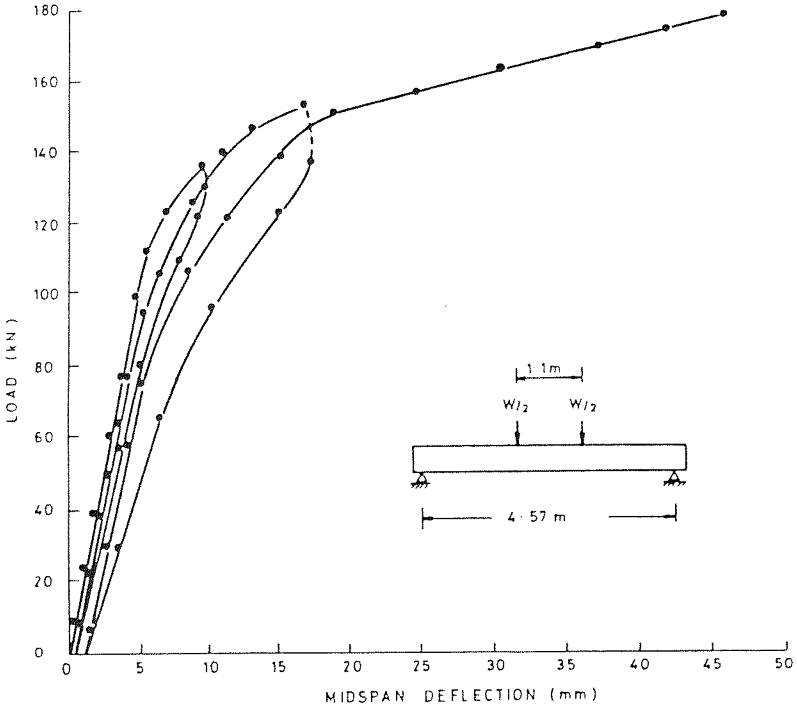


Figure 11. Load deflection curve for 5m Parafil prestressed beam.