Developments in the use of Unbonded Parallel-lay Ropes for Prestressing Concrete Structures

C.J.Burgoyne

Presented at FIP 93 Symposium
Kyoto, Japan, October 1993

Engineering Department
University of Cambridge
Trumpington St.
Cambridge CB2 1PZ

Developments in the use of unbonded parallel-lay ropes for prestressing concrete structures.

C.J.Burgoyne
Lecturer, University of Cambridge
England

SUMMARY

This paper describes the use of unbonded tendons, made from parallel filaments of aramid yarns, contained within a sheath with no resin. The principles of the use of such tendons are discussed, as are the methods of attaching terminations and anchoring the ropes.

1. INTRODUCTION

The advent of new materials such as glass, carbon and aramid fibres has ushered in a new range of prestressing systems. These offer potential benefits, including most importantly, lack of corrosion. Most of these systems are made from resin based pultrusions which are (or at least can be) bonded to the concrete, by analogy with steel tendons. But an alternative route for development is from ropes; one such system is described in this paper. The system was developed with a view to maximising the strength and stiffness of fibre ropes for mooring offshore facilities (1). Once the technology was developed, however, it was clear that the ropes had applications in the structural engineering field, especially in the form of prestressing tendons (2).

2. ARAMID FIBRES AND PARALLEL-LAY ROPES

Aramid fibres are today made by a number of companies, under a variety of trade names. The first such fibre was Kevlar (developed by Du Pont), which has been followed by Twaron (developed by Akzo), and Technora (developed by Teijin). Kevlar and Twaron are virtually identical, while Technora is a slightly more complex polymer but with very similar properties.

Aramid fibres are essentially made up from long straight chains of benzene rings, with extra carbon and nitrogen atoms between the rings. These atoms support oxygen and hydrogen atoms respectively which form multiple (but weak) hydrogen bonds between adjacent chains. The aramid molecules are liquid crystals when in solution, which leads to the formation of long parallel chains which achieve their strength by the cross-linking formed by the hydrogen bonds. In what follows, ropes made from Kevlar yarns will be described, but it must be expected that most of the results would be the same for ropes made from any of the aramid fibres.

Traditional rope construction is based on natural materials, in which any single fibre is relatively short (less than 50 mm in most cases). Ropes therefore had to be twisted to achieve load transfer between filaments, and in most cases involved several layers of structure; filaments twisted together to make yarns, which were twisted together to make rope yarns, then strands, sub-ropes and finally ropes. Any individual filament thus followed a serpentine path through the rope, which meant a significant loss of strength, and more importantly, stiffness. The advent of very long single filaments meant that this limitation could be overcome. By placing the fibres parallel to one another, it became possible to maximise the strength and the stiffness of the resulting rope.

Parallel-lay ropes, incorporating either polyester or aramid fibres, are now made by Linear Composites Ltd, under the trade name Parafil. The ropes have an external polyethylene sheath to give the rope some structure and to protect the core yarns from ultra-violet light. They were first made in the 1960s, and have been applied to offshore moorings, stay cables for radio antennae, supports for overhead electric wiring, stay cables for roofs, and as prestressing cables. They are now marketed jointly with VSL International.

3. TERMINATIONS AND STRESSING SYSTEMS

In order that the full strength of the ropes can be developed, an efficient termination system is required. External wedges are not ideal, as the ropes have spaces between the filaments in the core, and also because external wedges tend to set up hoop stresses in circular elements so do not grip the central core completely.

The system adopted for these ropes consists of a central spike which grips the fibres against a conical barrel. The transverse forces go through every filament in the rope, which then develops friction with its neighbours and with the barrel. In tension tests, ropes terminated with these fittings fail in the body of the rope, rather than in the termination, indicating that the terminals develop the full strength of the rope.

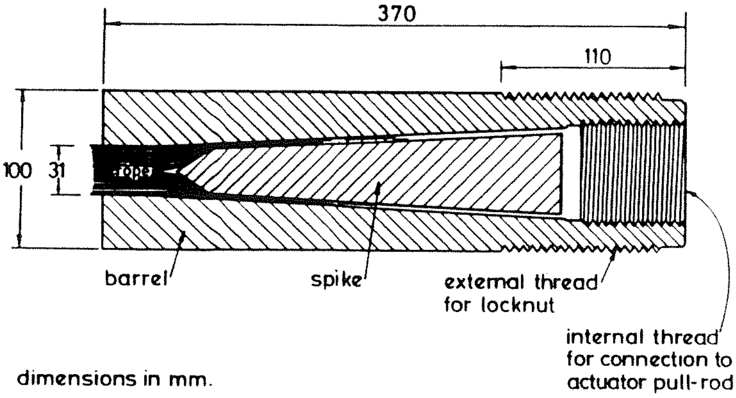


Figure 1.

Termination for a 60 tonne break load rope for use in prestressing.

For prestressing applications (3), the terminals are threaded twice (Figure 1); internally to receive a pull-rod which can be attached to a jack, and once externally to receive a back-nut to form the permanent anchorage. The stressing procedure (4) is shown in Figure 2.

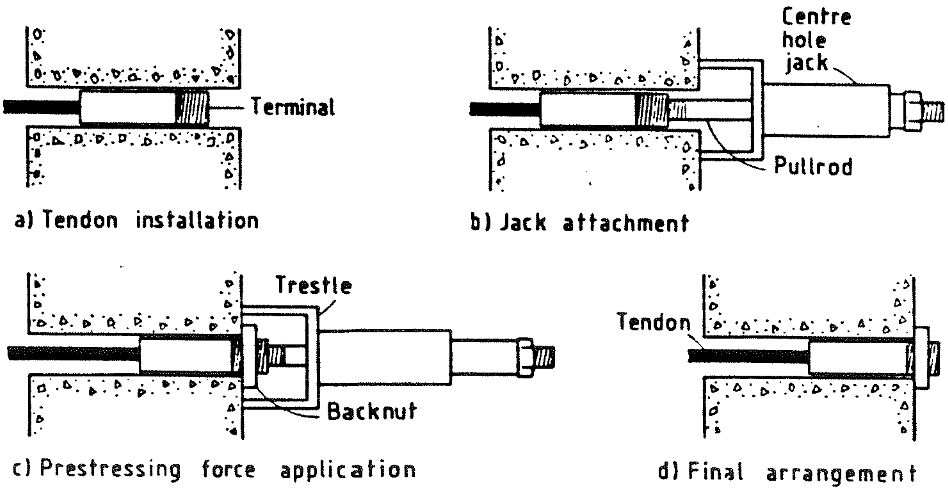


Figure 2.

Stressing system.

4. SHORT-TERM PROPERTIES

Strength

Even with a parallel-lay rope, it is not possible to develop the full strength of the fibres, since variability of the fibres means that the weaker fibres fail earlier and shed more load onto the stronger ones. There is a size effect, which is adequately explained by bundle theory (4,5,6), shown in Figure 3. For all practical rope sizes, the strength is the asymptotic strength quoted by the manufacturers (1930 N/mm2).

Fatigue

The fatigue characteristics of aramid fibres are very good (7). The resistance to tension-tension fatigue is better than that of steel, and is probably due to cumulative damage caused by stress-rupture (8), rather than simply the number of cycles. When 'fatigue' failures do occur, they are normally due to fretting of fibres over one another. This can only occur at the terminations, or at loading points, and the variation in force in prestressing tendons, especially when unbonded, is extremely low. Thus, it is not believed that fatigue is a problem in prestressing applications.

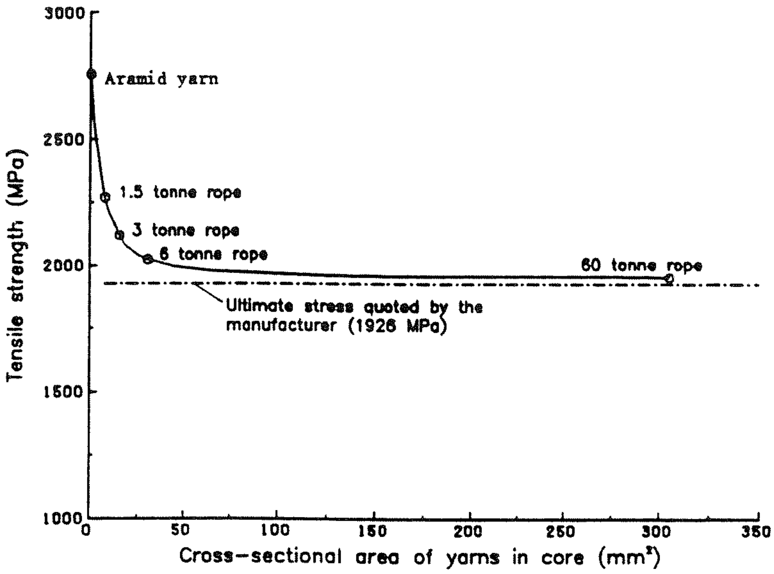


Figure 3.

Strength of rope as a function of rope size.

Fire resistance

Aramid fibres do not melt or support combustion, and very closely related materials (e.g. Du Pont's fibre Nomex) are widely used for making fire resistant clothing for firefighters. Nevertheless, aramids decompose at about 450 °C, and lose about half their strength at about 250 °C (4). The thermal conductivity of aramids is very low, so there will be a shielding effect in large ropes. It may be necessary to provide enhanced fire resistance for cables made from aramids in exposed situations. This could be done by clip-on covers where the prestressing cable must be outside the concrete, which would maintain the ability to inspect the cables.

5. LONG-TERM PROPERTIES

Creep, relaxation and loss of prestress

Aramid fibres offer significantly lower creep than most other fibres used in rope making (9); indeed, for many rope applications the creep is negligible. But when used for prestressing concrete, engineers are interested in the creep as a proportion of the initial extension, since this governs the amount of prestressing force lost.

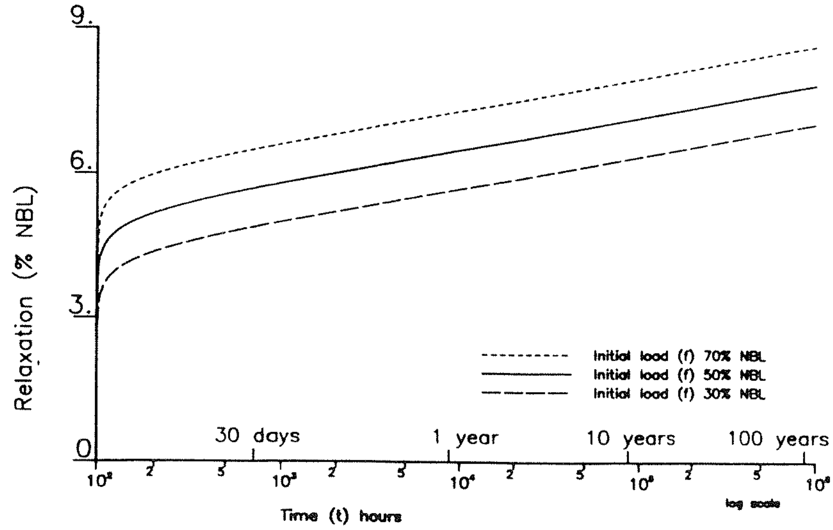
Total creep strains are of the order of 0.13%, which can be compared with a rope extension (when stressed to about 50% of its initial break load), of about 0.8%. Thus, we can expect to lose something like 16% of the initial prestress force in a parallel-lay rope tendon.

Figure 4 shows predicted stress-relaxation figures for different ages and for different initial stresses (expressed as percentages of the nominal break load NBL), based on a series of rope tests (3). It will be seen that they agree quite closely with the limiting value given above.

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

Figure 4.

Predicted relaxation of ropes at different load levels



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

Stress rupture

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

Stress rupture is clearly related to creep and relaxation. At higher stresses, materials creep more, and fail in a shorter period of time than at low stresses. There are strong theoretical arguments, related to the activation energy of the creep process, why there should be a linear relationship between the applied stress and the logarithm of the lifetime of the material. This is indeed observed in tests on both Parafil ropes and on Kevlar yarns. Figure 5 shows values of lifetimes as measured in tests on Parafil ropes, and compares them with theoretical predictions based on tests performed on Kevlar 49 and epoxy bars. The results have been normalised with respect to the short term strength, because of the bundle theory effects described above.

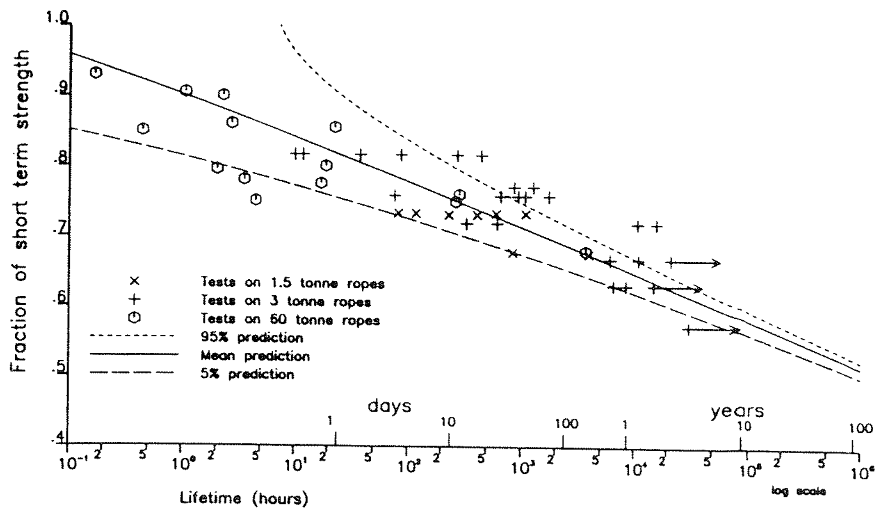


Figure 5.

Stress-rupture results compared with predictions.

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

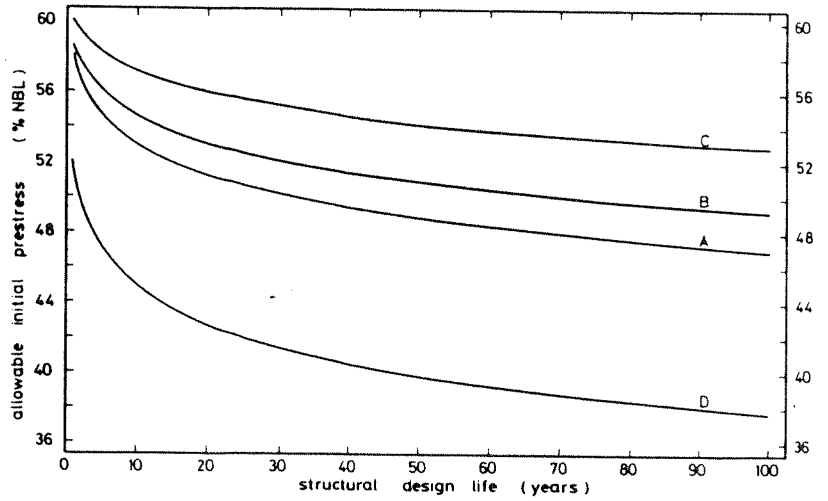
Work is currently underway identifying the cumulative damage rule that must be applied if a rope is subject to varying loads. The most likely rule appears to be one where the rope sustains stress rupture damage as a linear proportion of the lifetime that it spends at that load (3). This allows the stress rupture lifetime to be calculated where the load is reducing as the prestress force drops off because of concrete creep and tendon relaxation.

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

These ideas can all be combined. Figure 6 shows allowable initial prestressing forces in a beam to give a 10^{-6} chance of failure due to stress rupture for a given design life (4). Curve D shows the maximum allowable force for a constant load, but curves A, B and C show the situation for minimum, typical and maximum prestress losses respectively. For the case of typical losses, an initial prestressing force that is about 10% higher can be allowed, since the force will subsequently reduce, thus reducing the stress rupture damage that is taking place.

Figure 6.

Allowable initial prestress for different design lives and different amounts of loss of prestress.



Durability

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

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

6. PRESTRESSING APPLICATIONS

Thorpe Marsh Power Station.

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

Beam tests

Tests have been carried out on two beams prestressed with Parafil to demonstrate the feasibility of producing structural elements in this way (9). Two designs were produced; the first had a single, straight unbonded tendon, contained within a duct on the centreline of a simple I-beam, while the second had two external deflected tendons, one on each side of a T-shaped cross-section (Figure 7). In each case the tendons had a nominal break load of 60 tonnes, prestressed to about 50% of their short term strength.

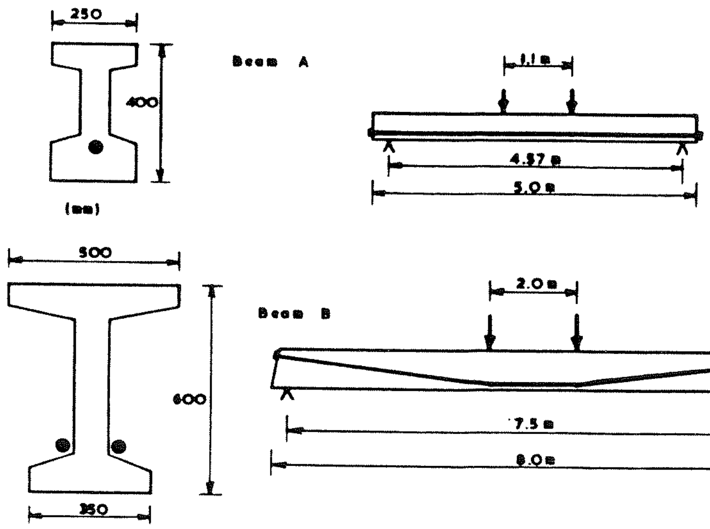


Figure 7.

Test beams.

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

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

The total loss of prestress in both tendons of the second beam, due to shrinkage and creep of concrete and due to stress relaxation in the tendons, is shown in Figure 8. The tendons were tensioned initially to approximately 22% of their tensile strength, when the age of concrete was 10 days. Losses of 13% and 14% of the initial force were observed in the two tendons after 23 days, when the full prestressing force was applied. Over this period of time the beam was subjected only to its own weight. 43 days after the application of the full prestressing, the losses of prestress under service load were 12% in tendon 1 and 11% in tendon 2. It can be seen in the figure that most of the losses occurred within the first day after prestressing. From then on the curves show a very low rate of loss. These figures are very similar to losses to be expected in steel tendons.

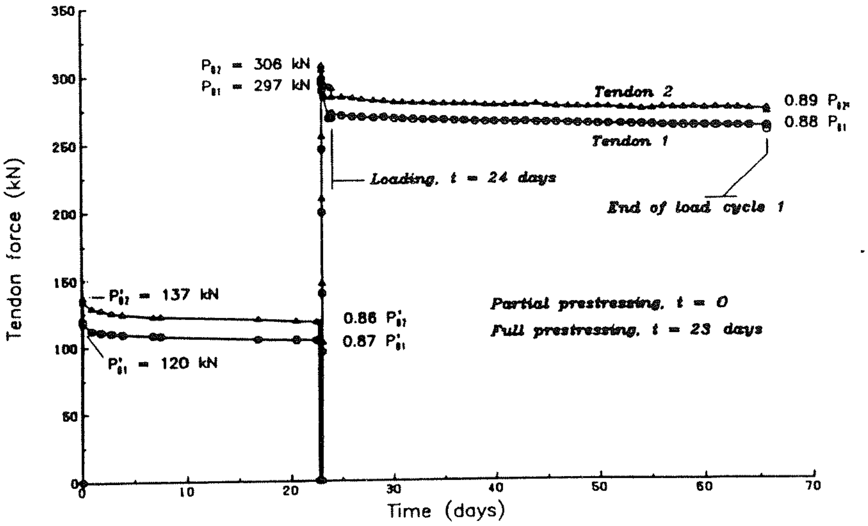


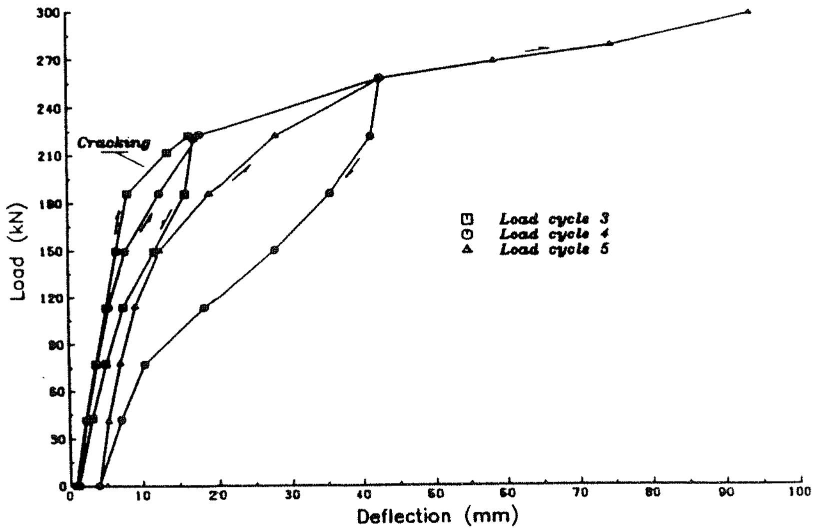
Figure 8.

Loss of prestressing force with time.

Ultimate load tests were carried out on both beams, which responded as expected. After passing the cracking load, the stiffness reduced considerably; when unloaded from the cracked (but still elastic) state, the stiffness remained lower until the cracks had closed up, but the full elastic stiffness was recovered and there was virtually no permanent set. When loaded until failure, both beams showed considerable curvature at virtually constant load, with large cracks forming in the bottom of the beam. Failure occurred in both beams by crushing of the top flange. Figure 9 shows the load deflection curves for the second beam; the results for the first are similar. Even though failure of the top flange concrete precipitated the final failure, there was a lot of warning of failure as the cracks opened up.

Figure 9.

Load-deflection response of beam showing ductility at the ultimate load.



7. BONDED OR UNBONDED?

Aramids, like carbon fibres and glasses, exhibit brittle behaviour when tensile loads are applied to them, which means that they are very sensitive to applied strains which exceed the design values. This is in contrast to steel, where the plateau on the stress-strain curve means that the tendon can absorb high strains locally with no significant problems other than a permanent set.

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

Thus, beams prestressed with new materials should be designed with unbonded tendons. This has some implications for design procedures, as there will be relatively little increase in tendon force as the beam is loaded (11).

8. CONCLUSIONS

It is expected that beams, both in bridges and buildings, will be prestressed with Parafil. The tendons will either lie outside the concrete, or unbonded in ducts within the concrete (12). No account will be taken of increased forces in the tendon due to live load.

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

REFERENCES

1. Kingston D.: Development of parallel fibre tensile members, Symposium on Engineering Applications of Parafil Ropes, 7-12, Imperial College, London, 1988.

2. Burgoyne C.J. and Chambers J.J.: Prestressing with Parafil Tendons, Concrete, 19/10, 12-16, 1985.

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

4. Guimaraes G.B.: Parallel-lay aramid ropes for use in structural engineering, Ph.D Thesis, University of London, 1988.

5. Amaniampong G.: Variability and visco-elasticity of parallel-lay ropes, Ph.D. Thesis, University of Cambridge, 1992.

6. Burgoyne C.J. and Flory J.F.: Length effects due to yarn variability in parallel-lay ropes, Procs. MTS-90, Washington D.C., 1990.

7. Crawford H. and McTernan L.M.: 'Fatigue' properties of Parafil, Symposium on Engineering Applications of Parafil Ropes, 29-39, Imperial College, London, 1988.

8. Kenney M.C., Mandell J.F. and McGarry F.J.: Fatigue behaviour of synthetic fibres, yarns and ropes, Journal of Materials Science, 20, 2045-2059, 1985.

9. Guimaraes G.B. and Burgoyne C.J.: The Creep Behaviour of a Parallel-lay Aramid Rope, Journ. Mat. Sci., 27, 2473-2489, 1992.

10. Burgoyne C.J., Guimaraes G.B. and Chambers J.J.: Tests on Beams Prestressed with Unbonded Polyaramid Tendons, Cambridge Univ. Eng. Dept Tech Report CUED/D - Struct/TR. 132, 1991

11. Burgoyne C.J.: Should FRP tendons be bonded to concrete? Int. Symp. on Non-metallic reinforcement and prestressing, American Concrete Institute, 1993.

12. Burgoyne C.J.: Properties of polyaramid ropes and implications for their use as external prestressing tendons, External Prestressing in Bridges, ed. A.E.Naaman and J.E.Breen, American Concrete Institute, SP-120, 107-124, Detroit, 1990.