COMPARISON OF FATIGUE DATA FOR POLYESTER AND WIRE ROPES RELEVANT TO DEEPWATER MOORINGS

Stephen J Banfield*, John F Flory**, John W S Hearle*, Martin S Overington*

* Tension Technology International Ltd
16 Milnthorpe Road, Eastbourne
Sussex, BN20 7NR, UK

** Tension Technology International Inc
4 Tower Lane, Morristown
NJ 07960, USA

ABSTRACT

Polyester ropes are now established in deepwater moorings, but more research is needed to understand long-term durability and to optimise systems.

Three categories of rope failures – environmental, surface damage, and structural – are not considered to be likely problems for deepwater polyester moorings which are properly designed and used. Fatigue of fibres in the rope is thus the concern of this paper. The fatigue mechanisms of interest are creep tensile fatigue, compression fatigue and internal abrasion.

Laboratory test data on potential fibre fatigue mechanisms is reviewed with reference to typical mooring system service conditions. For a 20 year life, a typical mooring might experience 60 million cycles, mostly due to small waves. The occasional severe cycling which might be experienced during storm conditions will cause little fatigue damage.

Tensile fatigue and creep rupture will not occur in polyester fibres at the applicable low loads. Hysteresis heating is not significant for strain amplitudes less than ±0.5%, but might be a problem with the larger amplitudes which might occur in shallow water moorings. Internal abrasion might begin to take effect after millions of cycles. Axial compression fatigue might occur after a large number of cycles in rope elements that go into compression, even though the rope as a whole remains under tension.

Existing fatigue data on large spliced ropes is compared with data for steel wire rope given in API 2SK. The demonstrated polyester rope fatigue life is at least as good as spiral strand and better than multi-strand steel wire rope.

Computer modelling of rope performance is discussed. Under conditions designed to demonstrate fatigue mechanisms, the model shows an early drop in strength due to hysteresis heating and a second drop as some yarns fail in axial compression fatigue. After a very large number of cycles, internal abrasion takes effect and finally creep rupture occurs.

The general conclusions are that, polyester ropes are suitable for deepwater moorings for expected lifetimes of 20 years and that their potential fatigue performance is at least as good as spiral strand steel wire rope at loads representative for FPS mooring. But more research may be needed to identify and quantify active fatigue mechanisms to enable engineers of mooring systems to satisfy regulatory bodies and certification authorities.

Keywords: POLYESTER ROPE FATIGUE MOORINGS DURABILITY

INTRODUCTION

The use of polyester ropes to moor floating production platforms in deep water has now passed from initial research studies into actual use. Petrobras has installed several systems in depths up to 1500 meters in the Campos Basin. Confidence needed for their future use in the Northern North Sea, North Atlantic, Gulf of Mexico and elsewhere is being gained by a number of completed, current and proposed Joint Industry Studies. The technology needed for employing polyester ropes in deepwater mooring appears to be well established. However, further research is needed in order to increase understanding of long-term durability for permanent moorings, to optimise designs, to reduce conservatively imposed “safety factors”, and to reduce costs.

Two aspects are of particular concern. The first is the effective stiffness, or more appropriately the total nonlinear load- extension relation, as it depends on mean load, cyclic loading range and prior history of the rope. This information is needed as input to mooring analysis programs, which, in addition to determining peak loads and offsets, are used to compute the loading history expected in a given installation during its lifetime. It is thus indirectly related to the second concern, which is the subject of this paper, namely the durability of “permanent” moorings.

The possible causes of rope failures were identified by Parsey (1982) in a paper on fatigue of SPM mooring hawsers and by Hearle and Parsey (1982). Flory, Parsey, and Banfield (1990) updated the listing. Causes of failures were categorised as: environmental; surface wear; tensile and structural failures (such as tensile overload or torque effects); and fatigue.

Corrosion due to sea-water is a potential hazard for steel. The analogous effect for polyester fibres is hydrolysis, but this is not a practical problem. Long times at relatively high temperatures are needed to cause appreciable strength loss due to hydrolisis. Studies by Burgoyne and Merii (1993) extrapolate to a 10% loss in strength after 6000 years at 0^{o}C, 200 years at 20^{o}C and 10 years at 40^{o}C. Polyester has excellent resistance to UV-degradation, so that it is a suitable jacket material for ropes of more susceptible fibres. Other environmental effects, such as microbiological attack, are not expected causes of failure in polyester ropes. However, the long term durability of fibre finishes is an unknown, which needs addressing.

Ropes can be damaged by cutting and by abrasion against external objects, particularly care is needed during installation where contact with rollers or work wires can cause damage. There are no recorded instances of fishbite in large ropes and this mode of damage has generally been ruled out. In locations where fishbite has been prevalent in small buoy mooring ropes, this aspect may need further attention.

Low-twist fibre ropes, which are used for deepwater moorings in order to optimise tensile strength, need tough braided or plastic jackets in order to avoid sensitivity to external abrasion. However, provided unduly careless handling is avoided, external damage should not be a problem. In a properly designed mooring, tensile overload should not occur. Other causes of structural disturbance, such as severe twisting or bending, should be avoided.

This leaves the effect of lifetime cyclic loading on the fibres comprising the main internal structure of the rope as the principal mechanism to be considered. Fatigue due to transverse crack growth under cyclic loading, as occurs in steel, is not a failure mechanism in polyester fibres. However, there are other effects of cyclic loading on fibres, which are not relevant to steel wires but are referred to as fatigue. These will be reviewed in the next section before presenting the analysis of data on ropes themselves, which is the main purpose of this paper.

FIBRE FATIGUE

The great variety of fibre failure forms have been covered by Hearle et al (1998). Five “fatigue” effects, in addition to structural fatigue, have been noted as relevant to ropes.

Tensile fatigue is a mechanism found by Hearle and Bunsell (1971) when nylon fibres are cycled down to zero load. An initial transverse crack turns under the influence of shear forces and runs at an angle of about 10^{o} across the fibre. In polyester, the effects are less severe because the cracks run almost parallel to the yarn surface. Tests by Oudet et al (1984) on tyre-cord polyester fibres, which are similar in this context to the marine grades used for deepwater moorings, gave a median fatigue life of 10^{5} cycles and a range of 1½ decades when cycled between zero load and 70% of break load. A 10% reduction in peak load increased the median to 10^{6} cycles. Contrary to earlier studies, these tests showed tensile fatigue up to 20% minimum load at 70% maximum. Typical deepwater loading histories will not approach these peak loads and thus, it is the considered view of the authors that the chance of tensile fibre fatigue failure is negligible.

Hysteresis heating is listed as a cyclic fatigue effect. It is not a problem of current interest in deepwater moorings, but should be addressed for shallow moorings, which might experience high strain amplitudes. In other applications, when ropes are subject to severe cyclic loading, it can cause melting. The heating is partly caused by energy dissipation due to hysteresis within fibres and partly to friction between fibres. A rise in temperature reduces the strength of polyester fibres and thus increases the susceptibility to other fatigue mechanisms. The fibre loss factor has been shown by Bosman (1996) to be proportional to cyclic amplitude. The results of tests on large polyester ropes in a Joint Industry Study, as reported by Banfield and Hearle (1998), show that the temperature rise becomes substantial at cyclic strain amplitudes greater than $\pm$0.5% extension, but is small (< 5^{o}C) for amplitudes less than $\pm$0.5% extension. It takes about 1 hour for half the temperature rise to occur. Cyclic load amplitude of about $\pm$15% of break load corresponds to extension amplitude of $\pm$0.5% for polyester ropes, and this condition is not likely to be exceeded for significant times in deepwater moorings.

Creep rupture occurs under both static and cyclic loading. For constant cyclic load amplitude, the conservative estimate, which is supported by experiment, is to use the peak load as equivalent to the static load. The appropriate summation for variable cyclic loads has not been properly worked out. Short periods of high loading under storm conditions should not have a major effect, so that it would be reasonable to calculate creep rupture times on the basis of an “average peak load”. Creep rupture is a cause for concern in HMPE and, to a less extent, in nylon. But for polyester it is estimated that it would take many thousands of years at 50% of break load to produce creep rupture. Modelling studies by Hearle et al (1993) show that creep rupture would be the final cause of failure after a rope had been weakened due to other fatigue effects.

Internal abrasion is a serious problem in highly twisted nylon ropes under moderate cyclic loading in wet conditions. The damage is less in low-twist ropes, due to the reduced relative fibre movement during cyclic loading, and it is much less in polyester than in nylon, especially for rope yarns with a suitable marine finish. Tests carried out with large cyclic stroke amplitudes on a laboratory yarn-on-yarn abrasion machine in Fibre Tethers 2000 (1995) showed lifetimes up to more than 300,000 cycles for polyester yarns.

Axial compression fatigue is caused by repeated bending of individual fibres when they are allowed to relax while tightly constrained within the structure of a rope. Aramid fibres are particularly vulnerable to axial compression fatigue. In laboratory tests conducted as part of Tethers 2000, aramid yarns lost approximately 50% of their strength after 1000 compression cycles.

This closely corresponds to the results of the Aker Omega (1993) cyclic load tests on very large aramid ropes, in which axial compression fatigue caused failures in splices within several thousand cycles. The trough cyclic load was 10% in some of these tests. But due to unequal load sharing among the strands in splices, some strands went into compression, and when these few strands failed due to axial compression, the structure of the splice was upset causing complete failure of the rope.

Flory (1996) discussed how axial compression fatigue is not likely to be a problem in polyester rope. Because polyester yarn has a lower modulus than aramid, unequal load distribution is much less likely to take place between fibres, yarns, and strands. Because polyester yarn has a lower friction coefficient than aramid, the fibres and yarns are less likely to become tightly bound within the rope structure, such that unequal load distribution can place them into axial compression as the rope relaxes.

And many more compression cycles are required to induce axial compression fatigue in polyester fibres than in aramid fibres. In the Tethers 2000 JIP, using the same laboratory test method as for aramid yarns, polyester yarn retained 97% strength after 100,000 cycles and 78% strength after 500,000 cycles.

Thus it is not necessary to take the same precautions against allowing polyester ropes to relax as must be taken with aramid ropes. From Phase ψψA (1994) studies it was found that polyester ropes can experience many thousands of very low trough load cycles or even complete relaxation without significant strength loss.

Axial compression fatigue differs from traditional “crack-propagation” forms of fatigue in that it is regressive instead of progressive. Thus axial compression fatigue does not lead directly to complete failure of the rope. However, there is a possibility that moderate strength loss due to axial compression can initiate or intensify some other failure mechanism.

A deepwater polyester rope mooring system can be designed and operated so as to maintain an adequate minimum tension on the lines in normal conditions. The tension may drop to lower values for limited periods of storm conditions, as long as this is not allowed for an excessive number of cycles. The deliberately conservative EDG (1998) recommendation for polyester ropes is that the tension should not drop below 5% of break load for more than 100,000 cycles, but note above that this only caused a 3% strength loss in polyester yarns.

In summary, it can be said that studies of fibre and yarn fatigue mechanisms give no reason to expect failures in polyester lines, designed to current standards and planned lifetimes. The fundamental science indicates that the performance of polyester ropes will be at least as good as steel ropes, and due to the absence of corrosion and of metal fatigue, polyester rope performance should be appreciably better. After longer periods, axial compression fatigue might fail some yarns and increase the load on others, but it is not apt to directly cause failure in well designed ropes. Ultimately, after millions of cycles, internal abrasion is the mechanism which appears most likely to cause loss of strength in polyester ropes.

FATIGUE CONDITIONS

Before reviewing the fatigue data on ropes, consider the loading conditions which might be used in testing in order to give a reasonable relation to conditions expected in operation. Note that 20 years at wave frequency generates about 60 million cycles. Extreme storm conditions can give cyclic loads up to ±15% of break load, but the limited number of cycles at these levels will cause little fatigue damage. It is the continuous cycling due to millions of small waves, which give much smaller cyclic load ranges, that has the potential to cause real fatigue damage. Further work is needed to establish a standard fatigue test procedure for comparative purposes or, if necessary, the criteria for customised fatigue testing of lines intended for particular installations. The ideal would seem to be a stochastic loading pattern related to predictions of loading in use.

There are two other complicating factors in fatigue testing.

Firstly, the nominal break strength quoted for a rope may be less than its real break strength. When required to supply a rope with a guaranteed break load, manufacturers will adopt varying degrees of conservatism to ensure meeting the specification. Paradoxically, the use of a conservative estimate of break load makes the fatigue response appear better. A mean load or load range based on a given percentage of a conservatively stated break strength, will be a smaller force than the same percentage of a higher actual break strength. Consequently, the actual fatigue-loading test conditions based on a conservative break strength will be less severe.

Secondly, metal fatigue test data is commonly plotted against cyclic range, because it has a greater effect than mean load. In fibre ropes, some mechanisms are less dependent on load range. Creep is strongly influenced by sustained maximum load. Axial compression fatigue is determined mainly by low values of minimum load. Fatigue data should be obtained and plotted in terms of two variables. The most obvious choices are *either* mean and range *or* maximum and minimum. As apparent above, there is also a question as to whether load values or strain values are most appropriate.

ROPE FATIGUE DATA

It is not surprising that there is no authoritative set of data on rope fatigue properties, given the complications mentioned in the last section, the variety of fibre types and rope constructions, the heavy and specialised test equipment needed, and the high cost of testing. Never-the-less, in the following we attempt to analyse the available data and compare it with the fatigue curves for steel chain and wire rope given in API 2SK (1997).

The fatigue life and residual strength data reviewed here is taken from a full analysis of available synthetic fibre rope strength and stiffness data being conducted by TTI. This review is restricted to ropes of 5 tonne and higher Minimum Break Strength (MBS) in parallel yarn, parallel strand and wire-rope constructions, which are the types applicable for deepwater mooring lines. For the following reasons, the review is restricted to spliced lines:

- Only spliced lines have been validated for fibre ropes over 500 tonnes actual break strength.
- In general spliced terminations give a higher mean strength than other terminations, with similar variability.
- Fatigue performance of spliced ropes is somewhat inferior to that of resin-socketed ropes, which means that the predictions will be conservative for ropes with properly designed resin sockets.
- Confidential developments by TTI confirm that improvements in strength and reliability over previous state-of-the art splices can now be made available.

The results are plotted in Fig 1a and 1b along with the API fatigue design curves.

In Fig. 1a, the Load Range is on a normal scale abscissa, while in Fig. 1b the Load Range is on a log scale as it is in the original API figure. When a straight line on a log-log plot is replotted on a semi-log plot, it becomes a curve, as depicted in Fig. 1a. These API wire rope curves are truncated at 60% load in Fig. 1a, and in Fig. 1b they are truncated at 1.75.

In each figure, a straight line has been fitted by regression analysis through the polyester rope data, indicated by the solid squares and triangles. This is the upper full line in each figure. Note that these lines are not equivalent, one having been derived on a semi-log basis and the other on a log-log basis.

During the regression analysis for each figure, the standard deviation for the data was also determined. The lower full line in each figure represents the “Mean - 2 Sigma” for all of the analyzed data. Note that the variation in these polyester rope fatigue data is most likely caused by including data from several different rope constructions and many different manufacturers and test programs together in the statistical analysis. It does not represent the expected scatter of fatigue performance for a single given type of rope from one rope maker. Thus it presents a very conservative estimate of the minimum cycles-to-failure for good-quality polyester ropes.

In Fig. 1a, the polyester “Mean – 2 Sigma” line is above the API six-strand wire rope curve for most of the range, and it is essentially the same as the API spiral-strand curve in the mid range of interest. In Fig. 1 b, this polyester line is above the API wire rope lines throughout the lower load ranges. The data points with a “+” sign to the right of the symbol are run outs.

The mean regression fit for the fibre rope data is

Range (%MBS) = - 12.4331*log cycles +109.4622

and the corresponding lower bound (-2 sigma) fit is

Range (%MBS) = -12.4331*log cycles + 90.1357

These regressions have been conducted with the same dependent and independent variables as Parsey (1982). However, a comparison of regression results is beyond the scope of this paper and would deserve a separate study.

Much of the available polyester rope fatigue data are for tests in which the rope was cycled a limited number of times and then loaded to break in order to determine residual strength. These residual strength data are plotted here in Fig. 2. All of the residual strengths are over 100%, meaning that the residual strengths were greater than the original MBS, assigned by the manufacturer. Note that several of these tests extended to one million (10^{6})load cycles or more. In comparison, NEL tests (1992) on 70mm six strand wire rope to 50% of life (231,000 cycles at 20% mean ∀ 12.5% load range) gave a measured 15% strength reduction.

This high residual strength phenomena is not unusual. The break strength of synthetic fibre ropes generally increases during initial cycling, as the splices set and the rope structure becomes better balanced and aligned. In the case of these data, which are based on MBS, it probably also reflects the conservatism of MBS values quoted by rope manufacturers.

COMPUTER MODELLING OF ROPE FATIGUE

The OP*TTI*-ROPE programs, which are described by Hearle et al (1993, 1995) derive from work by TTI for the US Navy. OP *TTI*-ROPE includes procedures for computing the progressive loss of strength and eventual failure of fibre ropes. The input to the programs consists of:

- load-elongation properties of constituent yarns
- rope construction geometry
- creep rupture parameter
- energy dissipation factor
- two constants to give shift of breakpoint with temperature
- rate-of-internal abrasion parameter
- number of cycles to yarn failure in axial compression
- cyclic loading range and frequency

A typical prediction is shown in Fig 3, where the values of the parameters have been chosen to bring in the several fatigue mechanisms. There are two small steps in the retained strength: an initial drop as the rope heats up to an equilibrium temperature; and a second drop when yarns under axial compression reach the failure limit. Internal abrasion causes a slow decrease in strength, which leads to a rapid drop at the end when the effective fraction of break load becomes large enough to cause creep. Final failure occurs when the residual break load, adjusted for creep rupture, matches the maximum imposed load.

The OP*TTI*-ROPE program is useful for exploring the way in which fatigue might lead to loss of strength in ropes. We are not aware of similar programs for steel wire ropes. The problem for actual prediction is a lack of the necessary quantitative knowledge of fibre properties. Reasonable estimates can be made for the creep and heating parameters in polyester ropes, or tests can be made to determine them. At present, there is no confirmed method of applying the results of fibre tests for the abrasion and axial compression parameters to the prediction of rope performance. A possible way forward, as proposed by TTI and NEL for a durability JIP, is to determine the incidence of these mechanisms in test ropes. The results could then be used as inputs to programs intended to determine the effects of changes from the test ropes and conditions.

DISCUSSION

This paper has demonstrated that the fatigue performance of large good-quality polyester ropes can be expected to be as good as that of the wire ropes now used in offshore moorings.

However, further testing and research may be needed to confirm and demonstrate this to the full satisfaction of potential mooring system designers and users, classification societies and regulatory authorities.

One school of thought is that polyester ropes will not be accepted for offshore moorings until it is demonstrated that they can be used for 20 years without failure.

In the absence of 20 years of field experience, this can be done by cyclic load testing using a realistic mean load and amplitude on a full-size specimen of a particular rope design. But it might take nearly 20 years of laboratory testing to reach the 60 million cycles needed to represent 20 years of mooring service. There may be ways to perform such testing in a reasonable length of time and at a reasonable cost but these are yet to be demonstrated .

An alternative testing approach is to conduct a number of tests on “standard” polyester ropes at higher mean loads or amplitudes. This would be similar to the effort used develop the API 2SK steel wire rope fatigue design curves, which are well accepted for design purposes by the industry. These design curves were compiled from a number of sources. The principal work was done in the wire-rope joint industry project, reported by Noble Denton (1991), in which the available wire rope fatigue data was evaluated and further testing was performed to gain additional confidence.

The TTI/NEL rope durability study has a similar objective to evaluate available synthetic fibre rope data and provide additional fatigue life data. Like the wire rope study, this joint industry project will investigate both large ropes and smaller model ropes representative of those polyester ropes which are now being considered for offshore moorings. This will be the first such testing to employ a stochastic spectrum simulating actual mooring load conditions.

But unlike wire ropes, polyester ropes are not yet “standardized”. Thus conducting extensive testing on one or several specific rope designs is not sufficient to demonstrate the performance of all other polyester ropes.

The mechanical properties of high-quality polyester yarns are similar. But different proprietary fibre finishes are used on these yarns to impart special abrasion-resistance and low-friction characteristics which are very important for rope performance. Rope constructions and terminations also differ. Existing designs are being improved and new designs are still being developed. Thus “standardization” at this time would favor certain fibre producers and ropemakers and would inhibit the development of better ropes.

The new ABS Guide (1999) recognizes this. It allows consideration of any viable rope design. It requires that the manufacturer document the rope design details, test prototype ropes, and establish quality control procedures in order to ensure that the rope supplied is the same as the tested prototype.

To demonstrate minimum fatigue performance, ABS requires a test in which the rope is cycled about a mean tension of 30% of mean wet break strength with an amplitude of 10%. If the rope survives 600,000 cycles, the synthetic rope fatigue properties are classified as equivalent to spiral-strand wire as given in API 2SK (1997). If the rope survives 100,000 cycles, ABS classifies the synthetic rope fatigue properties as equivalent to multi-strand wire. ABS then permits the applicable API fatigue design procedures to be used for the tested polyester rope design.

This fatigue test practice is sufficient to certify the initial installation of a polyester rope mooring system. But it may still be necessary to reverify and recertify the rope while it is in service.

One suggested practice is to periodically conduct break tests on short rope specimens removed from the mooring. Such break testing demonstrate the rope residual strength. But this does not demonstrate the remaining service life of that rope. Some forms of rope deterioration develop slowly but accelerate just before ultimate failure: 100% residual strength does not guarantee another year of service. Thus ABS may require that these short rope specimens be subjected to the same fatigue test as was used before installation. This will periodically demonstrate residual fatigue life, which is much more reassuring.

An alternative to extensive rope fatigue testing is to scientifically identify the principal mechanism(s) which cause rope deterioration and failure; to study these through testing of fibres, yarns, rope components, or small rope models; and then to use these findings in computer models to simulate and predict the performance of the full size ropes.

Ironically, because polyester ropes perform so well, there is not yet sufficient information on the nature, extent and rate of the potential polyester rope deterioration mechanisms to carry out such a study.

As this paper is being written, the authors are carrying out laboratory tests and pathological examinations of the near-full-sized polyester ropes which were recently retrieved after two years in the DeepStar TLM in the Gulf of Mexico. Ropes from the proposed TTI/NEL rope durability JIP will also be examined in detail to identify and quantify signs of any deterioration. If any found, these efforts will reveal the principal failure mechanism(s) in polyester ropes.

Computer models which simulate the fatigue performance of several different types of synthetic rope are now available. Once the principal failure mechanisms are known and quantified, it will be possible to use these models to perform a simulation of 20 years fatigue in only a few days. The effects of service variables, such as mean load, amplitude and period, can readily be investigated. And the effects of variations in polyester fibre properties and rope structure on rope fatigue life can be investigated without having to construct actual ropes.

Furthermore, it will then be possible to perform a complete fatigue performance of each leg of a mooring system using realistic load histories for the entire service life before installing the system, and then to reperform this analysis using real load histories while the system is in service. When this can be done, it should not be necessary to remove and test sample ropes from deepwater mooring systems to reverify fatigue life.

CONCLUSIONS

There is now sufficient information to justify the use of good-quality polyester rope in deepwater offshore moorings. Such ropes can be expected to have fatigue performance at least as good as that of typical wire rope. This conclusion is based on examination of the basic polyester fibre properties, performance analysis by computer of low-twist-construction ropes, evaluation of available fatigue test data on small and large ropes, and consideration of present field service information.

But the fatigue performance of polyester ropes depends upon the fibre quality, the rope construction, and the termination design as well as on the cyclic load history. Thus further laboratory testing may be needed to quantify the effects of the many variables and to provide additional design information for a particular polyester rope design and a particular mooring installation.

It should not be necessary to perform 20 years of fatigue testing before beginning to use polyester ropes in actual mooring systems. A simple fatigue test can be performed to demonstrate that a particular polyester rope has performance equivalent to that of the wire ropes now being used. And this performance can then be reverified by periodically removing samples of rope from service and performing further testing to demonstrate remaining fatigue life.

In the near future, it should be possible to use computer models to simulate synthetic fibre rope testing and field performance. Such computer simulations require an understanding of the principal fatigue mechanisms of polyester ropes, but this knowledge may soon be available from several present joint industry projects. Computer simulations will be much quicker, easier, and more economical than laboratory testing.

REFERENCES

API 2SK (1997) Recommended practice for design and analysis of stationkeeping systems for floating structures, 2nd edition, American Petroleum Institute.

S.J. Banfield and J.W.S. Hearle (1998) Comparative performance of fibre ropes for deepwater moorings, OMAE, Lisbon.

R.L. Bosman (1996) On the origin of heat build-up in polyester ropes, OCEANS 1996 Conference.

A.R. Bunsell and J.W.S. Hearle (1971) A mechanism of fatigue failure in nylon fibres, J.Mater. Sci., 6, 1303-1311.

C.J. Burgoyne and A.L. Merii (1993) Hydrolysis tests on polyester yarns, University of Cambridge, Department of Engineering Technical Report, CUED/D Struct/TR. 138.

Prediction of Wire Rope Endurance for Mooring Offshore Structures, Final Report 1991, JIP managed by Noble Denton.

Phase ψψA (1994), Axial Compression Studies, JIP Tethers 2000 Final Report, Noble Denton Europe Ltd, Tension Technology Int. Ltd and National Engineering Laboratory.

Prediction of Wire Rope Endurance for Mooring Offshore Structures JIP, Partial Life Fatigue and Residual Strength of Six Strand Wire Rope, NEL report 011/92, April 1992.

EDG (1998) Noble Denton Europe and Tension Technology International: Engineers Design Guide for Deepwater Fibre Moorings, Oilfield Publications.

Fibre Tethers 2000 (1995) Joint Industry Study: High Technology Fibres for Deepwater Tethers, NDE/NEL/TTI, Noble Denton Report L17317/NDE/rws, February 10, 1995, with additions June 20,1995.

... ABS Guide For Synthetic Ropes in Offshore Mooring Applications, American Bureau of Shipping, New York, 1999.

... Deep Water Aramid Mooring Line Joint Industry Joint Industry Project, Phase 2 Final Report", Aker Omega, Houston, 1993.

J.F. Flory, "Avoiding Fibre Axial Compression Fatigue in the Design and Use of Tension Members", Proc. Oceans '96 Conferenct, MTS/IEEE, Piscataway, NJ, 1996.

J.F. Flory, M.R. Parsey and S.J. Banfield, "Factors Affecting Life of Synthetic Fibre Ropes in Marine Service" MTS '90 Conference Proceedings, Marine Technology Society, Washington, DC, 1990, Vol 2, pgs 281 - 286

J.W.S. Hearle, R.E. Hobbs, M.S. Overington and S.J. Banfield (1995) Modelling axial compression fatigue in fibre ropes, Proc. 5th ISOPE, 377-383.

J.W.S. Hearle, B. Lomas and W.D. Cooke (1998) Atlas of Fibre Fracture and Damage to Textiles, Woodhead Publishing, Cambridge.

J.W.S. Hearle and M. Miraftab (1991) The flex fatigue of polyamide and polyester fibres, J. Materials Sci., 26, 2861-2867.

J.W.S. Hearle and M.R. Parsey (1983) Fatigue failures in marine ropes and their relation to fibre fatigue, Int. Conf. On Fatigue in Polymers, PRI, London.

J.W.S. Hearle, M.R. Parsey, M.S. Overington and S.J. Banfield (1993) Modelling the long-term fatigue performance of fibre ropes, Proc. 3rd ISOPE Conference, Vol II, 377-383.

R.E. Hobbs, M.S. Overington, J.W.S. Hearle and S.J. Banfield (1995) Element buckling within ropes and cables, Marinflex Conference, University College, London.

Ch. Oudet and A.R. Bunsell (1984) Structural changes in polyester fibres during fatigue, J. Appl. Polymer Sci., 29, 4363-4376.

M.R. Parsey (1982) Fatigue of SPM mooring hawsers, OTC 4307.

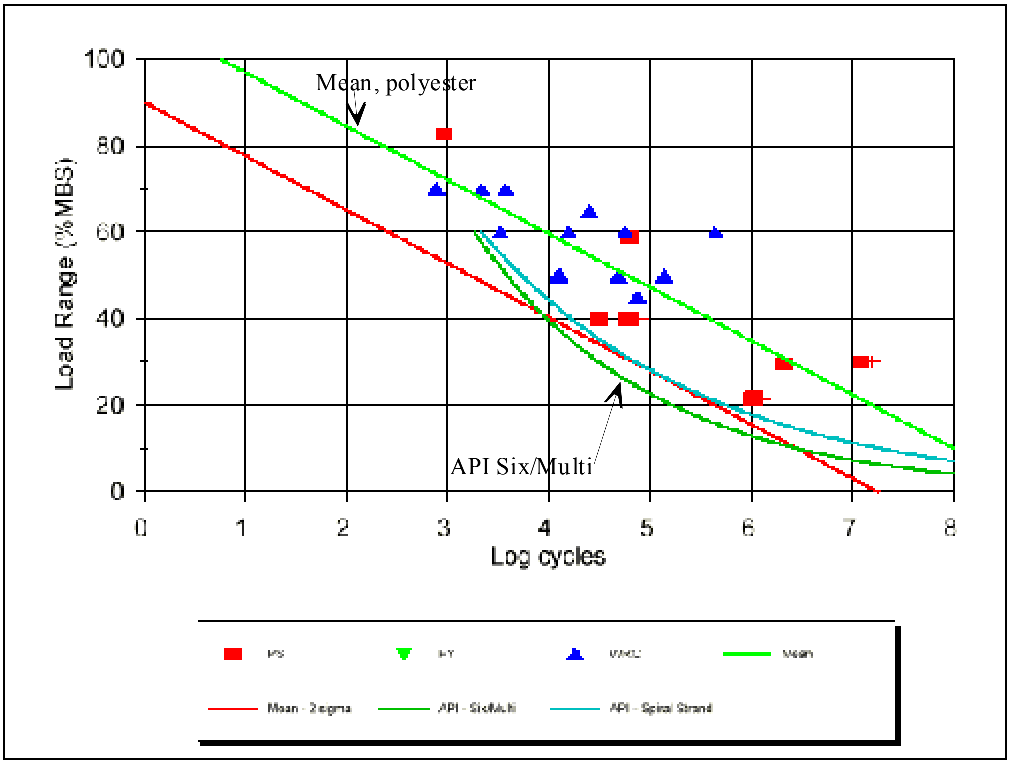

Figure 1a Cycles to Failure, Polyester Data vs. API Wire Rope Design Curve
Load Range on Normal Scale

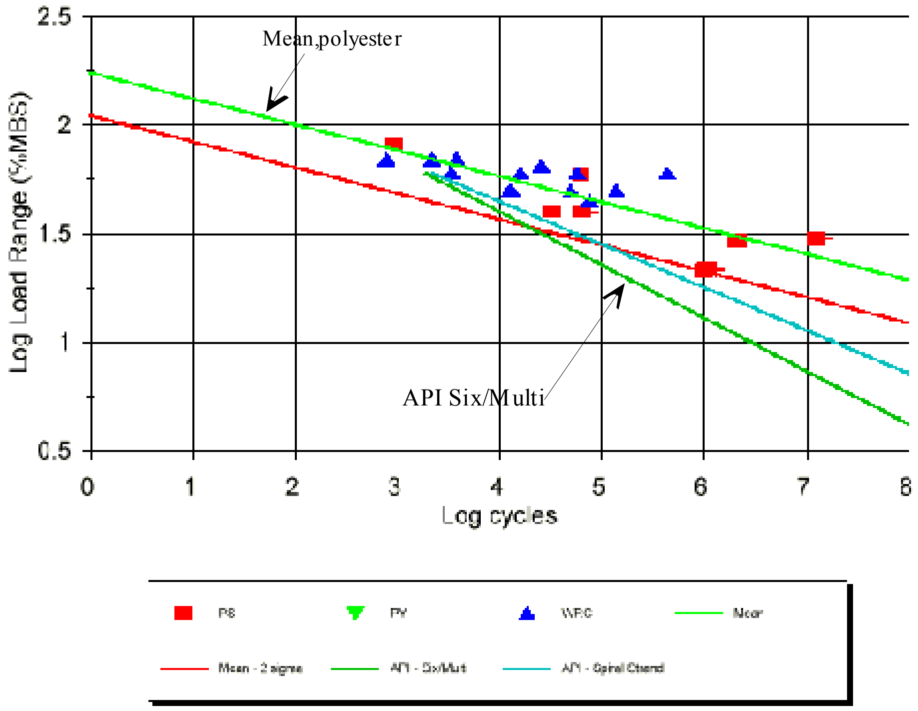

Figure 1b Cycles to Failure, Polyester Data vs. API Wire Rope Design Curve
Load Range on Log Scale

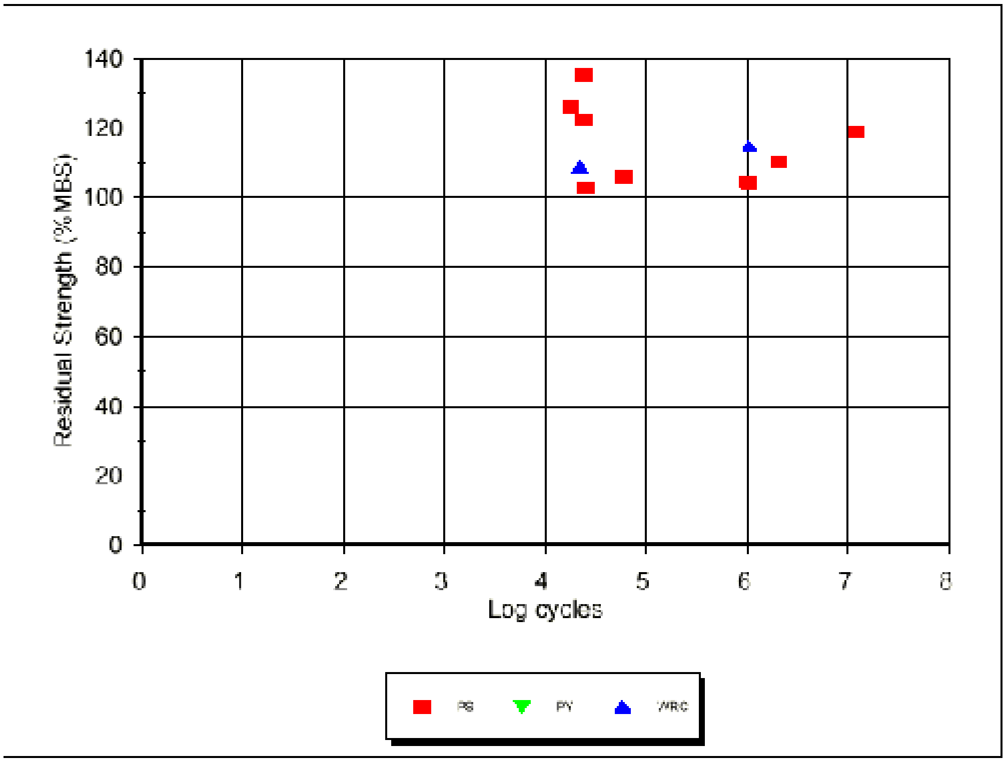

Figure 2 Residual Strength After Cycling, Polyester Rope Data

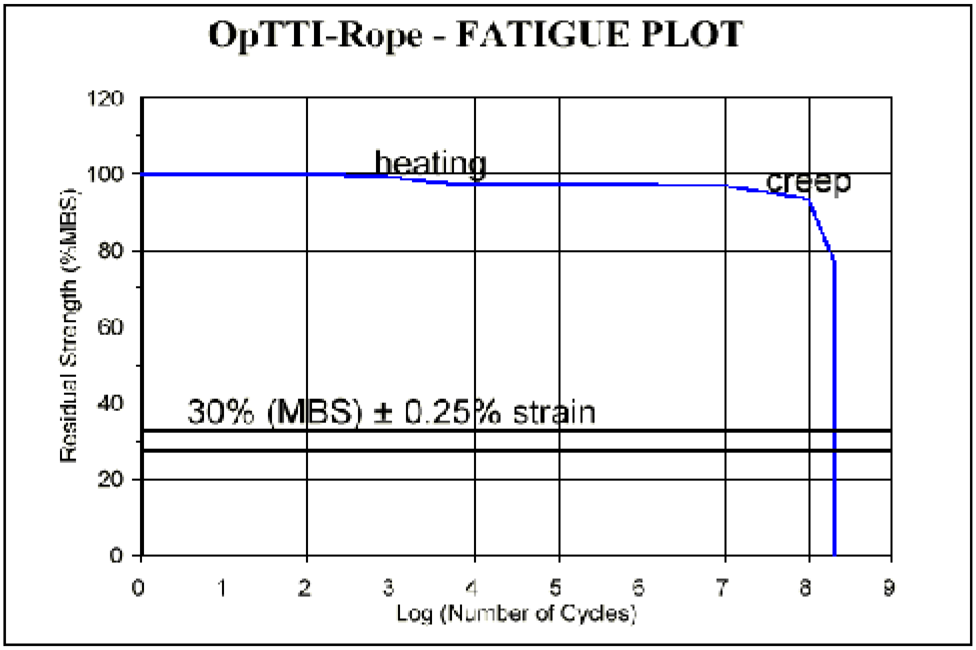

Figure 3 Residual Strength vs. Applied Cycles, Modelling Simulation Using OpTTI-Rope Computer Program