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LABORATORY TESTING OF PARAFIL ROPES

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les matériaux nouveaux pour la précontrainte et le renforcement d'ouvrages d'art

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INTRODUCTION

The paper given earlier in this symposium by Dr Kingston (1) has described the basic properties of Parafil ropes, and given some indication of possible applications. This paper will concentrate on practical descriptions of the testing of these ropes, giving particular regard to the correct handling of the ropes.

Work has been carried out at Imperial College over the last six years to determine the properties of Parafil. During that time, considerable experience has been built up in dealing with the ropes.

ROPES USED

Most of the tests have been carried out on Type G ropes, which have a core of Kevlar 49 yarns. These, being stiffer than Kevlar 29, are more suited to most structural applications. A variety of rope sizes have been used, varying from ropes with a nominal breaking load (NBL) of 1.5 Tonnes, up to ropes with 60 Tonnes NBL. The nominal breaking load is based on a notional failure stress of 1926 MPa; this is conservative for all rope sizes, but for large ropes (> 60 Tonnes NBL) the difference between the actual breaking load (ABL) and the nominal breaking load is not significant. Smaller ropes, which have fewer yarns in the core, are slightly stronger (Figure 1), but this is largely a function of the statistical properties of bundles of fibres, and is directly related to the variability in the constituent yarns. Bundle theory, as applied to Parafil ropes, is discussed in detail in reference 2. All rope sizes referred to in this paper are based on nominal breaking loads.

TEST PROGRAMMES

The test programmes carried out have studied a number of material properties. Direct tension tests have been undertaken on 60 Tonne and 6 Tonne ropes. The tests on the smaller ropes studied the variability of the ropes, and also the effects of length.

Stress rupture tests were also undertaken on the 60 Tonne ropes by loading in direct tension using a load-maintaining hydraulic pump. By the nature of these tests, it is possible to derive creep rate data from the same experiments.

The loading arrangement used in the tests on these large ropes is unsuitable for very long term loads, due to the cost of tying up equipment for long periods of time, and the reliance on uninterrupted power supplies. Indeed, one test was ruined by the inadvertent removal of an electrical fuse by a lighting maintenace worker! Thus, for the later phases of the work, which apply loads below about 70% of the NBL for longer periods of time, a more reliable loading system was required. Consideration was given to the possibility of stressing ropes against a mechanical system which could be periodically tightened to overcome the effects of relaxation. This would have had the advantage that large ropes could be used, but would have the disadvantage that the state of stress in the ropes would not be fixed, being neither constant stress (to give creep results) nor constant strain (to give relaxation results).

It was therefore decided to use a system in which the force was supplied by dead loads through a lever arrangement; the lever arrangement was kept simple (to avoid friction effects), so with a lever advantage of 10:1 a practical maximum rope size of 3 Tonnes was arrived at. This enabled the construction of a number of separate test rigs that were small enough to be moved but which could test representative ropes. Separate rigs were used, rather than having a number of tests on one frame, so that failure of one rope would not cause a shock load on its neighbours.

Six rigs for 3 Tonne ropes have been built, and are located away from Imperial College because of lack of space. They are, however, equipped with an automatic data logging system that is interrogated at regular intervals by telephone; for back-up, all data is also printed at the test site. After initial teething problems with the electronics, this system is now working reliably. Tests have been in progress on these rigs for about 16 months, and they will continue for at least the next few years (3).

Two similar, but smaller, rigs were constructed for 1.5 Tonne ropes (Figure 2), as prototypes for the larger rigs. These are located at Imperial College, and are used for a variety of purposes, including tests in which the load is varied periodically (say, once a week or once a month), to establish cumulative damage data. One of these rigs has had a rope under a load of 64% of ABL for nearly two years.

Tension-bending and sheave bending fatigue tests have been undertaken as part of a programme to investigate the properties of the ropes for use as mooring lines for floating oil platforms in very deep water. The test rigs for these studies are shown in Figures 3 and 4, and full details of the results are to be presented elsewhere (4).

Stress relaxation data were obtained by stressing 60 Tonne ropes against a steel box section and measuring the change in strain in the box with time (2). Similar tests are now in progress on smaller ropes, using Type F (Kevlar 29) and Type A (polyester) Parafil ropes.

In addition to these tests, and the beam tests described below, a variety of other tests have been carried out on the ropes to determine the ability of the ropes to bond to concrete (effectively none), and the effect of stressing the ropes over a deflector (as would occur in a deflected tendon in a prestressed beam).

TERMINATION OF THE ROPES

A rope is only useful as a tension member if there is some mechanism for getting load into and out of the rope. A variety of anchoring systems have been applied to composite and non-composite fibre ropes, but for a number of reasons (as outlined in (5)), the central spike anchoring the fibres to an external terminal body provides the most secure fixing (Figure 5).

In the work described here, ropes of many different sizes have been terminated in this way. Perhaps paradoxically, it has been found more difficult to reliably anchor the smaller ropes than the larger ropes. This is because of the difficulty of ensuring an even distribution of fibres around the circumference of the spike.

If the spike is not surrounded uniformly by fibre, some of the yarns will be gripped more tightly than others. This will lead to certain fibres taking a higher proportion of the load than intended, which will lead to premature failure of those fibres. This sheds load into neighbouring yarns, which may themselves then fail. When dealing with small (1.5 Tonne) ropes, the spike is surrounded by only a single layer of fibres, and it is difficult to ensure that these are uniformly spread around the spike. On the larger ropes (60 Tonne), there is a thickness of several millimetres of fibres around the spike. Thus, it is easier to ensure a uniform thickness of yarn, and mis-alignment of any one fibre will have a significantly lower effect on the overall strength.

This effect is reflected in the position of the failures that have been observed. In 60 Tonne and 6 Tonne ropes, failures normally occur in the body of the rope, remote from the terminal. Since there is little load sharing between the filaments, the fibre failures are distributed over a considerable length of the rope; in essence, each filament fails at its weakest point. Only in the tests on the longest (12m) ropes tested (6 Tonnes NBL) was there any tendency for the ropes to 'neck', with failures concentrated at one point. (In very long ropes, necking failure at one point is to be expected, since the friction between fibres, however small, will tend to produce a concentration of load in fibres adjacent to the first one to fail.) Failures in the body of the rope when loaded hydraulically are not brittle; friction between the core yarn and the sheath absorbs the energy released in the failure and the ropes do not have a tendency to whip. However, if the loading were applied by a mechanism with unlimited ability to impart energy to the system (such as dead loads), a more sudden failure could result.

The smaller ropes (1.5 Tonne and 3 Tonne) do have a tendency to fail near the terminal. This is due, not only to the possibility of a slightly uneven distribution of load between the fibres, but also to a slight concentration of stress at the end of the sheath. The sheath is disregarded when calculating the strength of the ropes, and because it has a low modulus and creeps significantly, it takes very little part in the load carrying process. Nevertheless, it must be carrying some load, and at the terminations, where the sheath is removed, this load must be carried by the core, leading to a slight load concentration.

Despite the comments made above, the ropes are not difficult to terminate effectively. Once it is accepted that the spike must be placed centrally within the fibre bundle, and that a little care is necessary, it is a straightforward procedure to anchor the ropes.

STRESSING SYSTEMS

For applications such as prestressed concrete, cable stays for bridges and ground anchors, some mechanism is required for stressing the ropes. The termination system provides a means of anchoring the fibres to the terminal body, so what is needed is some means of applying a load to the terminal itself.

As with stressing systems for steel tendons, two connections are required; one for the temporary connection to the jack, and the other for the permanent fixing of the load. A variety of systems can be considered, but with an axi-symmetric system which is to be loaded and anchored at one end, the logical arrangement involves two threads, one internally, and one externally. The internal thread is used to connect to a pull-rod, which passes through a centre-hole jack and is used for applying the load. A back-nut fits onto the outer thread and is used to provide the permanent anchorage (Figure 5). This allows a certain adjustment to the length of the rope.

In order to allow the back-nut to be fixed, a trestle system is used to hold the jack away from the anchorage. Figure 6 shows the system as used in the laboratory. As such, it is a compromise between what is desirable, and what is available. Clearly, in a practical production system the arrangement could be simplified; matched threads between the pull-rod and the terminal would allow the coupler to be eliminated, and the trestle could be incorporated into the body of the jack. It should also be possible to locate and tighten the back-nut by means of a mechanical system built into the jack.

The system described here has proved simple and reliable in operation. It has been used for the application of sustained creep loads, as well as for the application of loads which are subsequently locked off.

CUTTING ROPES TO LENGTH

One problem which needs to be taken into account is that of cutting ropes to length. The usual requirement is for ropes to be of a specified length when subjected to a known load.

The following data have been obtained from tests on 60 Tonne Type G ropes used for tension, creep and stress relaxation tests by Chambers (2); for tension-bending fatigue tests (4) and for beam tests by Guimaraes (3). These ropes were of lengths that varied from 5.5 m for the fatigue tests, to 8 m for the beam tests, so necessarily they involve only a limited range of sizes.

There are three causes of change in length of the ropes which must be taken into account:-

(a) Elastic extension of the rope. This is fairly constant and can be determined from an assumption that the Young's modulus is 118 GPa. It will clearly be a linear function of both stress and length, but will otherwise be independent of the size of the rope.

(b) Spike bed down. The spike must be drawn into the terminal body to be effective. The manufacturer's specfication calls for a preload to be applied to the rope of 60% NBL for one minute; this is specifically to ensure that the spike is firmly anchored. Chambers studied spike bed-down quite carefully; for 60 Tonne ropes, a bed-down of 15-25 mm at each end was typical. This bed down of the spike was directly reflected in change in length of the rope.

Once the spike has been drawn into the terminal, it does not move subsequently. Thus, this change in length can be regarded as a 'once and for all' movement. It is not a function of the working load of the rope (being primarily a function of the preload, which is constant), but will be related to the scale of the terminal body. Since the cross sectional area of the body varies directly with the rope capacity, any linear dimension of the terminal will vary as the square root of the rope capacity. Thus, spike bed-down can also be expected to vary as the square root of the rope size.

(c) Initial slack and disorientation effect. The rope contains some slack, which it is impossible to eliminate completely, and there is also some effect due to the coiling process used to put the ropes onto drums. There will thus be some tendency for the ropes to stretch on first loading as these effects are eliminated. Chambers (2) noted that on first loading there was an initial stretch which was not recovered on unloading, and that was not fully accounted for by the spike bed-down. This he ascribed to this disorientation effect. It will be independent of the stress in the rope, but, being a geometrical effect, can be expected to vary as the square root of the rope capacity. It should also be a direct function of the length of the rope. Chambers observed an extension due to these causes of about 7.5 mm/m of rope.

By combining the results of these studies, it is possible to cut the ropes to length, as taken from the coil, and to terminate the ropes so as to achieve a stressed rope of given length. There will, however, still be some variation, depending, for example, on how firmly the spike is tapped into place during assembly. Thus, when the rope length is critical, it is recommended that trials are made to ensure that the correct length is achieved, and that some capacity for adjustment is built into the stressing system.

BEAM TESTS

Two concrete beams prestressed with Parafil tendons have been built and tested. Both used 60 Tonne Type G ropes as tendons.

Beam A

The first beam was designed (2) to have a single tendon, which for reasons of symmetry had to lie on the centreline and thus, in an I-beam, within the concrete. This tendon was straight and no attempt was made to bond the tendon to the concrete. Indeed, the tendon was wrapped in PTFE tape before being inserted into the duct to reduce as far as possible any friction.

The terminals are larger than the rope, and so could not be threaded through the ducts. Thus, the rope was cut to length and terminated (but not pre-tensioned) before being placed in the duct. The duct itself was made from a plastic pipe, cut in two longitudinally, so that the rope could be inserted from the side. Once the beam had been cast and cured, the rope was pre-tensioned by reacting against the beam. The rope was then unloaded for one hour in the prescribed manner and retensioned to 70% to provide the permanent prestress. This level of force is higher than would normally be applied to a rope, but since the beam was to be tested after a few days, the stress rupture criteria that would normally be relevant were not applicable.

The beam was 5m long overall and had an I-shaped cross-section, as shown in Figure 7, except at the ends where a full rectangular cross section was needed to incorporate the anchor block. A cap was fixed over the terminals and tied back to anchor points in the concrete to prevent the terminals flying out of the beam in the unlikely event of a rope failure.

The beam was tested a few days after stressing, by the application of two point loads. Several load cycles were applied, of increasing intensity, before the beam was taken to failure. Figure 8 shows the load deflection behaviour.

The response of the beam was as expected; the initial response, before cracking, was linearly elastic. After first cracking, almost all of the deflection was recoverable, until very large cracks opened. Because the tendon was not bonded and in the absence of significant reinforcement, the beam formed a few large cracks in the tension zone. These extended from the bottom flange of the beam, right up to the underside of the top flange, before the beam failed by compression of the top flange. Once failure had started, it progressed rapidly, but stopped before the beam collapsed completely.

After removal of the load, the strain gauges indicated that the beam was still carrying significant prestress (principally in the bottom flange). The tendon was removed by de-stressing in a reverse of the normal stressing operation. The tendon was found to be carrying a total force of 34 Tonnes (c.f. the initial prestress of 42 Tonnes). This force had to be reapplied by the jack before the back-nut on the anchorage could be removed.

Beam B

The second beam was designed (3) to be more typical of beams that would be stressed with Parafil in normal applications (either in new construction, or for repair). Two deflected external tendons were used; this allowed the beam to have almost a T-section, with only a nominal bottom flange. The cross section could be larger than the first beam, and was thus suitable for a larger span. An overall length of 8 m was chosen. The geometry of the beam is shown in Figure 9.

An initial prestress of about 20% of NBL was applied at an early age to prevent shrinkage cracking and to allow the beam to be lifted off its soffit shutter. After 23 days, the full prestress was applied.

When the final prestress was applied, the tendons were stressed to only 50% of NBL, partly because the load was to be applied for a longer period of time, and partly to be more typical of practical applications.

The prestress was sufficient just to cause tensile stresses in the top flange. No cracking was visible at this stage. The beam was then loaded to its normal working load (sufficient to cause tension in the bottom flange) and this load was maintained for one month to study the effect of creep. Total losses of 11% were observed, due to a combination of creep and relaxation in both concrete and Parafil. Most of this occured within the first few hours, and was in accordance with predictions which indicate that total losses in beams prestressed with Parafil will be similar to those in beams stressed with steel (although the amounts due to the individual causes of loss will be different).

The beam was then tested in a similar manner to the first beam, with load being applied through a spreader beam to give two point loads. The loading was increased in stages, with an initially linear elastic response, followed, at higher levels, with larger deflections associated with significant cracking. As with the first beam, and in accordance with expectations, virtually all of the deflection is recoverable, since with unbonded tendons the prestressing force remains fully effective.

Final collapse of the beam was initiated by compressive failure of the top flange (which was virtually unreinforced). Unlike the other beam, failure was complete, in that crushing of the concrete proceeded right through the beam. This was aided by the fact that the tendons were not restrained to have the same vertical displacement as the concrete in the region of failure. It should be possible to increase significantly the strength of the beam by improving the compressive strength of the top flange (by a cage of reinforcement), and by providing guides to maintain the position of the tendon relative to the bottom flange.

Full details of both beam tests are to be reported shortly (6) elsewhere, but in summary it is clear that Parafil can be effectively used to prestress concrete beams.

CONCLUSIONS

Over the past few years techniques have been established for effectively using Parafil as a structural material. It can be handled, either on site or in the laboratory, without difficulty; termination and stressing are straightforward. It thus becomes a practical material to set beside more conventional materials.

The behaviour of concrete when subjected to a force is well known, through the established experience of concrete prestressed with steel. Now that it is known that Parafil is capable of applying sustained loads permanently, and so is an effective means of prestressing concrete, there is no difficulty in predicting the properties of Parafil prestressed concrete, and in the right application, we can expect to see structures prestressed with Parafil being used more frequently in the future.

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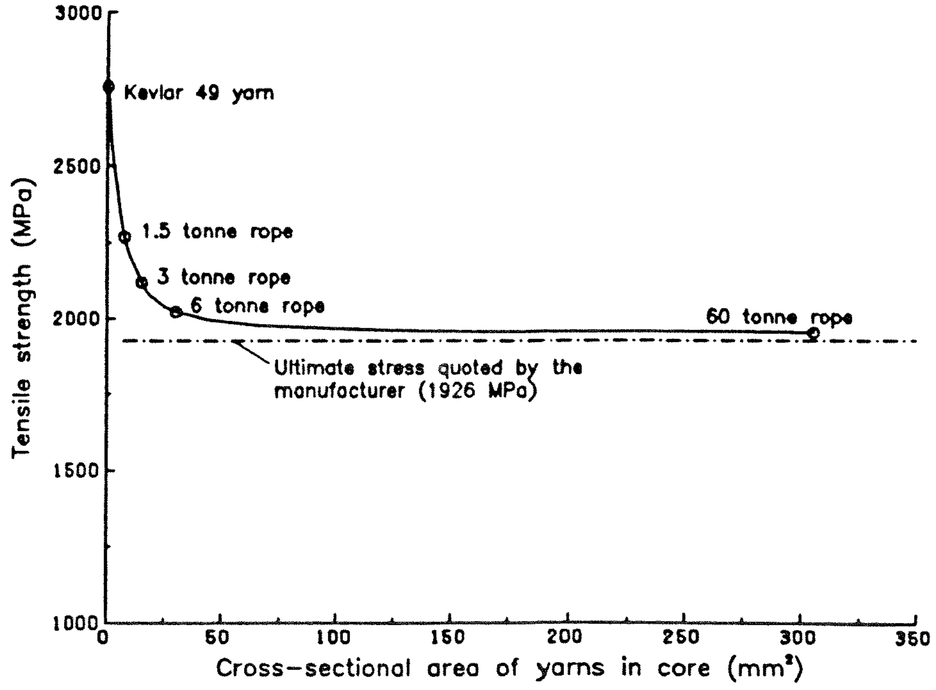


Fig. 1 Effect of size on the tensile strength of Type G Parafil

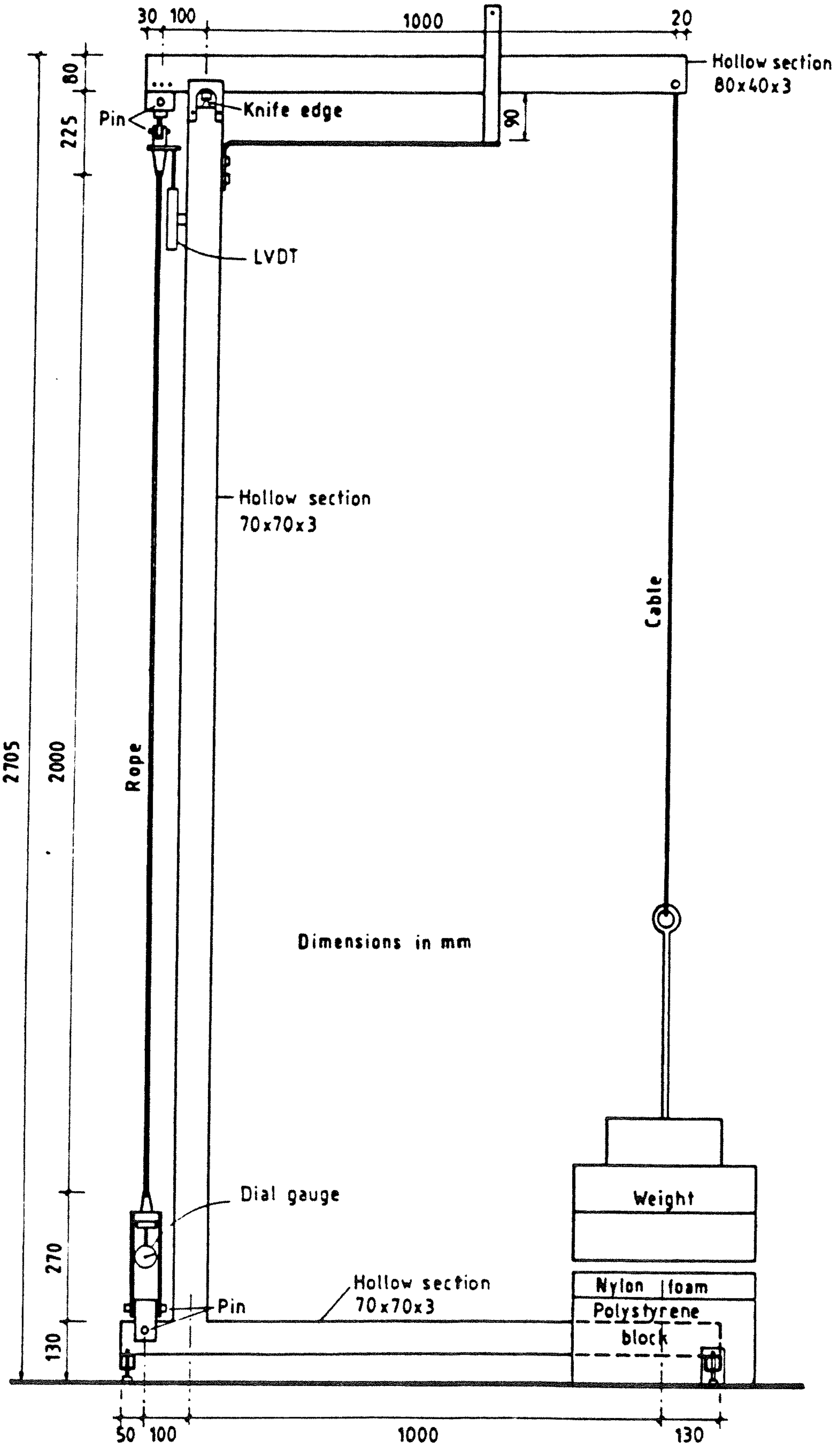


Fig 2. 1.5 Tonne stress rupture rig.

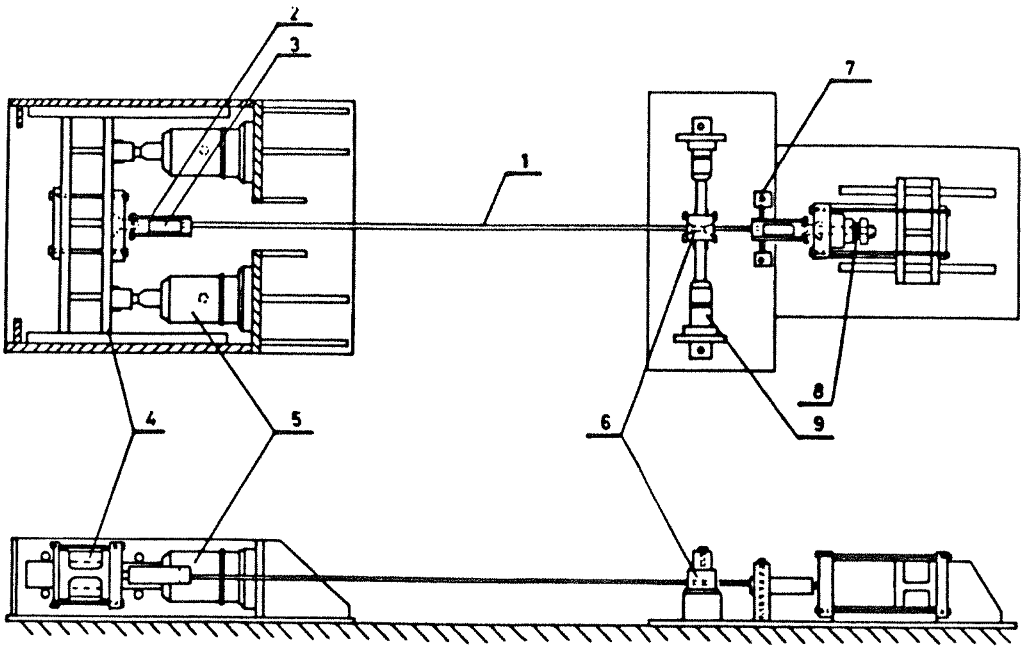


Fig 3. Tension-bending fatigue rig. (from ref.4)

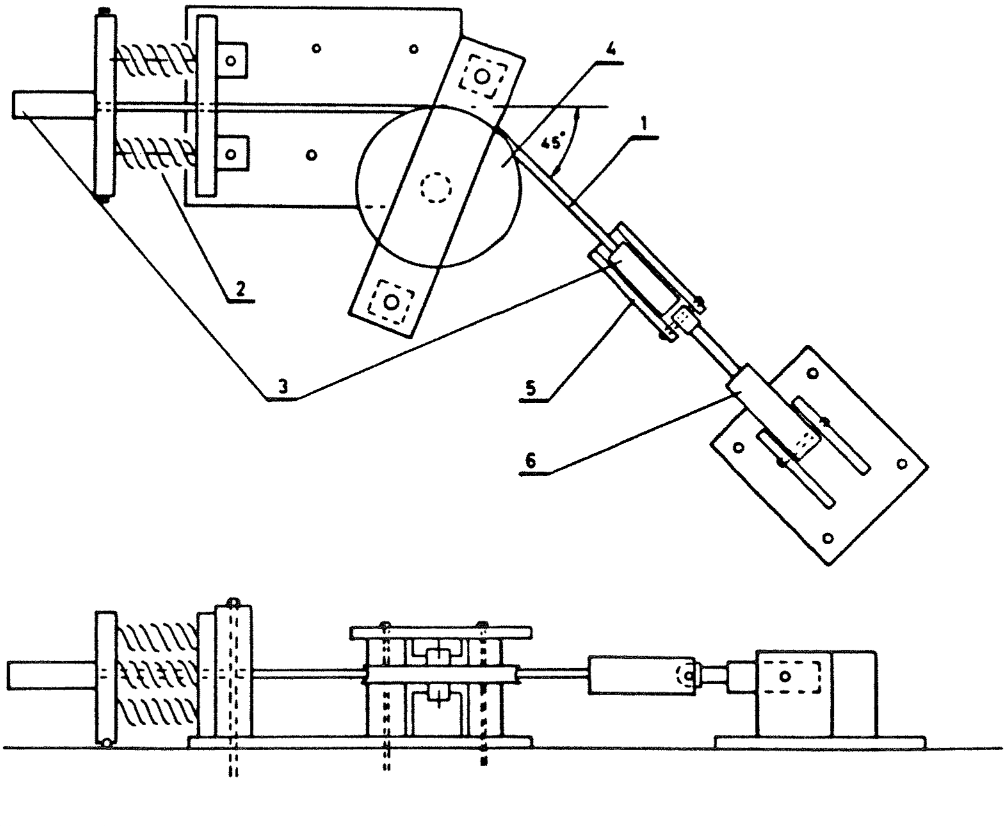


Fig 4. Sheave-bending fatigue rig. (from ref 4)

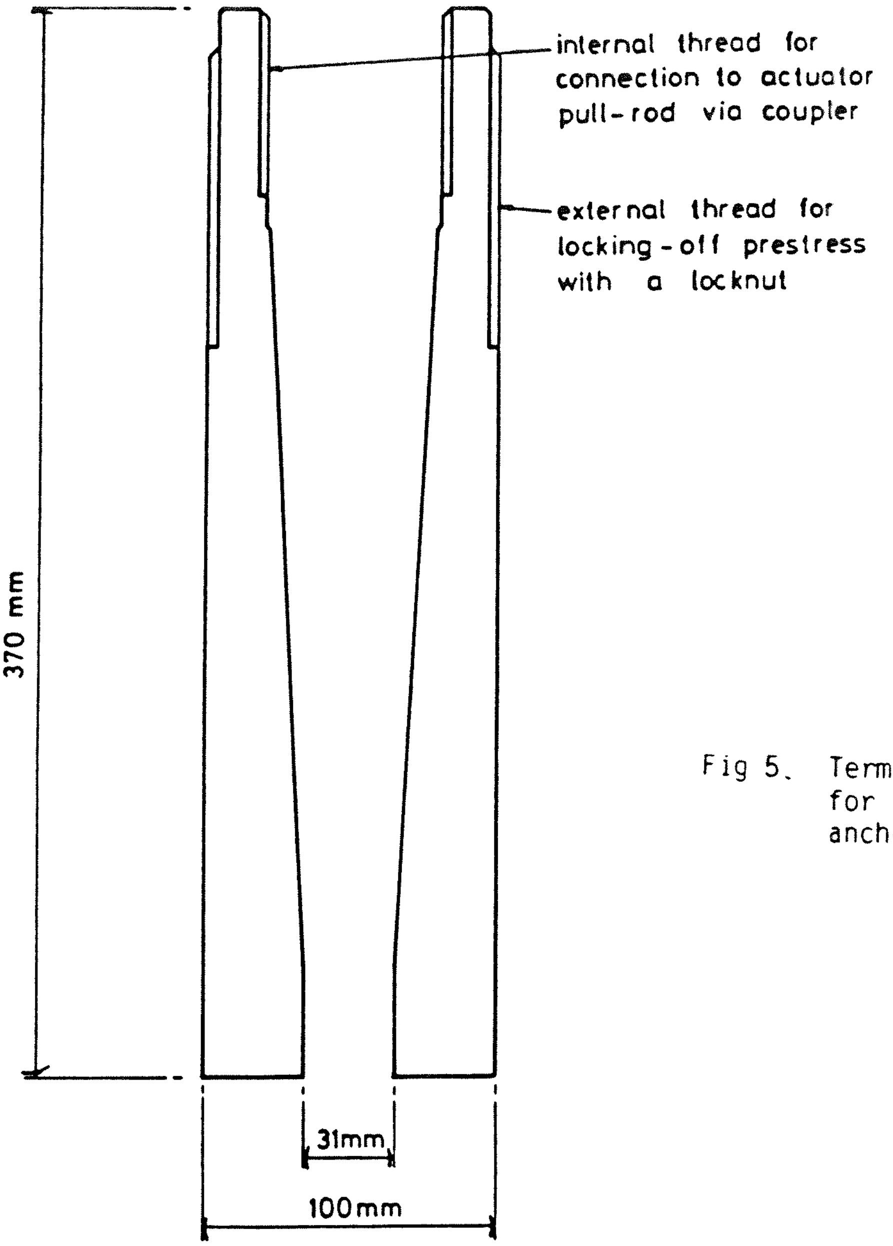


Fig 5. Termination modified for use as a prestressing anchorage.

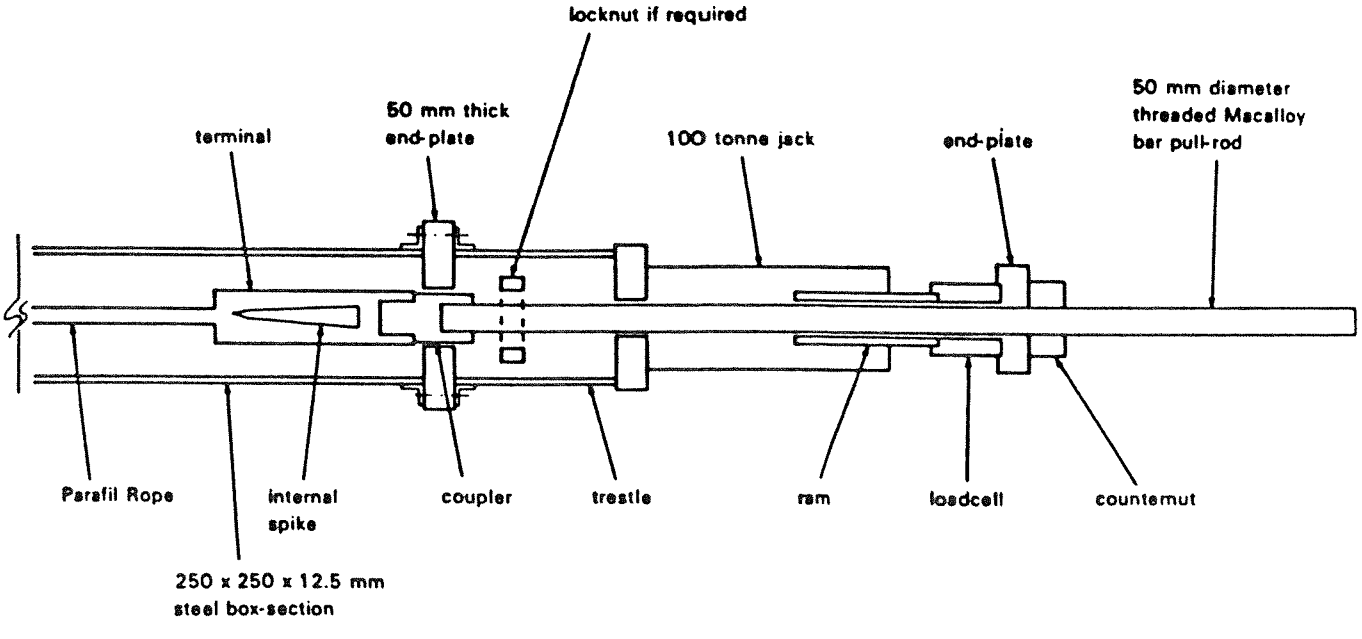
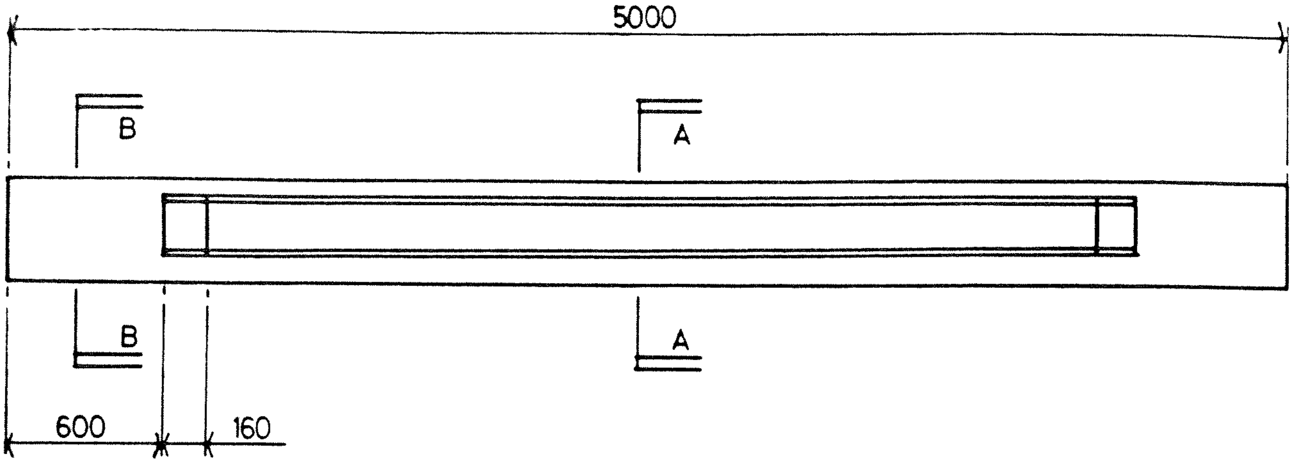
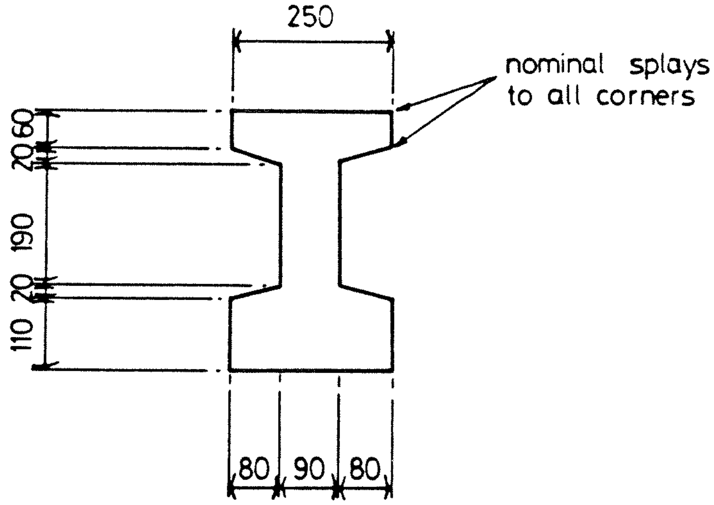


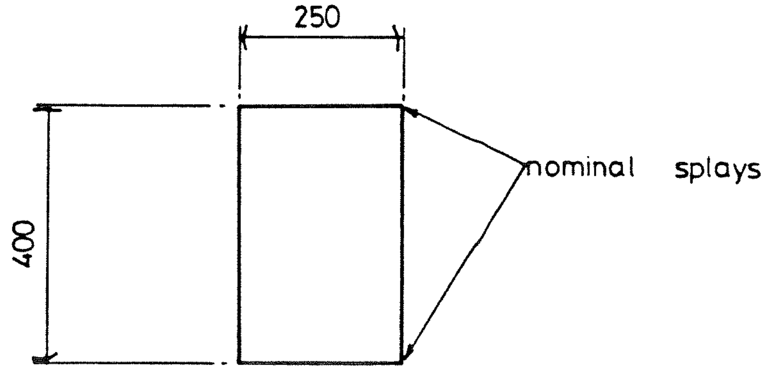
Fig 6. Laboratory stressing system.



ELEVATION



SECTION A-A



SECTION B-B

General Arrangement

Fig. 7 5m beam prestressed with single Parafil tendon

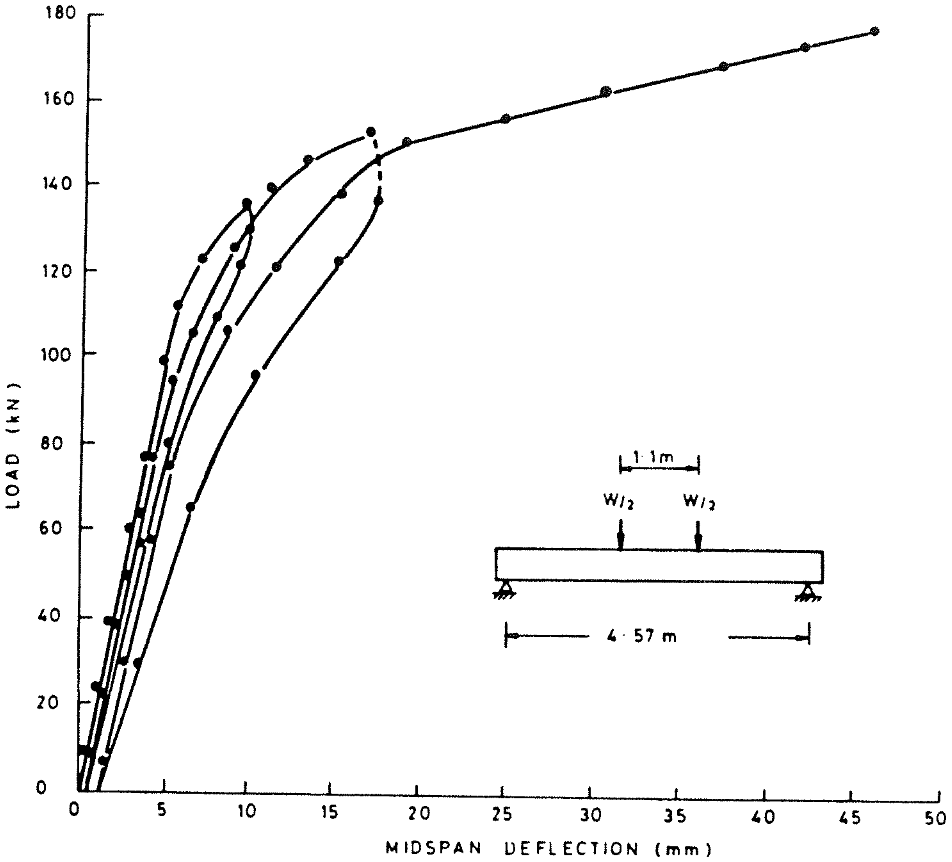


Fig. 8. Load deflection response of 5m beam.

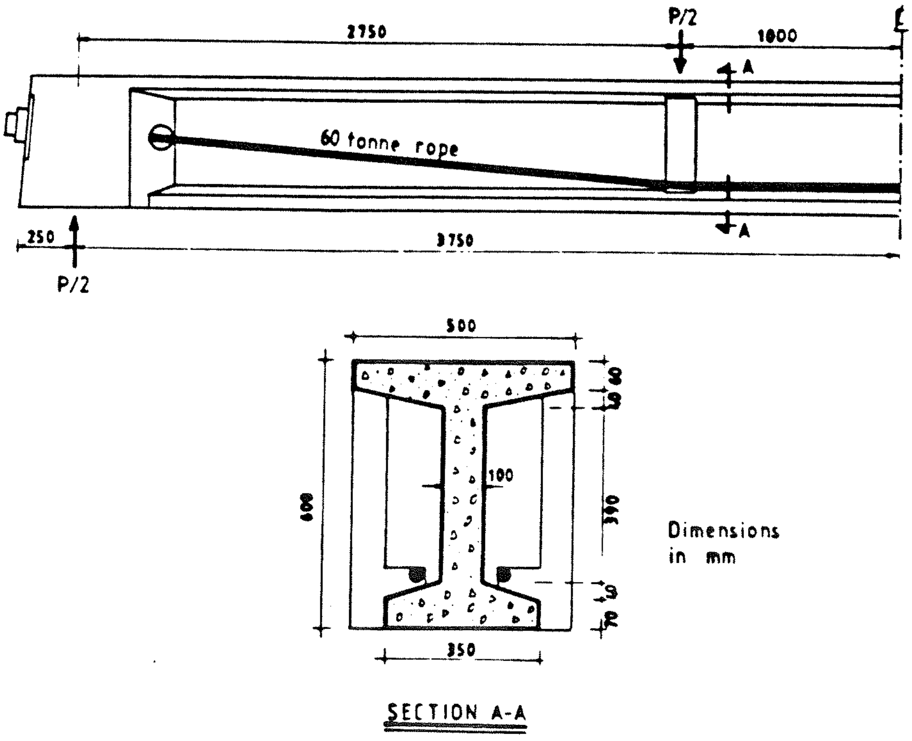


Fig. 9. 8m beam prestressed with 2 external Parafil tendons.