TENSION-BENDING AND SHEAVE BENDING FATIGUE OF PARALLEL LAY ARAMID ROPES

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ABSTRACT

The paper describes fatigue tests on parallel lay (Parafil) ropes of the aramid fibre Kevlar 49. Detailed descriptions are given of the test procedures for tension-bending and sheave bending fatigue.

The tension-bending tests were intended to produce failures at the mouth of the termination, but most failures occured at the deflector; one test was stopped after 1 million cycles. No curvature in the rope could be measured at the termination, indicating that the rope is acting as a bundle of individual fibres of negligible stiffness.

The sheave bending tests produced lifetimes of about 4000 cycles when tested at up to 50% of the static breaking strength.

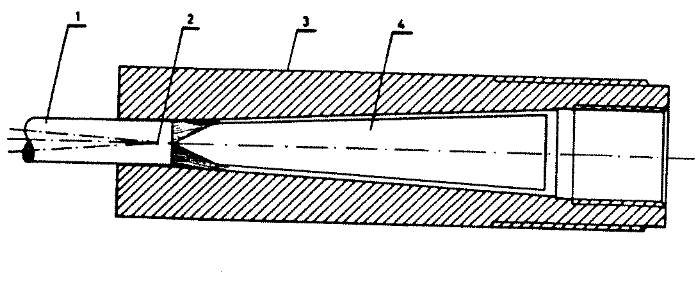
INTRODUCTION

As part of a wider project involving several different organisations (Baxter, 1988), tests have been carried out to investigate the bend fatigue performance of Parafil ropes. These ropes contain a core of parallel filaments; in the case of the Type G ropes used in these tests, the core yarn is Kevlar 49, which gives a rope with a strength of 1926 N/mm^2 at a breaking strain of about 1.6%. The yarn is contained within a black polyethylene sheath which maintains the shape of the rope, protects the core from superficial damage, and shields the core from ultra-violet light. All the ropes tested had a nominal breaking load of 600kN, equivalent to a cross sectional area of 305 mm^2.

Presented at the Eighth International Conference on
Offshore Mechanics and Arctic Engineering
The Hague – March 19–23, 1989

The advantages of these ropes for mooring large structures become apparent as the water depth increases. With a specific gravity close to unity, the ropes are effectively weightless in water, thus giving a significant consequential increase in the payload of the floating structure. (Kevlar has a specific gravity of about 1.44, but with the polyethylene sheath the ropes have a specific gravity of about 1.09 when saturated). In addition, the ropes are easier to handle than steel alternatives, and the resistance to corrosion is better.

The termination of the rope is provided by means of an internal spike which grips the fibres against an outer conical termination. This system provides a positive grip of all fibres, without overstressing individual yarns, and allows the full strength of the rope to be mobilised. Figure 1 shows a longitudinal section through such a terminal.



1 – Parafil Specimen
3 – terminal body
2 – Apparent pivot point
4 – spike

Figure 1. Termination for Parafil Rope.

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The studies presented here fell into two main groups :

1. The response of an axially loaded rope to lateral displacements with particular attention being given to the angular changes this produces close to a restrained termination. Because of the restraint, local bending of the rope took place, and the fatigue performance, bending stiffness and radius of curvature were all of interest.

2. The response of a rope to bending over a sheave while carrying a varying axial load. A 45° bending arc was used, and a number of different load ranges were considered.

The first group of studies is referred to as "tension-bending" and the second as "sheave bending".

The tension-bending tests were designed to load particularly the termination-to-rope interface to model situations where the rope deflects laterally, but the termination remains fixed, thus inducing an angular offset of the rope at the termination. Such loads frequently occur, either when the terminal is rigidly connected to the structure and the rope is allowed to deflect, or alternatively when the inertial mass of the termination is sufficiently high that it does not respond immediately to rapid movements of the rope.

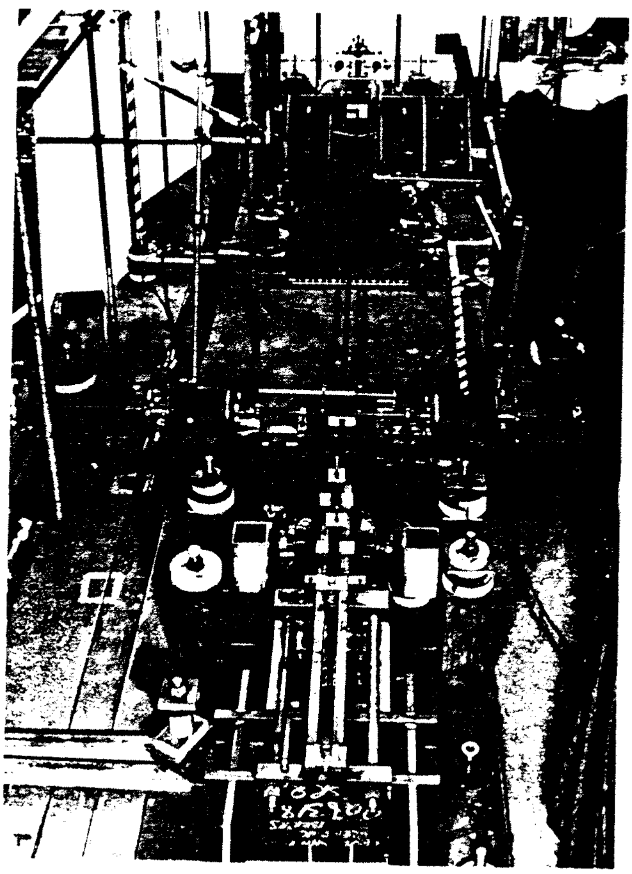


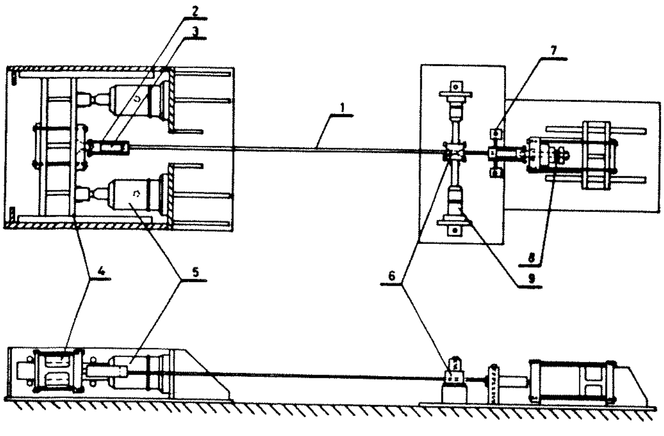
Figure 2. General view of tension-bending test rig, looking from the dead end.

The sheave bending tests were designed to simulate the conditions at the fairleads of a semi-submersible, rather than winching or craning operations. To that end, the rope was bent through 45 degrees on a sheave of fairly tight radius under a cyclically varying axial load and simultaneous small axial displacements to model the rope extension between fairlead and winch.

The paper also describes comparisons between the theoretical behaviour of parallel fibre multi-filament ropes in areas of high curvature, and that observed in the tests.

TENSION-BENDING TESTS

Figures 2 and 3 show the general arrangement of the axial testing rig. In this equipment, one end of the specimen was restrained by a hold-down bolted to a strong floor. The other



1 - Parafil specimen 2 - Connector
3 - Termination 4 - Moving frame
5 - Axial jack 6 - Clamping block
7 - Lateral restraint of termination
8 - Load cell 9 - Transverse jack

Figure 3. General arrangement of the tension-bending test rig.

end of the specimen was loaded by two 0.5MN dynamic capacity jacks through a cross-head moving on roller bearings, Figure 4. These jacks reacted against a robust frame also bolted to the floor, and were supplied with oil by a servo-controlled system with a low rate of oil delivery so that only quasi-static loading was possible. The axial load in the cable was monitored at the dead end by a very sensitive 1MN capacity quartz load washer. The electric charge from this piezo-electric force transducer was

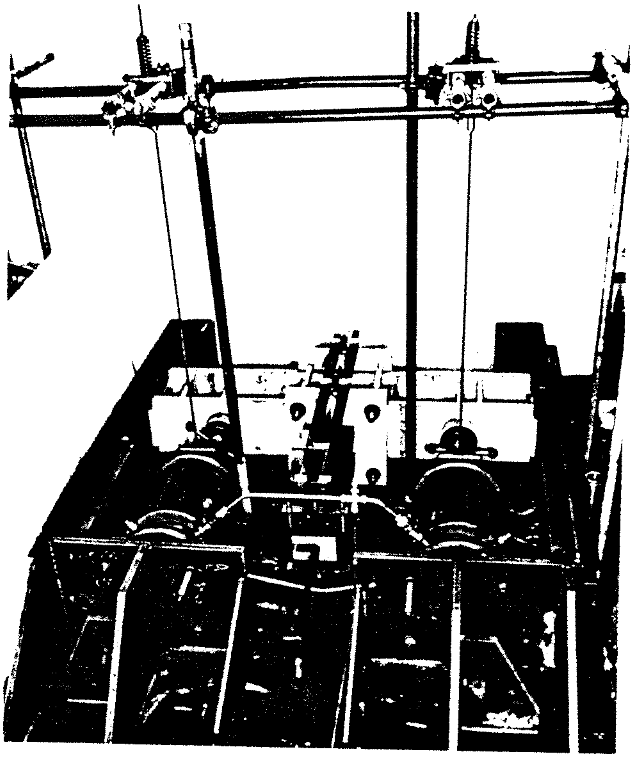


Figure 4. Tension–bending test rig. Moving end details.

fed into a charge–amplifier which converted the signal into a voltage. This could then be displayed on a digital voltmeter or, alternatively, on an X–Y plotter.

Cyclic lateral movements were imposed on the cable by a pair of 0.1 MN dynamic capacity jacks (Figure 5) acting on a block clamped onto the cable. This lateral exciter consisted of a light alloy block, with internal radii to reduce stress concentrations at the clamping point, which ran horizontally on four ball races on a machined steel table that was clamped to the laboratory floor. A top plate over the ball races prevented the clamp from lifting.

One jack was supplied with oil from an Amsler Pulsator (flywheel–based) fatigue machine, while the second acted as a constant force return spring, being connected to an Amsler accumulator which contained pressurized nitrogen over hydraulic oil and provided a nominally constant pressure.

The movement of the exciter (clamp) in the horizontal plane was continuously monitored by a displacement transducer. The frequency of the oscillation was 4Hz.

In order that the exciter movement could be converted into a local curvature in the specimen close to a termination, it was necessary to immobilize that termination against lateral movements. At the start of Test 1, the exciter was close to the moving crosshead and the termination at the crosshead was laterally restrained to form the test site. This location proved unsatisfactory for a number of reasons discussed below and the exciter was relocated during test 1 to a position close to the dead end, and the specimen turned round and reclamped against lateral movements at that end. This arrangement (Figure 6) employed shims against 200mm square hollow section supports, and was used in all subsequent tension–bending tests.

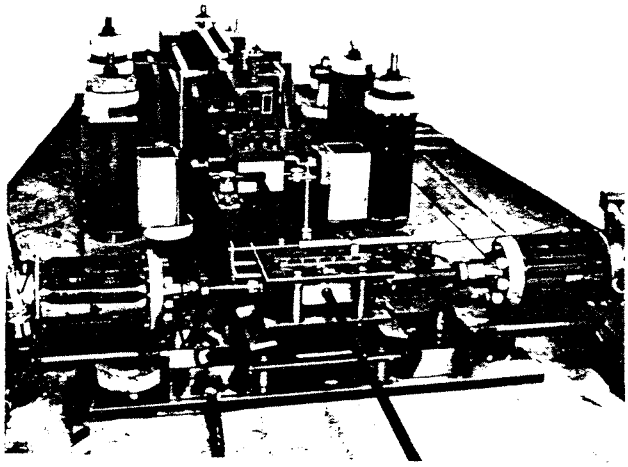


Figure 5. Transverse jacks and dead end details.

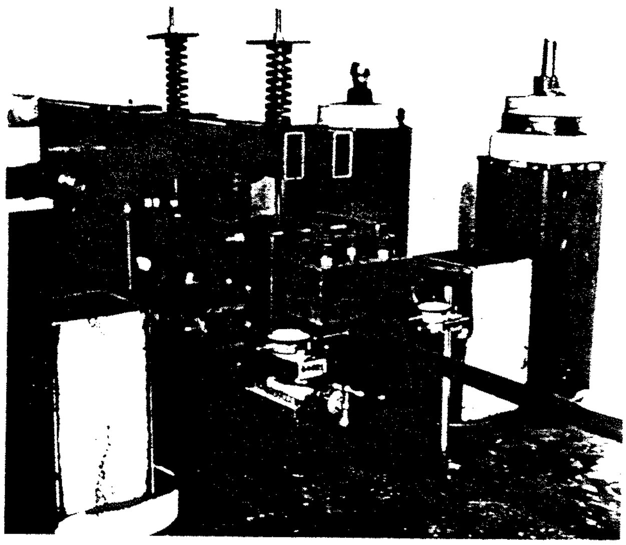


Figure 6. Lateral restraint on the termination and travelling head for deflection measurement.

Results and commentary

Table 1 summarizes the tension-bending tests

Test	Preload [kN]	Amplitude ± deg*	Cycles	Comments
1	300	0.7 then 1.5	237,000 94,600	Live end test site Dead end test site Failure at socket
2	300	1.5	69,000	Failure at deflector Radius of deflector then increased from 500mm to 1000mm
3	300	1.5	236,000	Failure at deflector
4	200	1.5	1,000,000	No failure in fatigue test Residual tensile strength 0.530 MN, failure at deflector
5	400	0.75	473,000	Failure at deflector

* i.e. half-range

Table 1 : Tension-bending tests

Test 1: Details

As noted above, the transverse jacks which applied a bending displacement near the rope termination were initially positioned close to the moving crosshead of the rig. This had been acceptable for testing steel spiral strands. Parafil ropes, however, are more extensible and this flexibility caused considerable problems in maintaining both the required axial tension and providing effective lateral restraint for the end connector at the same time.

As a result, the transverse jacks were moved close to the dead end of the rig. It was possible to get closer to the dead end with the exciter than had been achieved at the live end (1170mm from the front face of the socket as compared with 2450mm previously, in a specimen 6630mm long between socket faces), due to the different arrangement of holding down bolts at the two ends. The dead end termination then became the test site. In consequence, a much more rigid transverse support could be provided to the test termination so that the applied curvature could be measured and controlled much more accurately in static and dynamic tests. The maximum applied deflections of the rope were then equivalent to $\pm 1.5^{\circ}$ as compared to roughly half this value before. In addition, the axial force transducer, located in the dead end crosshead, was protected from lateral disturbances and functioned with much greater stability. A further advantage was that the curvature measurements were now taking place at the fixed end, so the rope was not moving relative to the transducer.

The rope had been subjected to 237000 cycles at an amplitude of ±0.7 deg. prior to the change over, and then failed after 94600 cycles of ±1.5 deg. in the new position. Failure occurred at the restrained socket. As with most failures of Parafil ropes, not all fibres failed at exactly the same point; in this case, failure was spread over a length of about 100mm.

Test 2 : Details

In this test failure occurred at the deflector at 69000 cycles rather than at the termination. It was suspected that while the clamp block held the outer polyethylene sheath of the specimen very snugly, the Parafil bundle inside contracted radially under axial load (as a result of Poisson's ratio or the very shallow helical lay present in the nominally parallel filament bundles) causing a radial clearance between bundle and sheath. The high localized pressures then induced as the deflector moved from side to side coupled with a bending angle some 20% greater than at the termination could have led to failure, in spite of the large internal radius of curvature (500mm) of the clamp block.

Additionally, there may well be some inter-fibre fretting as fibres on the outside of the bundle try to take a shorter path as the rope is displaced. The individual fibres within the rope do not completely fill the cross-section, and there is about 10% more space than would be required for perfect packing of cylinders. Thus, individual fibres may be able to move within the bundle, even if the outer sheath remains perfectly round. At the termination, every fibre is held by the spike in its original position relative to its neighbours, so the potential for such fretting is much reduced, although not eliminated entirely.

As a result of these considerations, the radius of the deflecting block was doubled (to 1000 mm), in an attempt to reduce the damage to the specimen at the deflector in subsequent tests.

Test 3: Details

As noted in Table 1, the increased radius of curvature led to a significant increase in the fatigue life in this test. However, failure again occurred at the deflector rather than at the clamp. Time did not permit further modifications to the exciter (although a number of ideas were debated).

Test 4: Details

In this test, at a reduced axial load, the specimen reached 1 million cycles, and rather than run the test until failure it was decided to check the residual axial strength of the cable. This was found to be 0.53 MN, with failure again at the deflector as compared with a mean value of 0.597 MN observed in short term static tests on similar ropes (Chambers, 1986). Chambers' tests were carried out using an identical rope and the same terminations, with a length between terminals of about 7.5 m; the results are thus directly comparable with the present tests.

Test 5: Details

In this test at a higher axial load (400kN) and a reduced angular movement (±0.75°) failure occurred yet again at the deflector.

Temperature measurements

During the tests the temperature on the surface of the rope was measured by thermocouples at :

- the mouth of the termination;
- half way between the termination and the deflector;
- the deflector;
- a point far from the influence of the deflector

As a typical example, for test 3 at an ambient temperature of 22°C the temperature rises found at these four locations were 12°C, 10°C, 2°C and 0°C respectively.

In spite of the high test frequency and rigorous test regime, these increases were all rather small: Similar tests on wire ropes (Strzemiecki and Hobbs, 1988) rapidly develop temperature increases approaching 80°C at the termination. The small increase at the deflector may be explained by the higher thermal conductivity of the aluminium deflecting block, as compared with steel. The deflecting block makes contact with a considerable length of the rope at the extremes of each cycle, whereas the body of the termination is in close contact with the sheath over a much shorter length of the mouth of the socket.

With the lateral exciter placed asymmetrically, the deflecting angle in the two ends of the rope are different. There will thus be a higher shear displacement in the fibres between the exciter and the dead end, than in the fibres between the exciter and the live end. This will lead to higher axial movement between the fibres, and increased heating in that part of the rope, as was observed.

Bending stiffness measurements

Several attempts were made to obtain a bending stiffness of the cable. In principle, this can be done by tensioning the cable, deflecting it at a known distance from the socket and deducing the curvature formed by the cable at the termination by measuring offsets from the undeformed position at several points along the rope.

In order to measure the curvature accurately a special device was designed which made it possible to eliminate rigid body movements (left hand dial gauge in Figure 6).

In each of several sets of measurements it was found that the cable had no significant curvature as it left the termination, so that any curvature took place entirely in the neck of the socket. The straight line measured intersected the termination centre line typically 13mm inside the termination. For an angular offset of 2.0°, the maximum static value used, simple geometry suggests that even if the curvature started immediately inside the socket neck, the radius of curvature was only 372mm, and it is likely to have been significantly less than this.

Tie beam theory suggests that the axial preload, T, the radius of curvature, ρ, the angular offset, θ, and the effective second moment of area I, are related by

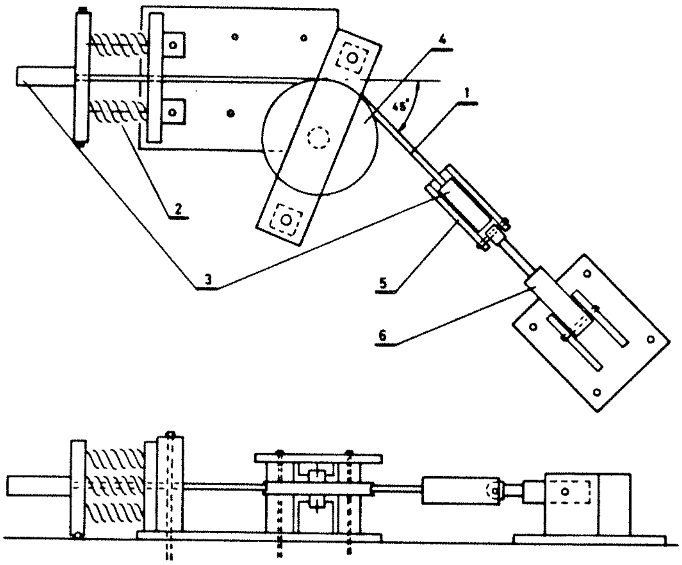
$$I = \frac{T}{E}\left[\frac{\theta}{\rho}\right]^2 \qquad (1)$$

Taking 372 mm as an upper bound on ρ, the effective second moment of area was only 400mm^4, or about 1% of that of a solid circular rod of the same diameter. Thus, in spite of the axial preload, the Parafil bundle was functioning very much as a bundle of discrete fibres able to slide freely over one another rather than as a solid rod. This freedom to slide also implies very small bending stresses in the individual fibres rather than the large axial stresses which would appear in the extreme fibres if plane sections were remaining plane across the bundle.

These low stresses are one factor in the unexpectedly high resistance to tension-bending fatigue at the termination. Another pertinent factor is the relatively small fretting movements which occur in bending as compared with those found in a purely axial (tension-tension) fatigue situation. In tension-tension fatigue, failures have been found by other authors (Crawford, 1988) to initiate from fretting on the nose of the spike (Figure 1). In bending, such movements on the spike are less than those that occur at the extreme fibres, and (of course) are concentrated at the two points on the spike at the greatest distance from the neutral axis rather than taking place uniformly all round the spike.

SHEAVE BENDING TESTS

Figures 7 and 8 show the general arrangement of the sheave bending rig, which provided a 45° wrap angle around a 700mm diameter steel pulley with a 35mm diameter semi-circular groove. This groove provided a fairly loose fit to the 30mm diameter polyethylene sheath of the specimen more typical of fibre rope practice than of wire rope practice.



1 - Parafil specimen
2 - Springs
3 - Terminations
4 - Sheave
5 - Connector
6 - Jack

Figure 7. General arrangement of the sheave bending test rig.

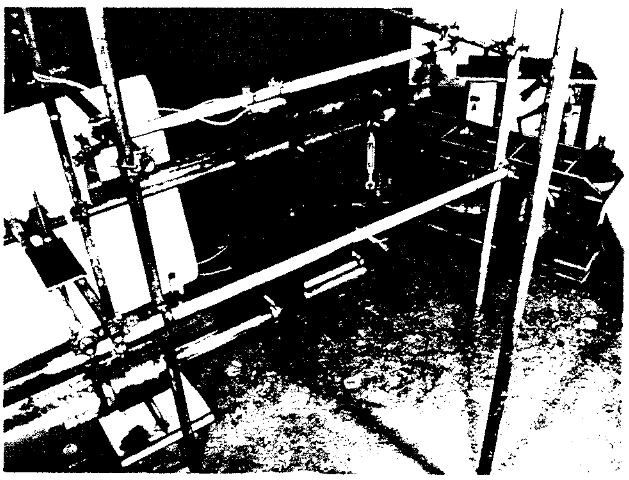


Figure 8. General view of sheave bending test rig.

One end of the specimen was connected to a 0.5MN jack which was supplied from a servo-controlled hydraulic system. The other end was fixed to a vertical plate (Figure 9) supported by six heavy springs reacting against a fixed vertical plate connected to the strong floor. This spring set provided a deliberate addition to the axial flexibility of the specimen. This flexibility (100mm stroke for a load change of 300kN with six springs, equivalent to a 12.2 m length of rope, and pro rata with a smaller number of springs) made it possible to provide the desired movement on the sheave while retaining a short specimen and a compact rig.

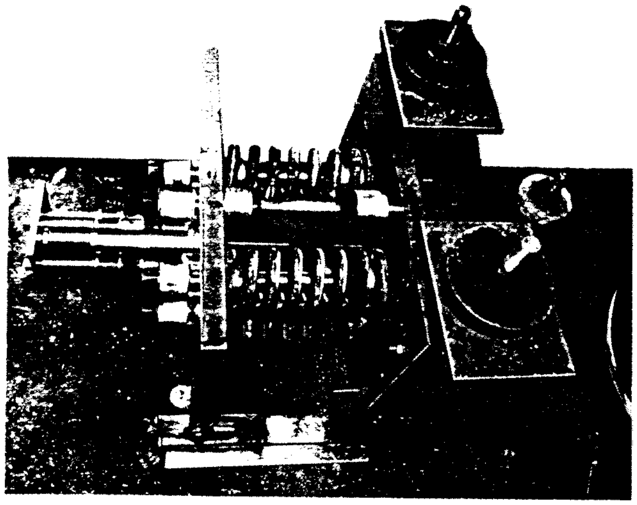


Figure 9. Sheave bending test rig. Spring end showing 4 springs for 20 Tonne test.

Using this arrangement, the load in the specimen was varied cyclically from near zero to full load. Because of the spring deflection and specimen flexibility, a movement of rather more than 100mm was achieved at the pulley, with an angle of rotation of the sheave of about 16°. The cycling frequency was low (about 17 sec/cycle), and was restricted by the limited hydraulic power available rather than by considerations of specimen heating.

Results and commentary

Table 2 summarises the sheave bending tests, while Figure 10 shows the same results in graphical form. Because of the high lives achieved in tests 4-6, a test with a load range of 150kN which had been included in the original programme was not run. All ropes failed at one of the points where the rope is alternately straight or curved during each cycle. It is thus presumed that failure was caused by inter-fibre fretting, which must be highest in these regions.

Test	Load range* (kN)	Number of cycles to failure	Comments
1	300	4000	In all tests failure occurred at the sheave
2	300	4550	
3	300	4045	
4	200	28000	
5	200	13100	
6	200	23250	

* with a minimum of circa 1.5kN in all cases

Table 2 : Sheave Bending Test Results

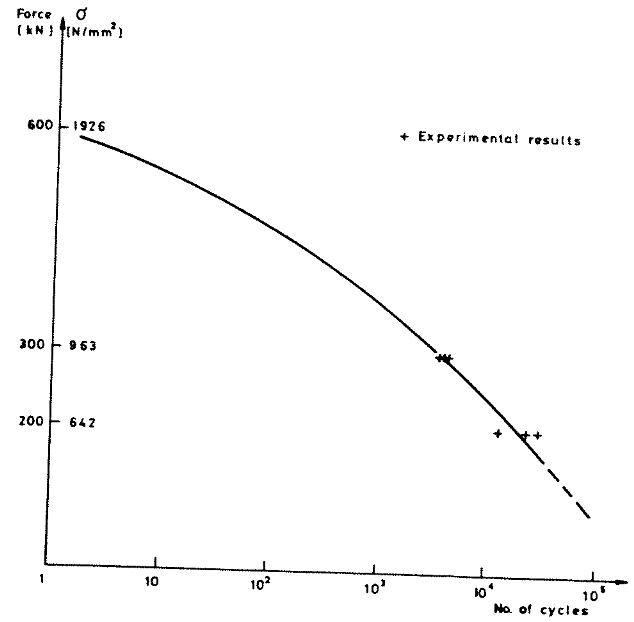


Figure 10. Axial load versus number of cycles to failure for the sheave bending test. 1926 N/mm² is the nominal strength of the ropes in static tension.

In the course of tests 3 and 4, a number of static measurements of Young's modulus were made, using a temporary pack to block the spring extensions. The results of the measurements during test 4 are shown in Figure 11.

The nominal radial pressure between sheave and specimen is given by

$$p = \frac{2T}{dD} \qquad (2)$$

where p is the pressure, T the axial load and d and D are the groove and sheave diameters respectively. For a 300kN axial load, this pressure is close to 30N/mm² in the present case. In spite of this high value, the lives to failure are certainly greater than some of the more pessimistic guesses made before testing started.

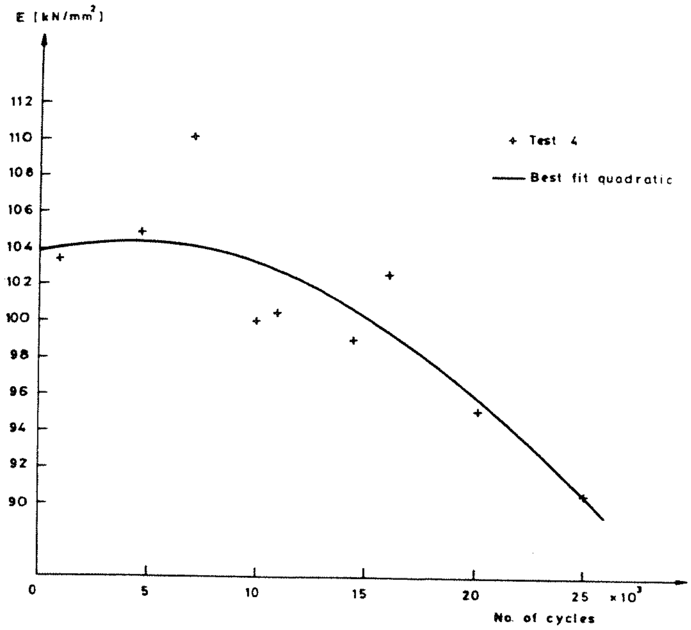


Figure 11. Measured Young's modulus versus number of cycles of loading during test 4. The axial load varied between 1.5 and 200 kN in each cycle.

CONCLUSIONS

In tension-bending fatigue, the area adjacent to the termination proved to be less vulnerable than had been expected, and indeed was less vulnerable than the area within a carefully radiused deflector clamp which caused an angular offset only a little larger than that taking place at the termination. With a preload of 300kN on a rope with an ultimate load of 600kN, a life in excess of 240,000 cycles can be expected at an offset of ±1.5° (3° range) at the termination.

In sheave bending fatigue, lives of around 4000 cycles were obtained with an axial load range of 300kN (that is 50% of the ultimate load of 600kN), and about 20,000 cycles with a load range of 200kN, using a pulley with a D/d ratio of 23.

Acknowledgements

The work described in this paper was undertaken as part of a study of the potential use of Parafil in mooring systems for offshore oil rigs. The project was coordinated by Advanced Production Technology Ltd on behalf of a consortium of industrial companies, whose assistance is gratefully acknowledged.

Kevlar is a trade name of EI DuPont de Nemours.
Parafil is a trade name of ICI Linear Composites Ltd.

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