Tests on Beams Prestressed with Polyaramid Tendons

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ABSTRACT

The paper describes tests on two concrete beams, prestressed with aramid ropes which consist of parallel yarns of aramid fibres without any resin. The anchoring and stressing system for the ropes are described. One beam was stressed with a single, straight, unbonded tendon in a duct on the centreline; the other had two external deflected tendons. The beams were loaded in 4 point bending; after initial elastic tests, higher loads were applied until the beams failed in flexure. In both cases, the ultimate load was reached when compressive failure of the concrete occurred, with the tendons remaining intact. Although both aramid and concrete are brittle materials, the beams demonstrated a considerable ability to absorb energy at failure. In one beam, the variation of force in the tendons was recorded for 65 days after first stressing. Losses were seen to be comparable with those in steel tendons. After the tests, the tendons were removed and were tested in simple tension, and were found not to have lost any strength. Implications for the design of beams using aramid ropes are also presented.

INTRODUCTION

Tests have been carried out on two beams prestressed with parallel-lay aramid ropes (Parafil), to demonstrate the feasibility of producing structural elements in this way. This paper summarises the tests that have been carried out, and the results that were obtained. Full details of the tests are given elsewhere (Burgoyne, Guimaraes and Chambers, 1991; Chambers, 1986; Guimaraes, 1989). The tests were carried out by the author and his co-workers at Imperial College in London. The work was sponsored by Linear Composites Ltd.

PARAFIL ROPES

Parafil ropes contain a core of *para*llel *fil*aments of yarn within a thermoplastic sheath. A variety of core yarns can be used; in the case of the Type G Parafil, the yarn used is a stiff polyaramid yarn. The combination of high yarn strength (2760 N/mm^2) and stiffness (126 kN/mm^2) makes this version of the rope suitable for structural applications, particularly prestressing tendons for concrete.

Figure 1 shows the short term stress-strain curve for a 60 Tonne nominal breaking load (NBL) tendon, as used in these tests. The response is essentially linear, with a slight stiffening once the load exceeds about 50% of the NBL. This stiffening is also observed in the response of the fibres themselves and is not due to the rope construction.

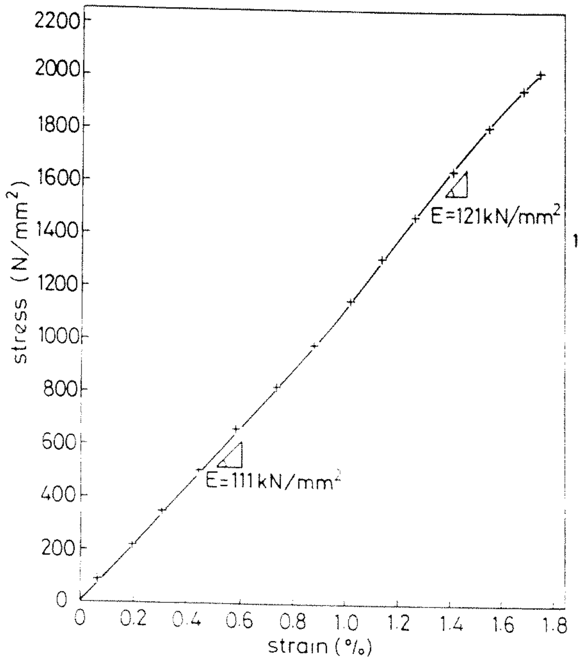

Figure 1. Typical stress-strain response for a Type G Parafil rope.

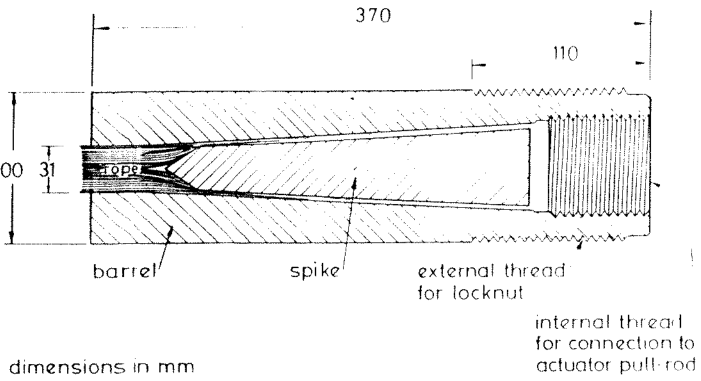

Figure 2. Barrel and spike termination for 60 T Parafil rope, modified for use as a prestressing tendon.

Terminal details

In tension members, the design of the terminations is clearly critical, since the rope is of no use unless the force can be transmitted to the rope. The terminals used for the Parafil ropes have been designed by the manufacturer and are used on all tests of the rope. The basic geometry consists of an internal spike which grips the fibres against an external conical barrel. In this system, every fibre is subjected to an evenly distributed gripping force, which allows friction to develop the full strength of each yarn; this contrasts with external wedge systems which tend to develop hoop compression in the outer layers of circular ropes and do not fully anchor the inner fibres. To modify the terminals for prestressing operations, two threads are placed on the end of the terminals, as shown in Figure 2. The inner thread is used to connect to a pull-rod which is used to apply the prestressing force, while the external thread is used for a back-nut which transmits the force to the concrete itself.

DESIGN OF TEST BEAMS

The ropes cannot be bonded to concrete, and indeed, with materials which do not show plastic yielding, this would be undesirable; thus, from the outset it was expected that these ropes would be used as external or unbonded tendons. Two designs were produced; the first (Beam A) had a single, straight tendon, contained within a duct on the centreline of a simple I-beam, while the second (Beam B) had two external deflected tendons, one on each side of a T-shaped cross-section (Figure 3).

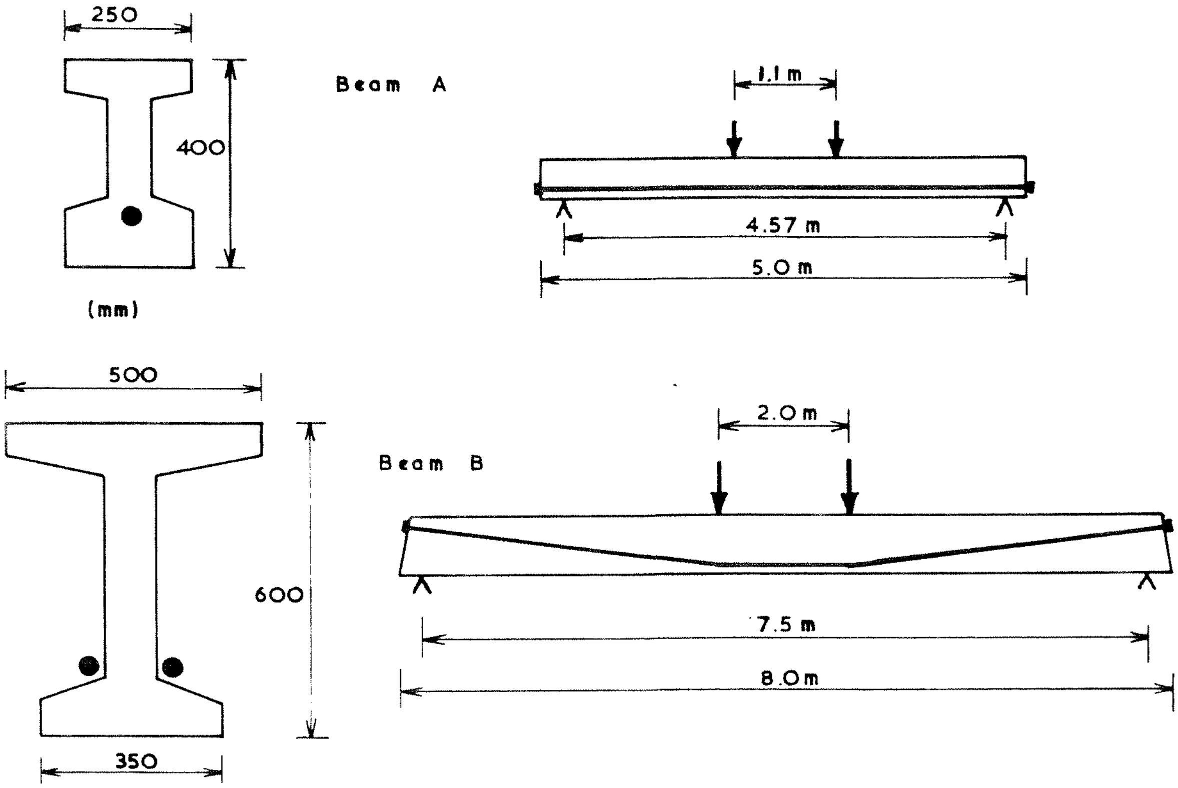

Figure 3. General Arrangement of Test beams.

Beam A was stressed with a 60 tonne Type G Parafil tendon stressed initially to 70% NBL. To enable the end anchorages to be accommodated and to limit the anchorage bearing stresses the main I-section of the beam was splayed-out to a full rectangular section at the beam ends.

Beam B was prestressed with two external 60 tonne Type G Parafil tendons, deflected by an angle of 4.57 degrees. Other tests (Chambers, 1986) had shown that there is no reduction in the breaking load of the ropes when deflected in this way. To avoid direct contact between the ropes and the rough surface of the concrete at the deflection points, which could damage the sheath of the ropes during the prestressing operation, a steel shoe was fitted to the concrete. This was formed from a piece of steel tube, of slightly larger diameter than the rope, cut in half along its longitudinal axis and bent to a smooth curve.

For an internal tendon, as in Beam A, 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. This was done in a straightforward way by making the duct in several pieces, which could then be easily joined together. 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.

PRESTRESSING OPERATIONS

The principles of the stressing procedure are shown in Figure 4. The tendon is placed in the structure, and a pull-rod fitted to the internal thread of the termination. The pull-rod is then passed through the centre hole of a hydraulic jack, and secured by means of a nut. The jack is held away from the beam by means of a trestle, which allows access to the terminal to secure the back-nut. Force is applied by the jack, which brings the terminal just outside the face of the concrete; the back-nut can then be fitted to lock the tendon in position in its stressed state. The jack, trestle and pull-rod can be removed, and a security cap fitted to prevent dirt and debris getting into the termination, and also to contain the anchorage in the unlikely event of a rope failure.

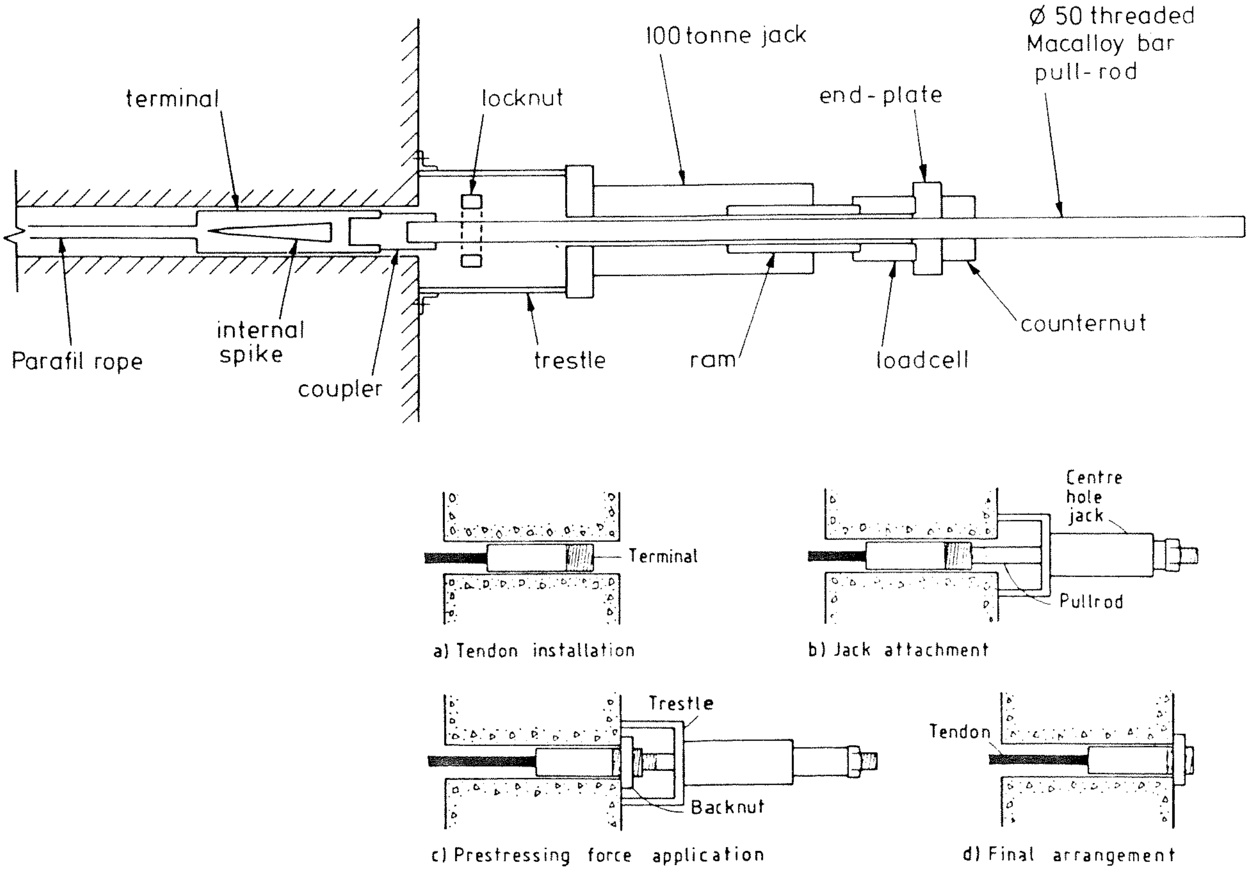

Figure 4. Prestressing system and sequence used in laboratory tests.

The prestress was applied to Beam A forty days after casting and 20 hours before testing, while the beam remained on the soffit shutter. The rope was first pretensioned to 60% of the nominal breaking load (in the usual manner specified by the manufacturers). One hour later, a prestress of 42 tonnes (70% NBL) was applied to the beam. The strain distribution gave good agreement with predictions, indicating a negligible loss of prestress due to friction between the rope and the prestressing duct, as would be expected.

The prestressing apparatus for Beam B was similar to that used in the earlier test; two identical jacks were used, one for each tendon, both connected to the same hydraulic cabinet. The prestress force measurements were taken by load cells fitted to one of the jacks at the live load end, and to both anchorages at the dead end. The beam had been designed with sufficient reinforcement to take its own weight without cracking, but for extra security during lifting, a partial prestressing force was applied, with the beam resting on the soffit formwork, ten days after casting. The beam was then lifted to allow the removal of the bottom shutter and placed on its bearing plates.

At the age of 33 days, the force in the tendons was removed and the initial readings of displacements and strains were taken with the beam subjected to the action of its own weight. The total initial prestressing force applied to the beam was 626 kN. The force at the dead-end of the tendons was measured while the prestressing was underway. This indicated that 5% of the prestressing force was being lost to friction; taking the standard relationship for friction in deflected tendons ($P_X = P_0 e^{-\mu\theta}$), with $\theta = 0.16$ radians, this gives $\mu = 0.32$. This value is slightly higher than would be expected with steel tendons, but could be brought down by a better selection of sheath and deflector material. Measurement of the force in the tendon, after the force had been transferred from the jack to the permanent back-nut, indicated that no loss of prestress occurred at this stage.

ELASTIC TESTS

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.

Tests were carried out on the beams at working (uncracked) load levels, before the tests to determine the load carrying capacity. In the case of Beam A, these tests were merely to get the short term elastic response, but for Beam B, the working load was applied for a period of 42 days, in order to monitor the combined effects of creep and shrinkage of the concrete together with relaxation effects in the tendons.

The elastic test on Beam A was designed to apply a load that would induce the allowable flexural tensile stress in the bottom fibre of the beam. The load-deflection curve was essentially linear, and 94% of the maximum mid-span deflection being recovered 5 minutes after the load was removed.

Beam B was subjected to two loading cycles at the service load. In the first cycle, the load was applied in increments until a small tensile strain was observed in the bottom flange. No visible cracks were present under this load. The beam was maintained under this load for 42 days, after which the load was removed. The second load cycle started immediately afterwards and consisted of the application of the same load as cycle 1, using the same load increments, followed by its immediate removal.

Time dependent variations

The relationship between the applied load and the deflection at the centre of the beam is shown in Figure 5; this is similar in form to the response of the concrete strain at the top fibres. On the application of the load, the response is almost linear, with the portions of the curves corresponding to loading and unloading being parallel. The instantaneous camber produced by the prestressing is indicated by the horizontal part of the curve at zero load. The increase of deflection due to the effects of shrinkage and creep of concrete after 42 days was 59% of the instantaneous deflection caused by the applied load. This figure is not affected by relaxation of the tendon, being due to loss of stiffness of the concrete.

In prestressed concrete only minor changes in stress are induced in the tendons when the dead and live loads are applied to the member; this is particularly true when the tendons are unbonded. The resistance to external bending moment is almost exclusively due to an increase of the lever arm between the internal compression and tension forces whose magnitudes remain

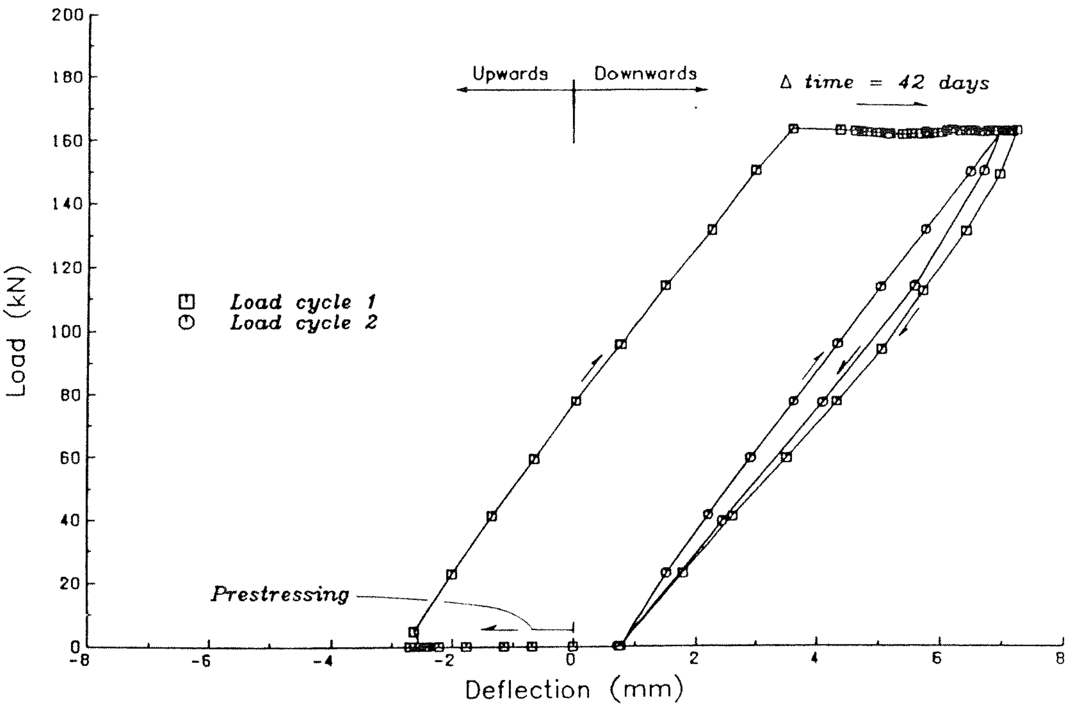

Figure 5. Load-deflection results for first two working load cycles for Beam B.

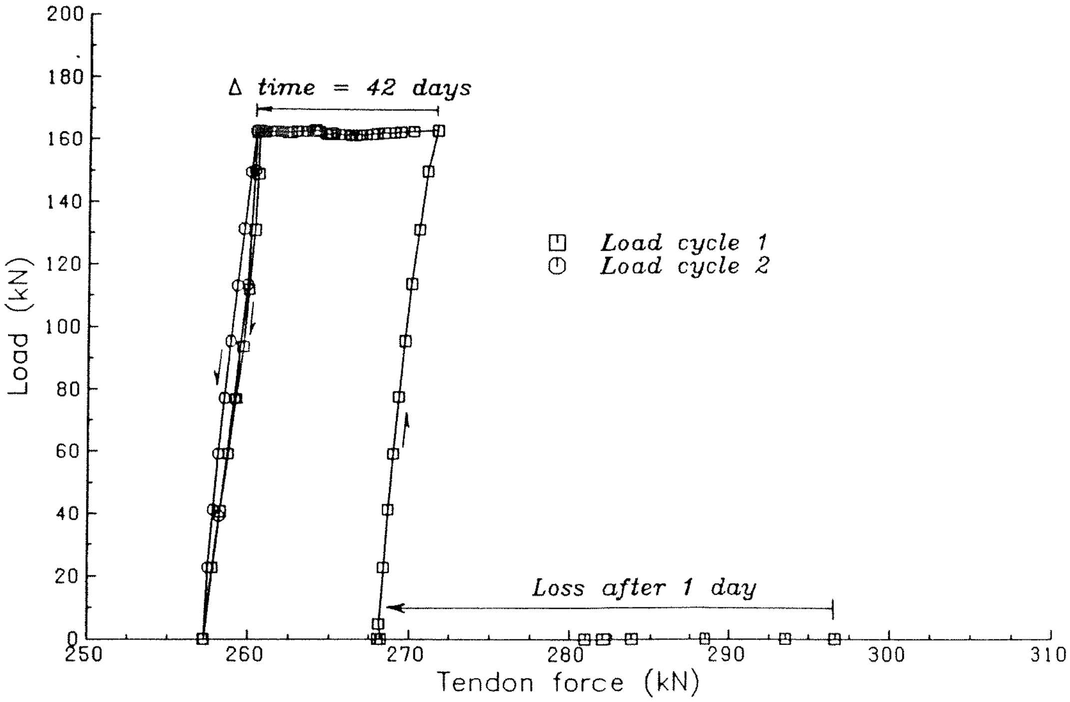

Figure 6. Load versus tendon force for tendons in Beam B.

relatively unchanged. This is shown in Figure 6 where the slope of the curves indicate a very small variation of the forces in the tendons due to the application of the load; the figure shows the expected linear variation of tendon force with applied load - small since the tendons are unbonded - together with time dependent variations due to creep and relaxation.

The total loss of prestress in both tendons, due to shrinkage and creep of concrete and due to stress relaxation in the tendons, is shown in Figure 7. 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) in tendons 1 and 2 respectively were observed after 23 days when the full prestressing force was applied. Over this period of time the beam was subjected only to the action of 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 1 day after prestressing. From then on the curves show a very low rate of loss.

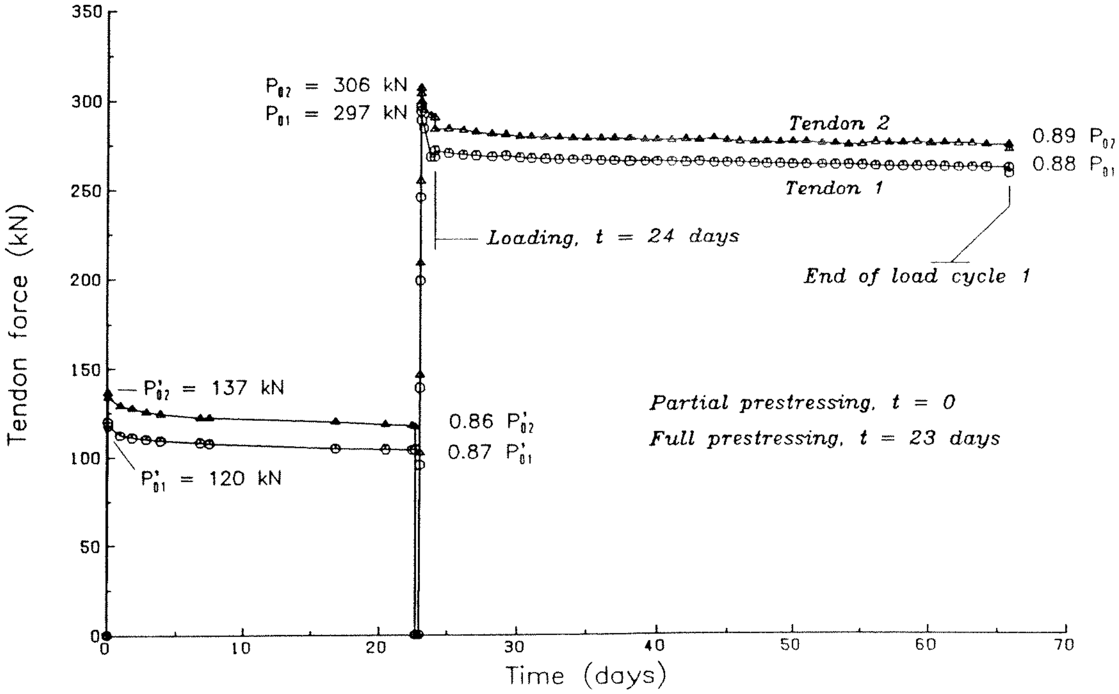

Figure 7. Variation of prestressing force with time for tendons in Beam B.

ULTIMATE LOAD TESTS

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 unloaded.

When loaded until failure, both beams showed considerable curvature at virtually constant load, with large cracks forming in the bottom of the beam. Failure occured in both beams by crushing of the top flange. Figure 8 shows the load deflection curves for Beam A; the results for Beam B are similar.

There were slight differences in the final failure mode of the two beams. In both cases, the top flange failed by crushing, but in the first beam, as the tendon was constrained in the bottom flange, the beam did not completely collapse. The compression zone passed down through the web, and into the top of the bottom flange, with a consequent reduction in load. However, the bottom flange did not fail, remaining axially prestressed. After the test, the tendon was found still to be carrying a force of 330 kN.

In the second beam, the tendon was outside the bottom flange, which could thus deflect while leaving the tendon in its original position relative to the ends of the beam. The beam thus failed suddenly and completely, with a total loss of prestress.

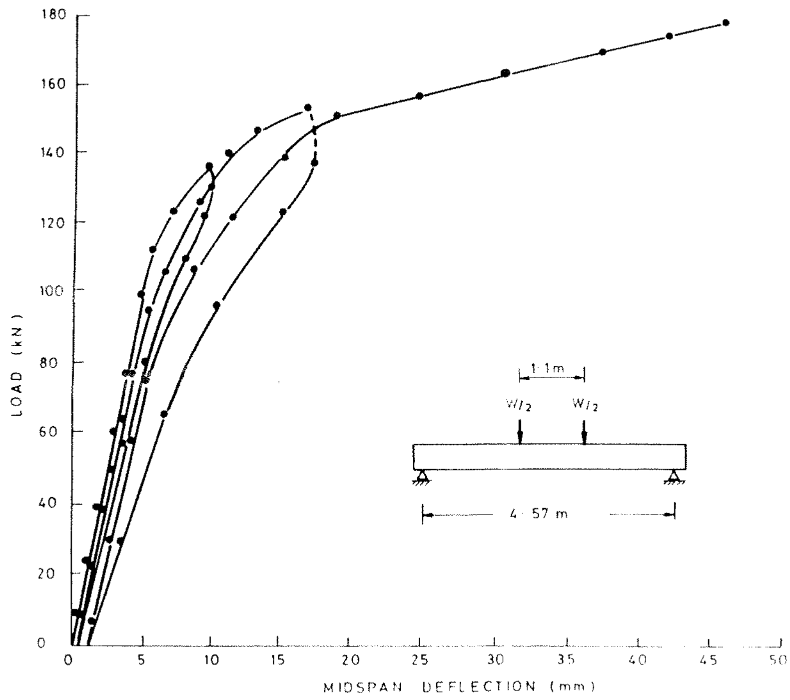

Figure 8. Load-deflection curve for ultimate load tests on Beam A.

TENSILE PROPERTIES OF THE TENDONS AFTER BEAM FAILURE

It was not practical to remove the tendon from Beam A without damaging it, so it was impossible to test whether the loading to which it had been subjected caused any reduction in tendon strength. However, in Beam B the tendons were external, so they were removed and subsequently tested 63 days later. The breaking loads were 668 kN for tendon 1 and 686 kN for tendon 2, and the elastic modulus for both tendons was 120 kN/mm^2. The breaking loads of both tendons were greater than the mean value (597 kN), and even greater than the maximum value (626.6 kN), observed in the tensile tests conducted on similar ropes (Chambers, 1986) tested in the same way.

This effect is probably due to increased creep in the more heavily loaded filaments, which will even out variations in the slack in the yarns. In subsequent loading, the rope acts as a bundle of yarns with less variabilty, and hence increased strength. Work is now underway at Cambridge University to study the implications of bundle theory when influenced by visco-elastic effects; it is hoped that this will shed more light on this phenomenon.

PRACTICAL LESSONS FOR THE DESIGN OF CONCRETE PRESTRESSED WITH PARAFIL

The results of the tests show that basic design principles for prestressed concrete do not need radically altering; the following are additional points which a designer should take into account when designing a beam with Parafil tendons.

1. The tendon should be pretensioned, with the terminals in place, to a load level in excess of that expected during both the initial stressing operation, or the service life of the structure. This will have the effect of ensuring that the terminal spike is properly bedded, and will also give a check on the tendon length before being placed in the structure.

   It is normal practice, according to the manufacturer's instructions, to pretension ropes to 60% of the nominal breaking load prior to use, whenever possible. These ropes, when used in conventional rigging arrangements, are normally stressed to much lower load levels than those in use in prestressing tendons; in these cases, 60% is perfectly adequate as a pretensioning load. However, in prestressing tendons, where high force levels are normal, a higher pretensioning level may be needed to ensure adequate bedding of the termination.
2. Any deflector points should be properly flared to ensure no damage to the sheath during stressing operations; this should not be difficult to arrange if taken into account at the design stage.
3. The coefficient of friction between the tendon and the duct (or the deflector) should be reduced wherever possible. This may mean undertaking some studies of friction coefficients between various possible sheathing materials and alternative duct materials. Alternatively, coating materials, such as PTFE or Nylon tapes, might be considered.
4. The working load design of prestressed concrete beams should be based on allowable stress limits taking account of the design prestressing force, after allowing for losses, and the ultimate strength of the section should be based on the assumption that only minimal increases of force take place due to geometry changes as the beam deflects.
5. The compression zone of the concrete should be provided with confining reinforcement to increase the ductility of the concrete in that area.
6. If the tendons are external to the concrete, they should pass through loose rings so that, in the event of failure, the tendons are forced to deflect with the beam. This will ensure that failure occurs in the more controlled manner of Beam A, rather than in the more sudden manner of Beam B.

Recommendations 4, 5 and 6 apply also to beams prestressed with steel tendons.

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