

EVALUATION OF FIBRE ROPE PROPERTIES FOR OFFSHORE MOORING

By

Steve Banfield

Tension Technology International

and

Neil Casey

National Engineering Laboratory

SUMMARY

An examination has been conducted of fibre rope mechanical properties measured in laboratory tests on materials, constructions and terminations intended for deepwater mooring applications. This data combined with field experience provides a better understanding of rope behaviour and enhances the knowledge required to engineer fibre ropes for these demanding applications.

This has also led to improved laboratory test techniques for measurement of mechanical properties relevant to mooring system response analyses required to meet regulatory requirements. Preliminary evaluation of this data also indicates that a post test evaluation method to determine retained properties of insert strops removed from mooring lines may be possible.

INTRODUCTION

Thirty years ago, fibre ropes were proposed for platform moorings and since then numerous studies, test programs and field trials have been conducted. Fibre lines should soon be installed for the taut mooring by Petrobras on an Early Production System, with three further planned for 1997/1998. This paper starts with a brief overview of current fibre rope use in offshore applications.

It is widely accepted that within a mooring line there are three line tension components⁽¹⁾. These are:

- \$ Static component due to mean environmental load.
- \$ Slow varying component due to platform second order motion.
- \$ Dynamic component due to platform wave frequency motion and dynamic line response.

The mooring system must be designed so that it has enough axial stiffness to stop the platform from drifting too far off station while having sufficient compliance to avoid overload in the lines resulting from the motions of the platform under the influence of first and second order wave forces. The behaviour of axial stiffness under loading conditions applicable to offshore mooring conditions has been seen as an important consideration for some time⁽²⁾. The work presented in this paper goes some way towards evaluating, under cyclic loading conditions, the behaviour of axial stiffness and to a lesser extent the other important properties of elongation and hysteresis. The potential for establishing an empirical relationship, between axial stiffness and residual breaking strength is also discussed.

As well as affecting the mechanical properties, the varying tensions within a mooring line means that fatigue damage can result. In order to take the possible effects of fatigue into account a benchmark to aid the design engineer is required. At present this benchmark comes in the form of design S-N lines. The API RP 2FP1⁽³⁾ recommends that a mooring component should have a fatigue life of three times the design service life. As stated in the API document the factor of three accounts for uncertainties in lifetime load prediction, scatter in fatigue data, approximations in linear damage theory and the effect of many mooring components being connected in series. Most design S-N lines are made up from constant amplitude tension - tension fatigue data but it is important that the data from which the design line is produced encompasses the range of loads expected to be seen in service. However, to demonstrate that fatigue may not be a problem for fibre ropes a comparison will be made between the fatigue performance of fibre rope to that of wire rope.

CURRENT FIBRE ROPE USAGE

A summarised list of rope usage is shown below to illustrate the wide variety of engineered applications where fibre ropes have already been used. This is not intended to be a complete list of all offshore mooring applications, since that would deserve a paper in its own right.

Some of these fibre rope systems have been designed for 20 year life taking into account tension-tension fatigue, creep and hydrolysis. In some of the applications listed below, yarn or rope residual strength was measured and gave typically between 90-100% retained strength when compared to new average strength. Since there is a margin between minimum and average strength, if this data were compared on a minimum strength basis it could be stated that the ropes still meet their design strength.

- X polyester parallel yarn 200 tonne break load riser arch tether with around 1 year usage to date in North Sea
- X polyester parallel yarn 100 tonne break load riser arch tether with around 10 years usage to date in North Sea
- X US Navy 1/3 scale polyester parallel sub-rope 40 tonne break load platform mooring in 890m w.d. (water depth) for over 2 years
- X supply vessel mooring with 300 tonne break load polyester parallel sub-rope in 300 metres w.d. for nearly 3 years in Gulf of Mexico
- X semi-submersible trials in 400 tonne break load polyester parallel sub-rope for one year in 220m w.d. In Campos basin
- X polyester wrc (wire rope construction) 400 tonne break load in riser protection nets on 2 TLPs, 2 and 3 years service to date
- X semi-submersible trials in 400 tonne break load polyester 7 strand wrc for one year in 115m w.d. in Campos basin
- X swamp mooring in 200 tonne break load polyester parallel sub-rope for 7 years service
- X polyester parallel yarn raft mooring after 20 year service in Brixham harbour
- X meteorological buoy moorings in polyester, nylon, aramid and HMPE ropes
- X aramid 36 strand wrc 450 tonne break load semi-submersible mooring trial
- X aramid 6 strand wrc 93 tonne break load buoy mooring trial
- X hmpe parallel strand 250 tonne break load oil flowline tether West of Scotland

FIBRE ROPE PROPERTIES - TEST PROCEDURES

Static Strength Tests

5 Tonnef Ropes

For each rope and termination type three tests were conducted to establish the actual break strength of the test strop. Testing was carried out with the strops fully immersed in tap water. Each strop was initially loaded up to 60% of the manufacturer's nominal strength. The load was then reduced to a nominal value before being loaded to failure.

120 Tonnef Ropes

These ropes were tested in the dry condition and were normally loaded to 50% of the manufacturer's nominal strength for 10 times before being loaded to failure. The strengths obtained for the aramid and polyester ropes were appropriate to the state of the art terminations that were used at the time. New splice technology was developed by TTI for the HMPE ropes.

Fatigue Tests

All fatigue tests were carried out using a fixed mean load, as opposed to a fixed minimum load, which has often been the approach adopted in the past. Testing about a fixed minimum load assumes that there is no mean load effect upon fatigue life.

5 Tonnef Ropes

The 5 tonnef ropes were fatigue tested whilst fully immersed in ordinary tap water. Each strop was pre-loaded once to 60% of the manufacturer's nominal strength before fatigue testing. Once on mean load the machine limits were set for overload, underload, overstroke and understroke. Exceeding these limits during a machine load cycle automatically closed down the system. Also at this stage in the process data logger initialisation (Kiethly 500A running Labtech Notebook) was carried out and the test started. Testing was continued until the sample could no longer support the fatigue test load. Once the sample had failed the location of main failure was noted. Testing was normally carried out at frequencies between 1 and 2 Hz.

120 Tonnef Ropes

The procedure for the 120 tonnef ropes was essentially the same as that adopted for the 5 tonnef ropes. However, whereas the 5 tonnef ropes were tested fully immersed in water the 120 tonnef strops were wetted by means of a water drip system. Testing was normally carried out at frequencies between 0.1 and 0.3 Hz.

Mechanical Properties

The mechanical property measurements presented in this paper were based on machine load and crosshead movement. Although not possible to quantify for the ropes tested, experience has shown that there is not a great deal of difference between mechanical properties measured by machine crosshead to those determined by an extensometer clamped to the rope. Work conducted on 40 mm steel rope⁽⁴⁾ revealed a maximum difference of 5% between crosshead and extensometer, after the extensometer readings had been adjusted to the full length of the sample. By collecting incremental values of machine load and crosshead movement during a given fatigue load cycle the following mechanical properties can be calculated.

Axial Stiffness (EA) [kN]

This is a measure of the resistance to rope elongation and is determined by evaluating the gradient of the rising load portion of the fatigue load cycle and multiplying that figure by the rope length. A linear fit has been assumed in determining the gradient of the rising load portion of the fatigue load cycle.

Modulus (E) [kN/mm²]

For a given fatigue load range the modulus is determined by multiplying the gradient of the loading curve by the test length and dividing by the area (A). For each rope tested the \sqrt{A} value was based on a reference diameter which utilised a packing factor. The packing factor is defined as the ratio between material volume and rope volume taking into account interstices between the filaments. The packing factors were used to define the rope reference diameter and only applied in the calculation of modulus.

Note: The modulus values of wire ropes were based on the steel area of the rope, not the circumscribed area.

Hysteresis [kN.mm]

This is a measure of the energy dissipated by the rope specimen during any given fatigue load cycle. The energy loss is represented by the area enclosed between the loading and unloading portions of the fatigue cycle.

Elongation [mm]

This is the increase in rope length which takes place during the course of a cyclic load fatigue test. The calculation is based around the mean length of the rope within any given load cycle. The origin is based on the first recorded load cycle.

RESULTS AND DISCUSSION

Figure 1 shows a sample set of axial stiffness values obtained for 5 tonne rope, plotted against load range. The plots show results from tests conducted on:

- \$ Aramid (type 1) wire rope construction, parallel strand and parallel yarn constructions.
- \$ Polyester (type 1) wire rope construction, parallel strand and parallel yarn constructions.
- \$ Aramid (type 2) parallel strand and torque balanced constructions.

Each of the ropes tested were terminated with potted resin sockets. The load ranges were expressed as a percentage of the manufacturer's nominal strength (MNS) value of each rope type. It can be seen from the legend key in Figure 1 that the MNS values were all very similar. All the ropes were tested at the same mean load of 40% MNS.

There are a number of observations to be made from the plots in Figure 1.

- \$ In each case there is a trend of decreasing axial stiffness with increasing load range.
- \$ There is a distinct material effect present, with polyester (type 1) having by far the lowest axial stiffness (50-150% lower than the aramid (type 2) and aramid (type 1). The aramid (type 2) material produced the highest values of axial stiffness with the aramid (type 1) material yielding values not much lower than those obtained for the aramid (type 2).
- \$ Both the polyester and aramid (type 2) materials do not appear to exhibit any noticeable construction effect. In contrast the aramid (type 1) material does appear to exhibit a pronounced construction effect with the axial stiffness of the wire rope construction being about 40% lower than the values obtained for the parallel strand and parallel yarn constructions.

Figure 2 shows the axial stiffness values plotted against load range (% MNS) for a series of tests conducted on:

- \$ Aramid (type 3) parallel yarn construction with potted resin sockets.
- \$ High Modulus Polyethelene (HMPE) parallel strand construction with looped and spliced terminations.
- \$ Polyester (type 2) wire rope construction with looped and spliced terminations.

The ropes were each rated at an MNS of 120 tonne (1177 kN). There are a number of observations to be made from Figure 2.

- \$ As with the 5 tonne ropes there is a trend of decreasing axial stiffness with increasing load range.
- \$ Since the tests were conducted at two different values of mean load the results show (albeit limited) that axial stiffness is also dependent upon mean load.

Although the data set is limited it would appear that axial stiffness increases as mean load increases.

§ Again, as with the 5 tonne ropes there is a noticeable material effect present. The polyester (type 2) again exhibits the lowest axial stiffness values. Aramid (type 3) and HMPE are around 3.5 and 4.5 times greater respectively.

In order to make a comparison of properties between fibre rope and wire rope, modulus values were worked out for the test results presented in Figure 2 at 40% mean and presented as a ratio of the modulus of steel. These results are presented in Figure 3. Also in Figure 3 are modulus values of three constructions of 40 mm wire rope. This size of rope was chosen because they are broadly equivalent in strength to the 120 tonne fibre ropes. The three steel wire rope constructions chosen also compare favourably with the fibre rope constructions.

§ Steel six strand wire rope approximates to wire rope construction fibre rope

§ Steel multi-strand wire rope approximates to parallel strand fibre rope.

§ Steel spiral strand wire rope approximates to parallel yarn fibre rope.

It can be seen from Figure 3, that the modulus of both fibre and wire rope decrease with increasing load range. It can also be observed from the figure that the range over which modulus varies is greater for the fibre rope than the wire rope. Modulus can decrease by as much as 50% for the polyester rope. With wire rope the variation is primarily associated with construction, whereas with fibre rope the variation is associated with material and possibly some constructional effect.

The graph in Figure 4 shows the relationship between axial stiffness and cyclic period for the three types of 120 tonne ropes considered. It can be readily observed from the graph that over the range of cyclic period considered (3 to 77 400 seconds) the axial stiffness of the polyester (type 2) rope remained effectively constant. In contrast the axial stiffness of the aramid (type 3) rope reduces slightly as the cyclic period increased, but by far the biggest reduction in axial stiffness as cyclic period increases occurs with the HMPE rope. The reduction between 3 and 77 400 seconds was around 24% and is probably associated with creep effects. The effect of increasing mean load upon increasing axial stiffness is also apparent from Figure 4.

The damaging effects of hysteresis heating upon fatigue life is demonstrated in Figure 5. The plots show the hysteresis energy resulting from two tests conducted on 120 tonne polyester (type 2) ropes. The test conditions for both ropes were identical with the exception of cyclic period. One rope was tested using a cyclic period of 6 seconds and the other rope was tested using a cyclic period of 3 seconds. It can be seen from Figure 5 that for both ropes, hysteresis reduces dramatically during the bedding-stage of a fatigue test. After that the hysteresis remains effectively constant until the end of the test where it shows signs of increasing as failure occurs. The fluctuations in hysteresis that occur in the plot resulting from the test conducted at a cyclic period of 3 seconds are thought to be associated with the uneven cooling effect resulting from

the use of a drip water feed system. The most interesting feature of the hysteresis plots in Figure 5 is highlighted when the two plots are compared against one another. After the ropes have bedding-in and the hysteresis is in the constant phase it can be seen that the hysteresis energy resulting from the test at a 3 second period is about 40% greater than the energy resulting from the test at 6 second cyclic period. Significantly, the test conducted at 3 second cyclic period failed after 49 640 cycles whereas the test at 6 second cyclic period failed after 138 300 cycles.

Figures 6 and 7 show the rope property plots resulting from two fatigue tests that were conducted on LCAP parallel yarn with potted resin sockets (MNS=49.02kN). In each case the fatigue test loads were the same, i.e. a mean load of 40% MNS and a load range of 65% MNS. The first test (Figure 6) resulted in failure of the rope within 50 mm of a termination after 12,420 cycles. This test was repeated (Figure 7) and the rope failed mid length after 185,480 cycles. Examination of Figure 7, which represents the mid length failure, shows that after approximately 80,000 cycles a gradual fall-off in axial stiffness started to occur. Also the rate of elongation increased during the last 10,000 cycles. These changes suggest that some form of measurable degradation was taking place within the rope material and the endurance achieved was representative of that particular material/construction. In contrast, however, the rope properties which resulted from the test that was an end failure (Figure 6) indicated that there were no obvious changes in stiffness and elongation to suggest that measurable material degradation was taking place. This, together with the differences between the two endurance values, suggest the test represented by Figure 6 was a genuine end failure and the endurance achieved was not representative of the rope material/construction.

The use of rope property plots to identify test results that were affected by poorly prepared terminations, and other factors such as too fast a loading frequency and lack of torque restraint, has been used successfully in the fatigue testing of wire rope⁽⁵⁾. With a steel wire rope the main form of degradation in fatigue is wire breaks and the occurrence of wire breaks tend to be uniformly distributed along the length of the rope. The occurrence of these wire breaks have a noticeable effect upon the properties and the resulting shape of a typical property plot is similar to those presented in Figure 7. For tests that failed due to poorly prepared terminations the condition of the rope was relatively good and the shape of the property plot similar to those presented in Figure 6. The use of the property plots in conjunction with counting the number of wire breaks in short lengths of tested rope proved to be very effective at highlighting results that were effected by poorly prepared terminations. Using this method of fatigue test assessment means that for steel wire rope not all end failures have to be rejected .

Whether or not a similar post test assessment method can be adopted for fibre rope depends largely on being able to relate changes in properties to a damage mechanism. The fact that gradual changes in properties have only occurred in ropes of parallel yarn construction, and these changes have not yet been related to a particular damage mechanism means, that further work is required in this area before fatigue test assessment criteria can be developed.

More recent work using 40 and 70 mm six strand rope⁽⁶⁾ has demonstrated the existence of an empirical relationship between axial stiffness and residual breaking strength. The approach adopted was to conduct a series of partial life fatigue and break strength tests. The axial stiffness recorded at the point each fatigue test was stopped was correlated with the residual break strength of the rope. No partial life fatigue and break tests have been conducted on fibre ropes to establish if a similar relationship exists. However, as a demonstrator, the following discussion assumes that such a relationship may exist for fibre ropes. The axial stiffness-fatigue cycle plot in Figure 8 resulted from a test conducted on a 5 tonne aramid (type 4) sample of parallel strand construction and terminated with resin potted sockets. The mean load was 40% with a load range of 50% MNS (MNS=49.01kN). Also shown in Figure 8 is a plot of approximate residual breaking strength with fatigue cycles. This plot was obtained by converting the axial stiffness data to residual breaking strength data. Assumptions were made to allow this plot to be generated.

1. The load at which the rope failed in fatigue was assumed to be the upper fatigue load value. The last recorded value of axial stiffness was taken to correlate with the assumed failure load.
2. Experience has shown that during the early stages of a fatigue test the breaking load of a rope can increase. In producing the residual breaking strength plot in Figure 8 it has been assumed that the strength of the rope increased by 5% over the value obtained during static break strength tests. The axial stiffness between 50 000 and 100 000 cycles was taken to correlate with that breaking strength value.

Using the two pairs of values of axial stiffness and residual breaking strength slope and intercept values can be obtained and used to convert the axial stiffness data in Figure 8 to approximate residual break strength. The graph indicates that for the fatigue test load considered, that rope breaking strength starts to fall off after around 400 000 cycles with the biggest fall off taking place during the last 60 000 cycles. It should be noted that this work is unsubstantiated but has been included to illustrate the potential of measuring rope mechanical properties for future practical applications.

Of key interest to the platform owner or operator is the mean fatigue life and fatigue life variability of the platform mooring lines in operational conditions. Variability is an important consideration, not least for fatigue but also static strength and mechanical properties. Although not addressed in this paper there are several factors which will have a direct bearing on variability, including⁽¹⁾:

- \$ Consistency of manufacture and assembly of the yarns into rope.
- \$ Termination design.
- \$ Termination procedures.
- \$ Test methods and procedures.

- \$ Variation in degradation mechanisms.
- \$ Traceability of measurement.

Of the above, one factor which has significant influence on the variability on fibre rope static and fatigue strength is the design and consistency of termination procedure. One termination type can perform better than another type for the following reasons ⁽¹⁾.

- \$ Variations in the current stage of development of the termination for the particular material and rope constructions involved.
- \$ Variations in consistency during termination preparation and fitment between termination types.
- \$ The effect of yarn surface finish upon termination efficiency.
- \$ The effect of rope construction upon termination efficiency.

The majority of fatigue data for both wire and fibre rope has been generated in the laboratory using relatively short sample lengths. Also as for fibre ropes this has led to a pre-ponderance of failures at or near the terminations. After surveying the existing literature on wire rope fatigue, Chaplin ⁽⁷⁾ in his contribution to the Wire Rope Endurance Joint Industry Study ⁽⁷⁾ concluded that the most reliable data is that presented by NEL ^(4,8) and others ^(9,10) and that these data are preferably plotted in terms of actual breaking strength (ABS) rather than list strength. The data also agrees quite well with the subsequent data obtained by Reading University ⁽¹¹⁾.

Since fibre rope is now being actively considered for deep water mooring applications, it is appropriate to include a brief comparison of wire rope and fibre rope fatigue. In order to make the qualitative comparison between mean fibre rope and wire rope data as meaningful as possible, only the 120 tonne fibre rope data has been considered. The data will be compared with the 40 mm rope data (six strand rope, multi-strand rope and spiral strand) that was generated during the Department of Energy Pilot Study ⁽⁴⁾ and the Wire Rope Endurance Joint Industry Study ⁽⁷⁾. These data can be found in tabulated form in a paper by Casey ⁽¹²⁾. The 40 mm wire ropes were chosen for the comparison because they have similar breaking strengths as the 120 tonne fibre ropes. All of the wire rope data was obtained using potted resin inside steel cylindrical sockets with the load being transmitted through the front faces of the sockets.

The wire rope data presented in Figure 9 was assessed as being suitable for the generation of design load/endurance curves. The assessment was made using criteria developed at NEL ⁽⁵⁾. Every wire rope fatigue test was subjected to a post test assessment which involved an examination of rope property (and temperature) plots, and a wire break count in a one lay length section of the tested rope. The section was completely dismantled to obtain the total number of wire breaks. This work also demonstrated that for wire rope subjected to constant amplitude fatigue the occurrence of wire breaks are distributed uniformly along the length of the sample ⁽⁵⁾. Conducting a wire break count, therefore on a one lay length section provides meaningful information on the condition of the entire length of the sample.

The rope property (and temperature) plots together with the results of the wire break counts were used to determine if the results were adversely affected by:

- \$ Poorly prepared terminations - usually misalignment of the sockets.
- \$ Overheating of the rope - resulting in the blocking material changing viscosity and running out of the rope.
- \$ Rotation of the sample - the terminations were normally held within torque restraining brackets but occasionally the system failed to work thus allowing the sample to rotate⁽⁵⁾.

The use of post test assessment criteria means that the wire rope data presented in Figure 9 probably represents the best performances that can be achieved by 40 mm wire rope in the various constructions tested and the test lengths used.

In comparison to the wire rope data only a small number of 120 tonne ropes of a given material and construction were tested during Fibre Tethers 2000¹ and as yet, no fatigue test assessment criteria have been developed for fibre rope. It is known that some of the 120 tonne fibre rope data have been affected by poorly prepared terminations and it is believed that some of the ropes were affected by overheating to some extent due to accelerated test conditions, particularly the HMPE and polyester (type 2) ropes. For both wire and fibre ropes the failure criterion was that testing was continued until the rope could no longer support the fatigue test load. Owing to the small number of data points available for the 120 tonne fibre ropes the following analysis is a qualitative one only. The trendline lines fitted to the data points must be regarded as being equivalent to drawing the best line >by eye= fit through the data in the way the axes are presented.

Most previous studies of fibre rope tension-tension fatigue were dominated by failures at/near the termination^(13 18).

In Figure 9 the wire rope data is compared with the fibre rope data. For both the fibre and wire data the fatigue load ranges have been expressed as a percentage of the ABS of the rope, as fitted with the terminations with which they were fatigue tested. First observations suggest that the performance of the aramid (type 3) is far in excess of steel wire rope. However, it should be noted that the average ABS (992 kN) obtained for the aramid (type 3) rope was below that of the 1177 kN MNS value. The low ABS is directly attributable to poorly prepared terminations and with correctly prepared terminations the ABS should have exceeded 1177 kN. This would have the effect of lowering the % ABS value of each of the aramid (type 3) data points. That being said, however, the poor termination efficiency will have also adversely affected the fatigue endurance values, since two of the tests resulted in end failures. Taking both factors into account it can be concluded that the performance of the aramid (type 3) material is probably superior to that of 40 mm wire rope, with the potential for significant improvements to be made through improved termination efficiency.

The performance of the HMPE in parallel strand construction with looped and spliced terminations is also probably superior to that of 40 mm wire rope as illustrated in Figure 9. The average ABS of the HMPE ropes was some 5 per cent above the 1177 kN MNS value.

Finally, Figure 9 shows that the polyester (type 2) is on par with the performance of wire rope. This result is somewhat misleading because the average ABS of the polyester rope was 1528 kN, essentially making it overstrong for its 120 tonne rating. Even without taking that fact into account (which has the effect of lowering the %ABS values) the polyester samples suffered from eye failures due to the absence of factory prepared protection and some degree of overheating also took place. The potential for improvement means that substantial gains in fatigue performance could easily be made. To help serve to confirm that axial tension fatigue may not be a problem for fibre rope three fatigue tests were conducted on 5 tonne polyester (type 1) rope of parallel strand construction. The tests were all conducted wet and under the same load conditions. The only difference in each case was the terminations. One strop was terminated by splicing, the other was fitted with potted resin sockets, and the third strop was fitted with barrel and spikes. Details of the tests can be found in Table 1. The strop that was fitted with barrel and spikes failed after 8 306 200 cycles. Abrasion of the rope within the barrel and spike caused the failure. Testing of the other two strops was stopped after 12 000 000 cycles with no sign of impending failure.

CONCLUSIONS

The results of the work conducted on rope mechanical properties have shown that they can be influenced by the following factors.

- \$ Material/scale
- \$ Construction/geometrical properties
- \$ Material degradation
- \$ Load range and mean load
- \$ Cyclic loading period (at rates faster than expected in offshore mooring)

The axial fatigue performance of fibre rope compares well against that of wire rope and fatigue may not prove to be a problem for future fibre rope mooring lines. However, other factors such as heat and compression effects may need to be addressed.

For the purposes of mooring response analysis, those fibre ropes that show significant non-linear properties should be taken into account. Software tools need further development to fully take into account such non-linearities.

Bedding-in effects significantly change rope properties. Any test procedures should monitor and record this effect by having an increasing load incremental bedding-in procedure. Otherwise, interpretation of test data with bedding-in effects can lead to false data intended for engineering analyses.

For deepwater mooring ropes, currently rejection criteria can only be determined by testing short insert strops periodically removed from service. Measurement of strop residual strength only gives one data point and does not give any information to the residual fatigue life. Property plot monitoring could be developed to determine residual fatigue life on strop inserts removed from service.

The knowledge from laboratory, field trials and applications is accumulating and showing plenty of good evidence that fibre ropes will find many applications in temporary and permanent deepwater moorings.

REFERENCES

- 1 Fibre Tethers 2000. A High Technology for Fibres for Deep Water Tethers and Moorings@. Noble Denton Managed Joint Industry Study. Final Report L17317/NDE/RWPS. 10 February 1995.
- 2 Chaplin, CR and Del Vecchio, CJM. A Appraisal of Lightweight Moorings for Deep Water@. OTC 6965. 1992 Offshore Technology Conference. OTC Houston. May 1992. pp 189-199.
- 3 API 2FP1. A Draft Recommended Practice for Design, Analysis and maintenance of Mooring for Floating Production Systems. First edition. May 1991.
- 4 Department of Energy Pilot Study. A Tension-Tension Fatigue Tests of 40, 70 and 127 mm Diameter Six Strand Steel Wire Ropes. NEL Report ENER/30. May 1996.
- 5 Casey, NF. and Waters, DM. A Condition Monitoring for Fatigue Test Assessment and Life Prediction@. Conference Proceedings. OIPEEC Round Table Conference on Wire Rope Discard Criteria. Zurich. September 1989. pp 7.1 to 7.20.
- 6 Casey, NF. A The Use of Axial Stiffness to Approximate Residual Breaking Strength of 40 and 70 mm Six Strand Rope Subjected to Constant Amplitude Tension-Tension Fatigue. Un-published document.
- 7 Final Report of a Noble Denton Managed Study into the A Prediction of Wire Rope Endurance for Mooring Offshore Structures@. April 1991.
- 8 Department of Energy. A Wave Energy Moorings Study@. NEL Report ENER/14. 1984.

- 9 Reemsnyder, HS. AThe Mechanical Behaviour of Fatigue Resistance of Steel Wire Strand and Rope@. Homer Research Laboratories. Bethlehem Steel Corporation. Bethlehem PA. June 1972.
- 10 Zimmerman, Z and Reemsnyder, HS. A Axial Corrosion Fatigue of Wire Rope@. Offshore Technology Conference. OTC 5027. May 1992.
- 11 Potts, AE, Chaplin, CR and tantrum, NRH. A Factors Influencing the Endurance of Steel Wire Rope for Mooring Offshore Structures@. Offshore Technology Conference. OTC 5718. May 1988.
- 12 Casey, NF. AThe Fatigue Endurance of Wire Ropes for Mooring Offshore Structures@. Proceedings of the OIPEEC Round Table Conference on the Application of Wire Rope Endurance Research. Delft. 8-10th September 1993. pp I.24 to I.49.
- 13 Crawford, H. and McTernan, LM. A Cyclic Testing of Continuously Wetted Synthetic Fibre Ropes@. Proceedings Offshore Technology Conference. OTC 4635. Houston. Texas. 2-5th May 1983.
- 14 Crawford, H. and McTernan, LM. A Fatigue Properties of Parafil@. Proceedings of the Symposium on Engineering Applications of Parafil Ropes. 6th January 1988.
- 15 Crawford, H. and McTernan, LM. A Cyclic Load Testing at Sea-wave Frequency of Continuously Wetted Man-made Fibre Rope@. Proceedings Offshore Technology Conference. OTC 5061. Houston. Texas. May 1985.
- 16 OCIMF Hawser Test Report. A Data on Large Synthetic Ropes in the Used Condition@. April 1982.
- 17 Karnowski, SR. and Liu, FC. A Tension and Bending Fatigue - Test Results of Synthetic Rope@. Naval Civil Engineering Laboratory. Proceedings Offshore Technology Conference. OTC 5720. May 1988.
- 18 Werth, J. A An Evaluation of Materials and Rope Construction for Mooring Hawser Design@. Proceedings Offshore Technology Conference. OTC 3851. Houston. Texas. May 1980.

ACKNOWLEDGEMENTS

Dr Casey gratefully acknowledges the support provided by his colleagues and management of NEL.

Both Authors acknowledge the support provided by the sponsors and project manager (Noble Denton Europe) of the Fibre Tethers 2000 Joint Industry Project. Much of the data presented in this paper was generated during that study.

Table 1

**Test Settings and Results of Axial Fatigue Tests Conducted on 5 Tonnet Polyester
(Type 1) Rope**

Cyclic Period 0.5 Seconds

MNS 49.04 kN

Test No	Termination	Min load (kN)	Max load (kN)	Mean load (kN)	Test length (mm)	Cycles	Comments
1	Splice	4.9	14.7	9.8	1 788	12 095 000	Run-out
2	Potted resin sockets	4.9	14.7	9.8	1 765	12 000 000	Run-out
3	Barrel and spike	4.9	14.7	9.8	1 955	8 306 200	Failed at termination