External Prestressing
with Polyaramid Ropes

C.J.Burgoyne

Dept of Civil Engineering
Imperial College
London SW7 2BU
September 1988

Dr C.J.Burgoyne is a lecturer at Imperial College in London, 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. Dr Burgoyne is shortly to take up an appointment at Cambridge University.

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 lack of the corrosion protection that is normally provided by the concrete. In the absence of the passivating environment provided by the highly alkaline cement matrix, the steel will corrode very rapidly unless extensive measures are taken to prevent corrosion occuring.

In the United Kingdom, 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.

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). 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 act like springs when stretched, and the axial stiffness of the rope is 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, 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.

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 variety of methods are possible, including external wedges, bond or cast resin cones, but for a variety of reasons, 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 gripping force between the spike and the external body, so that all the fibres are anchored. The length of the spike can be chosen to ensure that the transverse stresses are within the capacity of the fibres.

Figure 1 shows a typical termination for parallel lay aramid ropes. Once the load has been transmitted from the fibres to the terminal body, further connection to the structure can be made by fitting a variety of devices, such as clevis pins, anchorage plates, or whatever is required. The figure shows such a terminal modified for use as a prestressing tendon. The terminal body has two threaded regions; the inner thread is used for connection to a pull rod which is attached to the jack during stressing, while the outer thread is used to provide a connection for a permanent back nut, which also allows

Tonne ropes already contain many thousands of filaments.) The largest rope tested to date (1500 Tonnes) 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.

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)

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

where   r is the stress-relaxation expressed as % NBL

           (NBL = Nominal Breaking Load)

           f is the initial stress expressed as % NBL

           t is the time in hours

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. 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 log. 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.

A correlation between stress relaxation and (secondary) creep has been published for pultrusions of the aramid fibre Twaron (12), and a similar correlation for Parafil is in preparation (13).

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 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 and 3 Tonne 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 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 60 Tonne tests, and the predictions of this work for the lifetime of the ropes are also shown Figure 7, represented as 5% and 95% confidence limits. Clearly, the results obtained so far from the smaller rope tests indicate that these predictions could, if anything, be pessimistic; 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.

Predictions, 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 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 initial high stress of 940 N/mm^2 reduces rapidly with creep of the concrete and relaxation of the Parafil to about 730 N/mm^2 in service. Analogous arguments 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, and 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 deg 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 high stress ranges. There is also work on other filaments (17), such as Nylon, which indicates that 'fatigue' failures are related to duration of loading, rather than the number of cycles. Thus, lifetimes are better estimated on a stress–rupture basis, rather than on a fatigue basis.

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), 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.

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), 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 bond 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.

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, which makes the ropes equally useful for the repair of existing structures, as well as 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, was prestressed with a single straight 60 Tonne 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 ropes mounted externally to the concrete, and deflected at saddles close to the loading points. This beam was 8m 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 occured 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 after failure (*cf* initial prestress of 42 Tonnes); 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) in excess of the short term breaking load of the tendons (60 Tonnes nominal, normal mean figure about 61.5 Tonnes). 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. This possible explanation will be tested in due course.

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 advatages 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.

References

1. O'Niell W., "Easing the tension over Braidley Road Bridge, New Civil Engineer", pp12–13, 31st August 1978.

2. Lord J.E.D., Gill J.M. and Murray J., "The new Redheugh Bridge", Proc. Inst. Civ. Engrs, Vol 86, pp497–522, May 1984.

3. Stafford D.G. and Watson S.C., "Cables in trouble", Civil Engineering, p38, April 1988.

4. Stafford D.G. and Watson S.C., "A current world-condition survey of cable elements on stayed-girder bridges", Proc. 1st Oleg Kerensky Memorial Conference on Tension Structures, pp12/2–17/2, London, June 1988.

5. Tilly G.P., "Performance of bridge cables", Proc. 1st Oleg Kerensky Memorial Conference on Tension Structures, pp22/4–28/4, London, June 1988.

6. Smith N.J. and Withey K., "River Coquet Bridge: an assessment of the use of precast webs in a box-girder bridge", Proc. Inst. Civ. Engrs, Vol 82, pp153–168, 1987.

7. Woodward R.J. and Williams F.W., "Collapse of Ynys-y-Gwas Bridge, West Glamorgan", Proc. Inst Civ. Engrs, Vol 84, pp635–670, Apr. 1988.

8.   Ferer K.M. and Swenson R.C., "Aramid fibre for use as oceanographic strength members", Naval Res. Lab., Washington D.C., Report No. 8040, 1976.

9.   Burgoyne C.J., "Polymers for reinforcing and prestressing concrete", in: "Structural polymer composites and polymers in the construction industry", ed L. Holloway, Thomas Telford, London, 1988.

10. Chambers J.J., "Parallel-lay aramid ropes for use as tendons in prestressed concrete", Ph.D. Thesis, University of London, 1986.

11. Coleman B.D., "On the strength of classical fibres and fibre bundles", Journ. Mechs. and Phys. Solids, Vol 7, pp60-70, 1958.

12. Gerritse A. and Schurhoff H.J., "Prestressed concrete structures with Arapree; Relaxation", Proc IABSE Symp., Paris 1987.

13. Guimaraes G.B., "Parallel-lay aramid ropes for use in structural engineering", Ph.D. Thesis, University of London, in preparation.

14. Glaser R.E., Moore R.L. and Ciao T.T., "Life estimation of aramid/epoxy composites under sustained tension", Composites Technology Review, Vol 6, No 1, pp26-35, 1984.

15. Chambers J.J., "Long term properties of Parafil", Proc. Symp. on Engineering Applications of Parafil Ropes, ed. C.J.Burgoyne, pp21-28, London, January 1988.

16. Wilfong R.E. and Zimmerman J., "Strength and durability characteristics of Kevlar aramid fibre", In: "Fibre Science. Journ. of Appl. Polymer Sci., Applied Polymer Symposium", ed M. Lewin, Vol 31, pp1-21, 1977.

17. Kenney M.C., Mandell J.F. and McGarry F.J., "Fatigue behaviour of synthetic fibres, yarns and ropes", Journ. Mat. Sci., Vol 20, pp2045-2059, 1985.

18. Crawford H. and McTernan L.M., "'Fatigue' properties of Parafil", Proc. Symp. on Engineering Applications of Parafil Ropes, ed. C.J.Burgoyne, pp29-38, London, January 1988.

19. Burgoyne C.J., Hobbs R.E. and Strzemiecki J., "Tension bending and sheave bending fatigue of parallel lay aramid ropes", to be presented OMAE Europe 89, The Hague, March 1989.

20. Guimaraes G.B., "Short term properties of Parafil", Proc. Symp. on Engineering Applications of Parafil Ropes, ed. C.J.Burgoyne, pp 13-20, London, January 1988.

21. Burgoyne C.J., Guimaraes G.B. and Chambers J.J., "Full-scale tests on beams prestressed with Parafil Ropes", in preparation.

internal thread for
connection to actuator
pull-rod via coupler

external thread for
locking-off prestress
with a locknut

370 mm

31mm

100mm
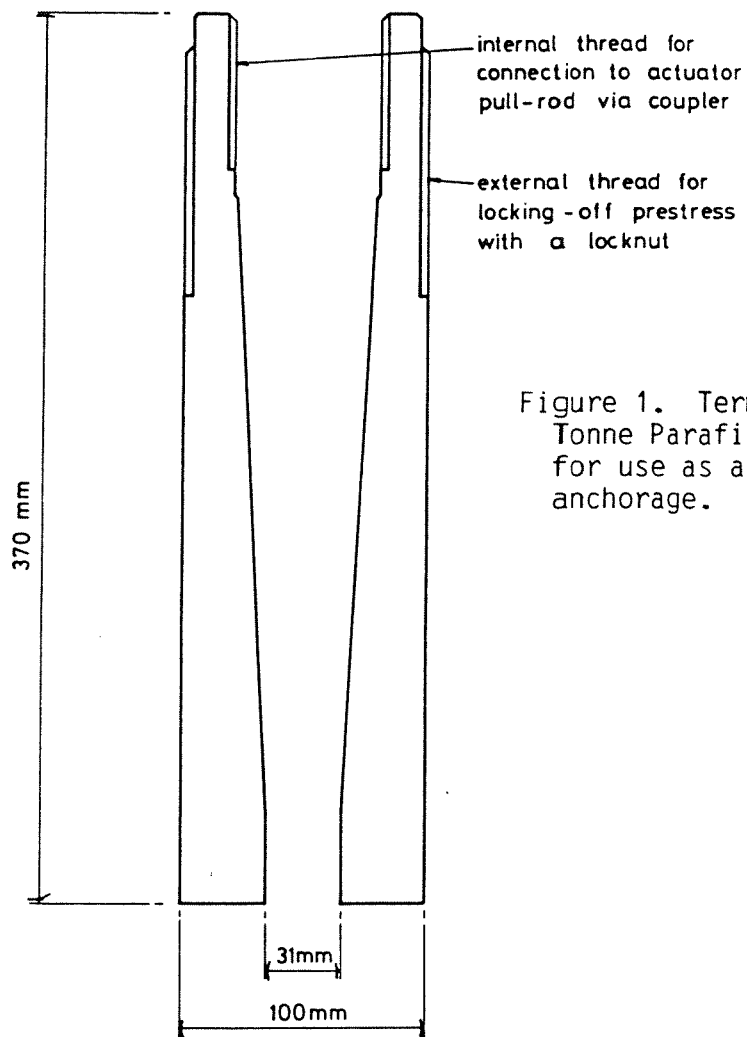
Figure 1. Terminal for a 60
Tonne Parafil rope, modified
for use as a prestressing
anchorage.

Terminal

a) Tendon installation

Centre
hole
jack

Pullrod

b) Jack attachment

Trestle

Backnut

c) Prestressing force application

Tendon

d) Final arrangement
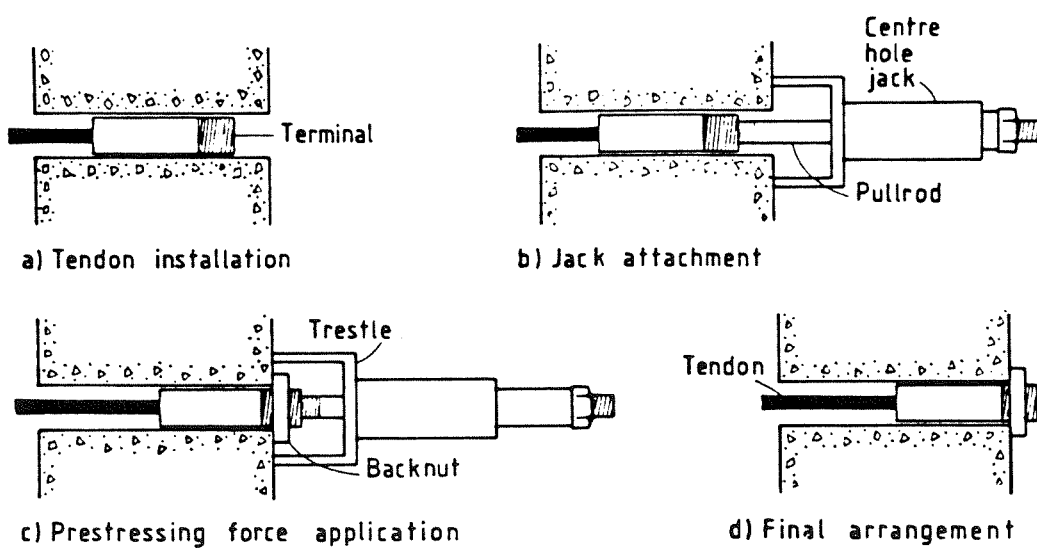
Figure 2. Stressing sequence for Parafil prestressing tendons.
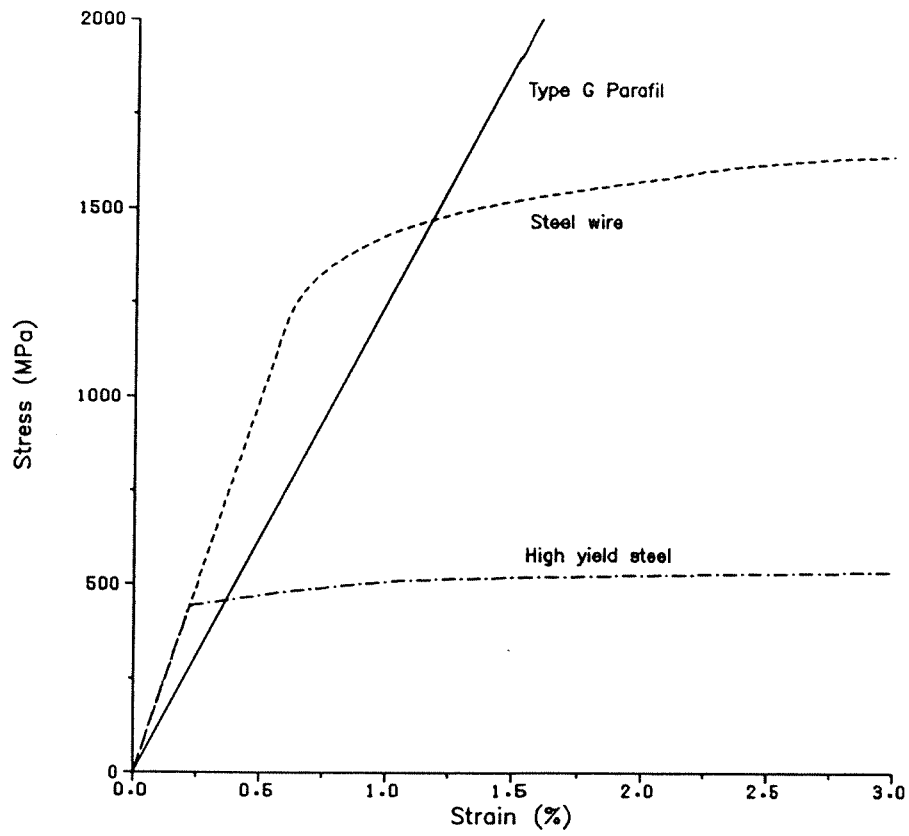
Figure 3. Stress-strain curves for Type G Parafil and steel.
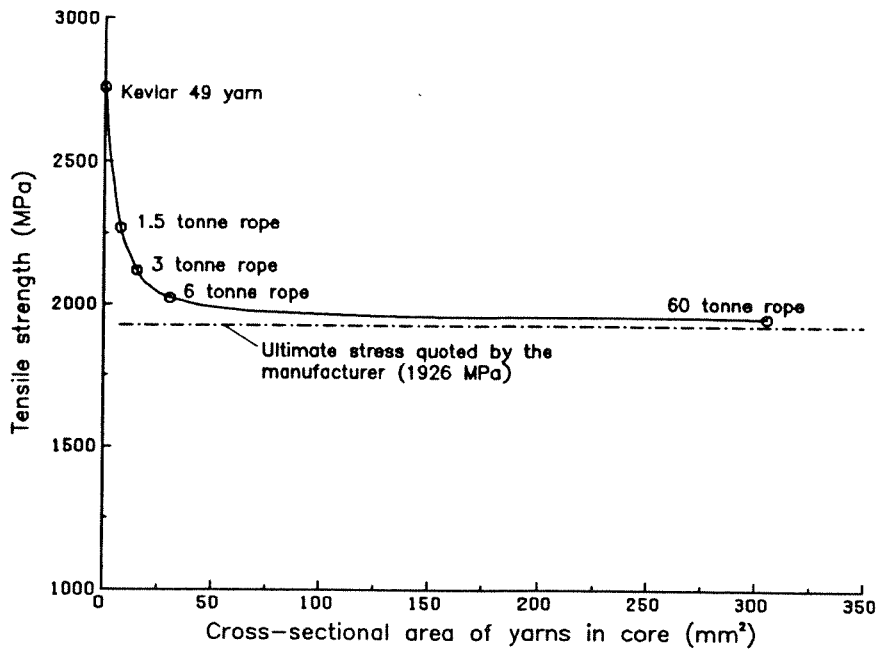
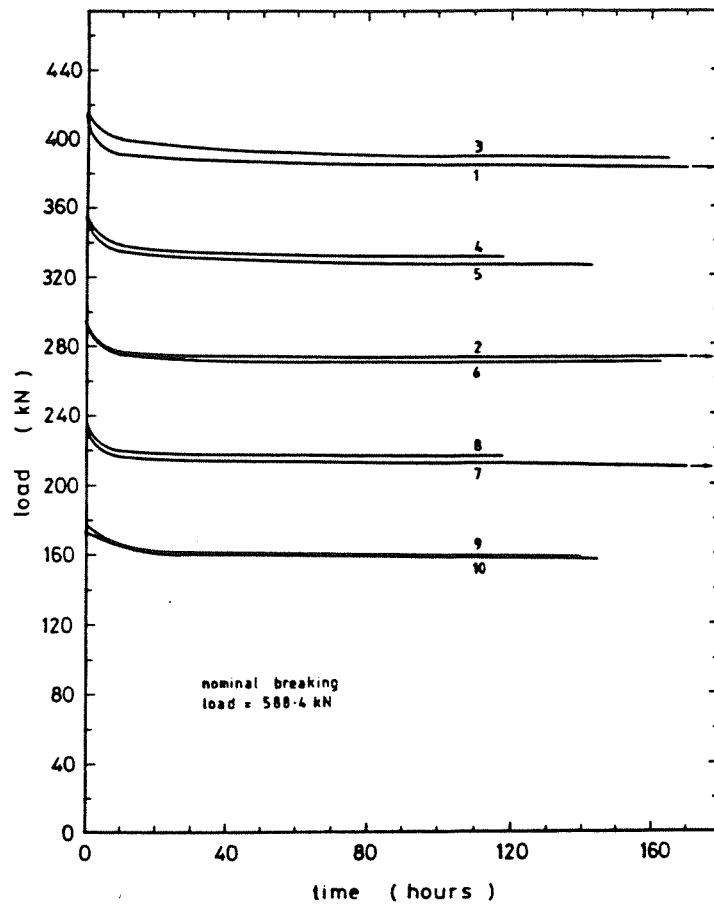Figure 4. Effect of rope size on strength for Type G Parafil.

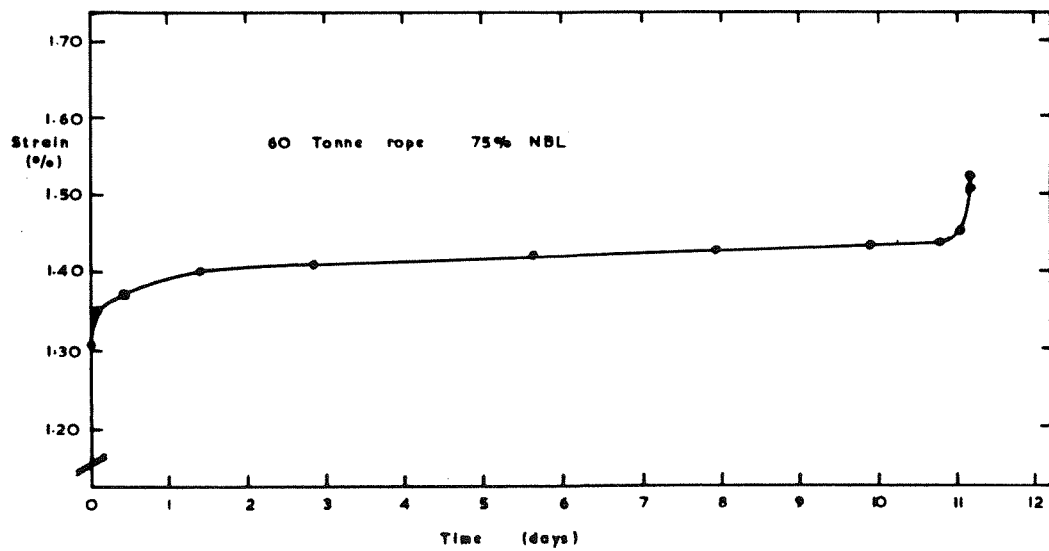Figure 5. Relaxation behaviour of Type G Parafil ropes.

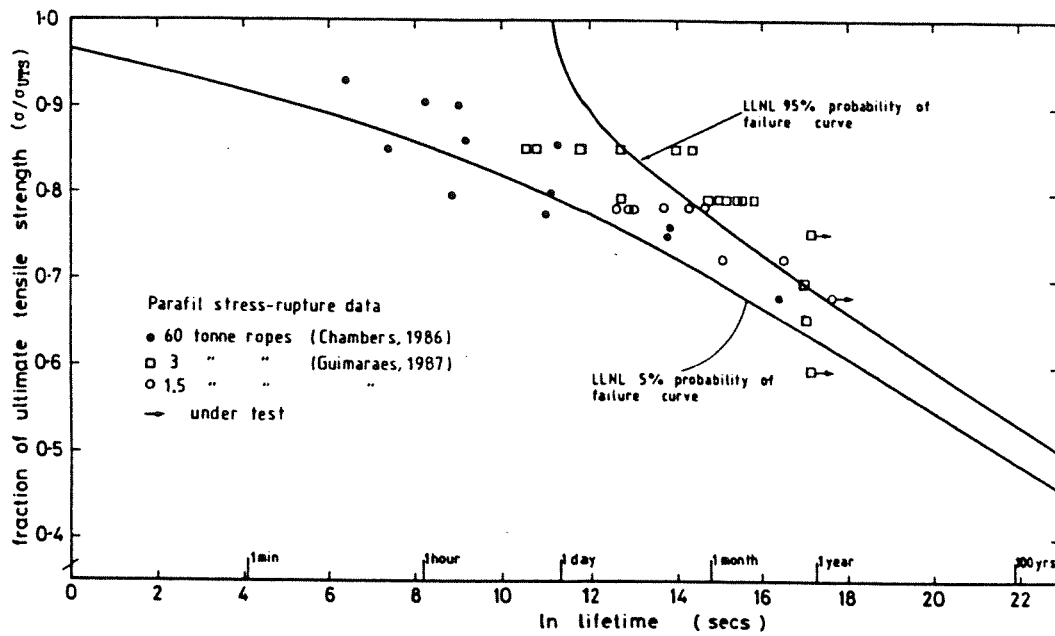Figure 6. Typical creep behaviour at high load levels.

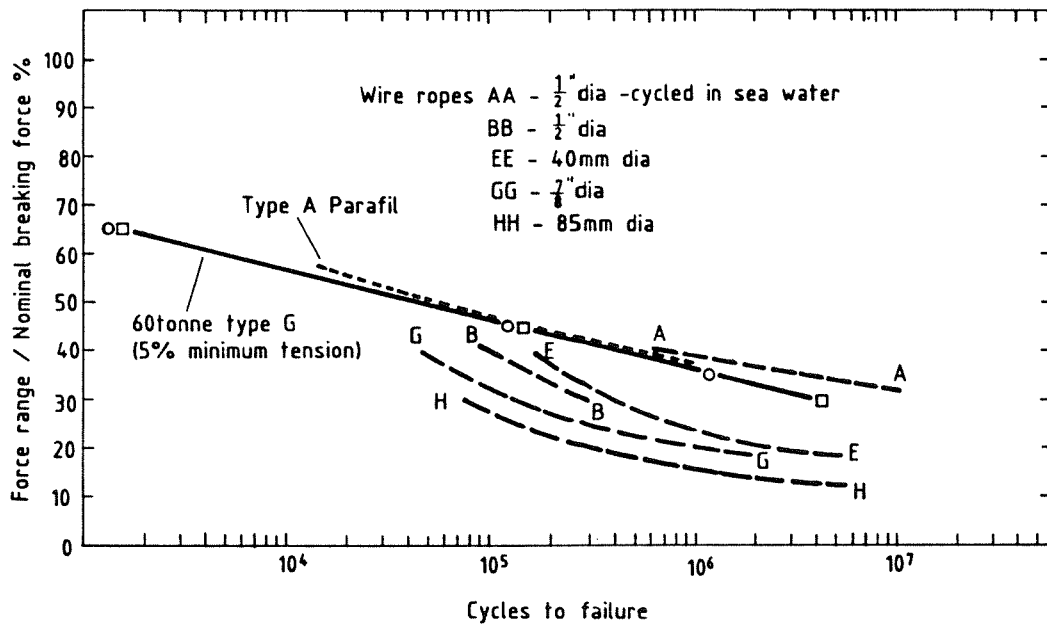Figure 7. Stress rupture behaviour of Type G Parafil ropes.

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

beam repeats
about ℄

2500 mm

Parafil rope   60 tonne
terminal   Parafil rope

B   A

℄

B   sheet steel trumpet   40 mm diameter   A
           welded to end-plate   prestressing duct

15mm   450 mm

Longitudinal Section

B
12 mm dia. links at 75 mm ℃
    8mm dia links at 100 mm ℃
                                                A
        8 mm dia. links at 200 mm ℃

℄

B   A

8mm dia links   8 mm dia. longitudinal steel   all reinf. is
at 75 mm ℃   mild steel

Steel Reinforcement Details

103 mm dia.
trumpet

190×190×15 mm
end - plate

rope
terminal

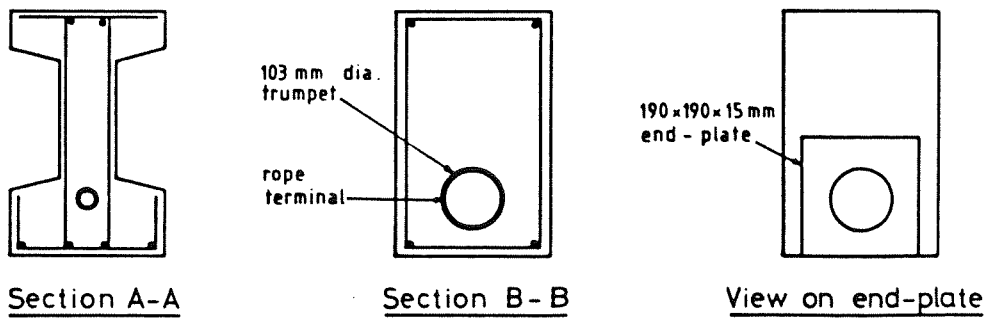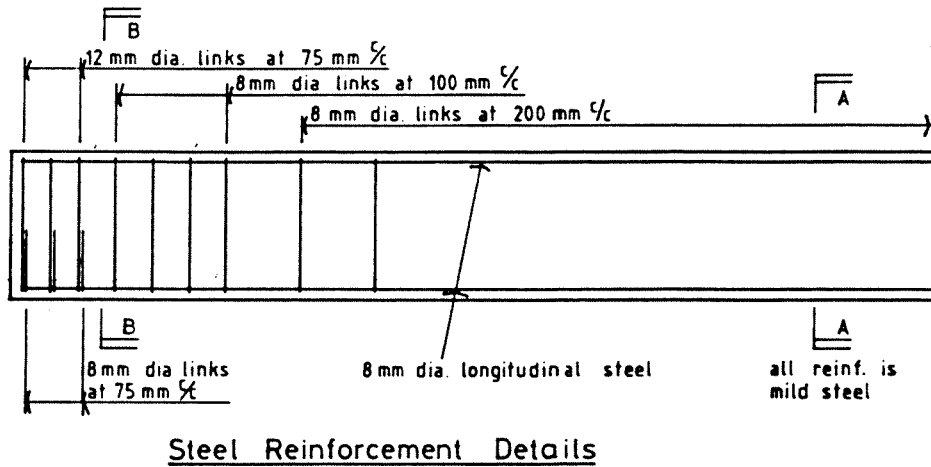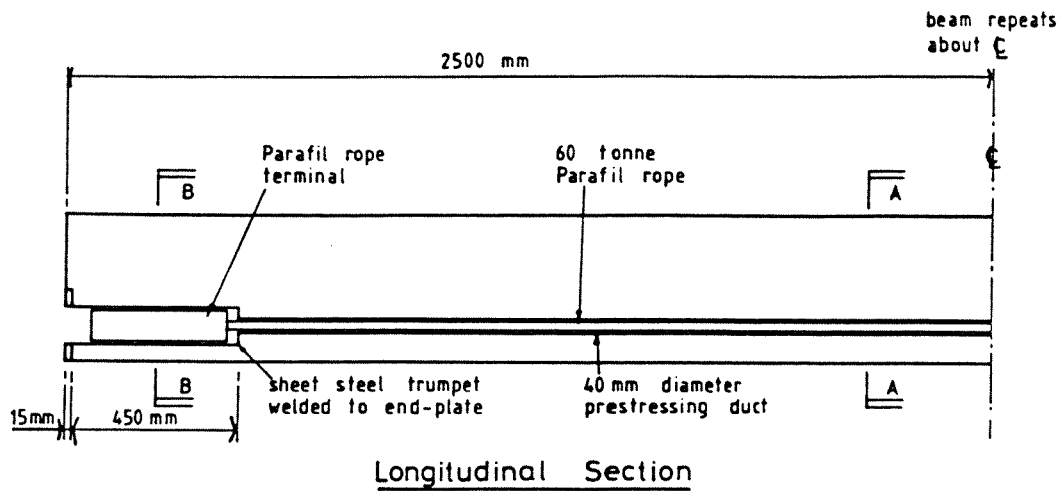### Section A-A   Section B-B   View on end-plate

Figure 9. Details of 5m Parafil prestressed beam.

Photograph here.

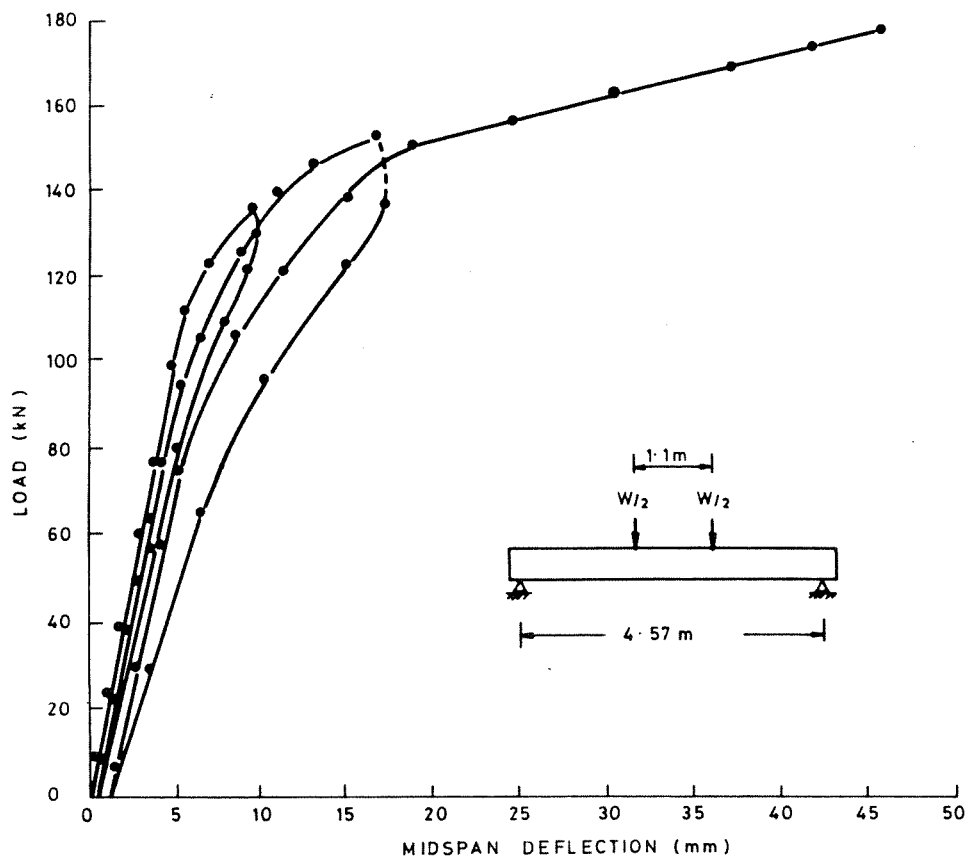Figure 10. 8m beam prestressed with two 60 Tonne Parafil tendons

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