OTC 19315

Deepwater Moorings with High Stiffness Polyester and PEN Fiber Ropes

Davies P /IFREMER Brest, Lechat C, Bunsell A, Piant A /ENSMP, François M /BV, Grosjean F / IFP,
Baron P/Doris, Salomon K/Saipem, Bideaud C /Technip, Labbé JP /Acergy, Moysan AG /Total.

This paper was prepared for presentation at the 2008 Offshore Technology Conference held in Houston, Texas, U.S.A., 5–8 May 2008.

Abstract

The benefits of synthetic fiber ropes for deepwater station keeping are now well established and their use is expanding. Nearly all current applications use a single grade of polyester fiber, but for different supports and environments this may not be the optimal choice. Properties of polyester fibers can be modified by adjusting processing parameters and there are other fibers available such as PEN, which offer higher stiffness. This study examines the benefits of intermediate stiffness fibres, stiffer than standard polyester but less stiff than the high performance fibers. The results indicate that there is scope for improving mooring line performance and reducing line weight by careful evaluation of material options.

Introduction

Polyester fiber ropes are finding increasing applications in offshore mooring systems as production moves to deeper water. Following successful installations offshore Brazil in the late 1990's [Pellegrin 1999] the first Gulf of Mexico mooring was for the *Mad Dog* spar [Bugg 2004] in 2004, which employed 1200 tons of polyester down to 1670 meters water depth. The recently installed *Independence Hub* platform also used polyester moorings, in 2440 meters water depth [Paganie 2007]. Different rope constructions have been used but these mooring lines were all composed of similar high tenacity polyester fibers. The *Red Hawk* spar [Haslum 2005], also installed in 2004, used a modified polyester fiber with a higher initial stiffness to facilitate installation, and this raised the question of whether a higher fiber stiffness might be beneficial for other supports and allow rope diameter to be reduced. Previous work within the French Mooring line project [Davies et al 2002] studied high performance fibres such as aramids and HMPE and concluded that their very high stiffness, while allowing much smaller rope diameter and weight, did not improve durability as it would result in high fatigue loading of the metallic components of the mooring line. However, there is an intermediate stiffness region, shown in Figure 1, situated between the currently used fibres, with initial tensile modulus around 10-15 GPa, and the high performance fibers (> 60 GPa) which has not been explored previously for deepwater mooring applications.

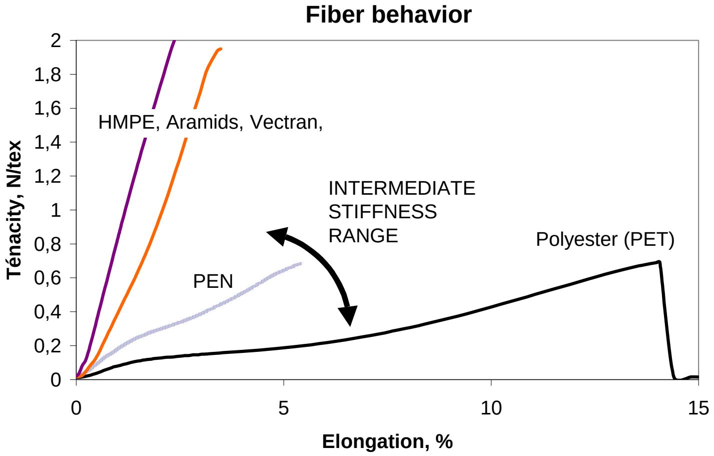

Figure 1. Available fiber properties and unexplored intermediate stiffness region

The aim of the present study is to examine under what conditions intermediate stiffness fibers would be attractive for deepwater moorings. In order to do this it was first necessary to examine how the properties of these intermediate stiffness fibers transfer to ropes. Samples were then manufactured in order to characterize the ropes under appropriate loading conditions, as few stiffness data were available when the study started. Based on these results mooring line analyses were performed for different supports and environmental conditions to determine the influence of the improved rope stiffness. Finally, a series of long term characterizations including creep and cyclic loading was performed, to check whether increased stiffness results in deterioration of long term properties.

Materials and samples

Three fibers have been studied, a standard polyester (PET, polyethylene terephthalate) fiber, widely used today for offshore tethers, an improved polyester, and PEN (polyethylene naphthalate), chosen to represent the intermediate stiffness range (fibre modulus around 30 GPa). The difference between the PET and PEN polymers is the presence of a double aromatic ring in the PEN molecule, Figure 2. Figure 3 shows the tensile response of new yarns, the PEN shows an initial modulus roughly twice that of the standard polyester.

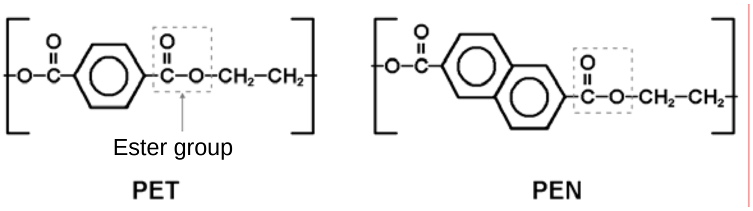

Figure 2. Structures of polyester PET (polyethylene terephthalate) and PEN (polyethylene naphthalate) molecules

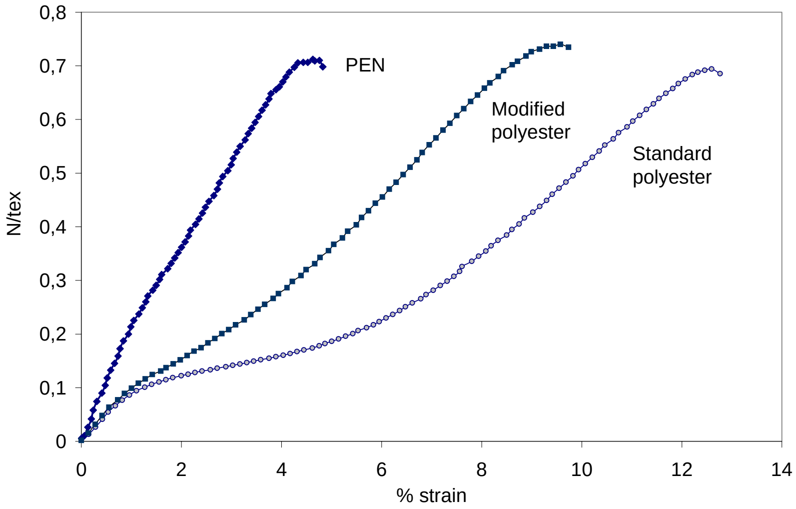

Figure 3. Tensile behavior of standard and modified PET, and PEN, tests on new yarns.

Stiffness data for the standard fiber ropes are available from previous work e.g. [François 2000], so the present study concentrated on testing the two improved stiffness variants. Table 1 shows the samples studied.

Scale	Dimensions diameter/test length	Nominal break load
Single Filament	20-30µm / 50mm	0.5 N
Yarn 110 tex	0.4 mm / 1 meter	90 N
Assembled yarn	4 mm / 1meter	5 kN
Sub-rope	32 mm / 8 meters	330 kN
Rope	132 mm / 12 meters	5000 kN

Table 1. Sample sizes tested

All materials were supplied by Performance Fibers, Longlaville, France, with marine finish. Rope yarns and 3-strand twisted sub-ropes were produced by Bexco, Belgium with the same construction for both fibers. Full size modified polyester ropes, an *Integra* parallel 7-strand construction, were manfactured by Scanrope, Norway.

Test procedures

Various test machines were employed to measure the properties over the range from single fiber up to full size rope. The single filaments were tested on a special machine, Figure 4a [Bunsell 1971]. Yarns and assembled yarns were tested on a 10 kN test frame, Figure 4b. 500 and 1000 kN test frames were used to test sub-ropes. Two digital cameras linked to an image analysis system were used to measure strains, together with more conventional extensometry. More details of tests can be found elsewhere [Davies 1999, Lechat 2007]. Some samples were in the new state, others were subjected to a bedding-in sequence of 5 load-unload cycles to 50% break load.

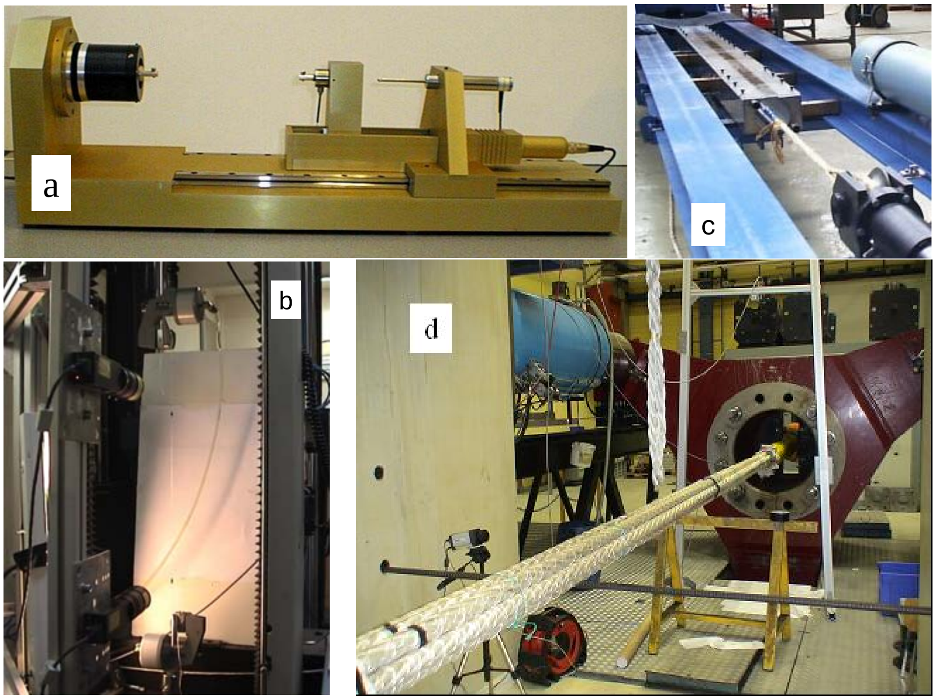

Figure 4. Test machines
a) Single filament testing, b) yarn tests, c) sub-rope test machine, d) full size rope test.

Single fiber and some assembled yarn tests were performed at the Ecole des Mines de Paris (ENSMP), yarn and assembled yarn tests were also performed at Ifremer in Brest, tests on over 20 sub-rope samples were carried out at IFP in Lyon and at Ifremer, and full size ropes were tested at the LCPC civil engineering laboratory in Nantes.

Fiber to rope transfer

By testing the components of large ropes at the different steps of fabrication it is possible to evaluate the influence of the fiber properties on the rope behavior. This is important, as if the transfer is poor there may be little to be gained by improving fiber properties. Figure 5 shows mean results from tests at each scale, for the improved PET and PEN fibers.

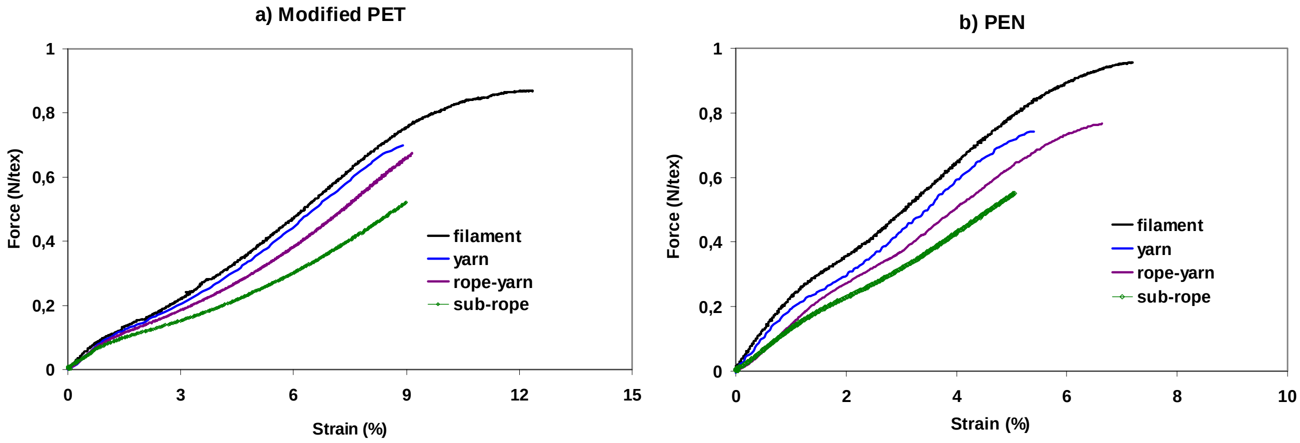

Figure 5. Stress-strain results, tension loading to failure after bedding-in. (Note different strain scales).

Figure 5 shows the similarities and differences between the two materials. The failure strains are significantly lower for PEN fibers but failure stresses are similar. There is a drop in stiffness of sub-ropes compared to rope yarns but the stiffness transfer coefficients are similar for both materials. The behavior of the PEN fiber is more linear than that of PET after bedding-in. A permanent strain after bedding-in of around 1% is noted for both materials, significantly lower than that measured on standard polyester fibers and ropes. The similar permanent strains for the three levels of construction indicates that this strain is mainly due to orientation of the polymer structure rather than alignment of the rope construction. Based on low level material properties and geometrical parameters rope mechanics equations can be used to predict the quasi-static behavior of sub-ropes quite accurately. This will be reported elsewhere.

Stiffness properties

Mooring line analysis requires stiffness values measured under appropriate loading conditions. These are available for standard polyester but not for modified PET nor PEN, so it was necessary to perform a complete stiffness characterization for these materials. Tests were performed on sub-ropes to measure these values under quasi-static and dynamic loading as specified in the recent ISO document [ISO 2007]. All samples were bedded in by 5 cycles to 50% break load followed by a one hour hold period before starting stiffness measurements. Figure 6 shows examples of both types of stiffness test for PEN.

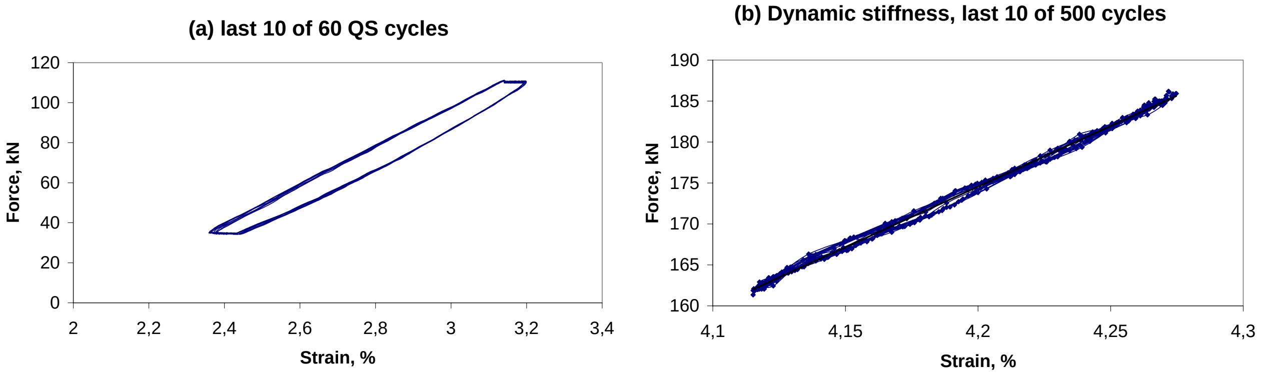

Figure 6. Stiffness tests, a) Quasi-static, b) Dynamic high load , PEN sub-ropes

Tests were also performed on a full size modified PET rope to examine whether these sub-rope values correspond to those of full size ropes. Table 2 presents results, Kr is the normalized load/strain.

Material	Quasi-static stiffness Kr
Standard PET [François 2000]	15
Modified PET sub-rope	14
Modified PET full-size rope	14
PEN sub-rope	20

Table 2. Example of measured quasi-static stiffness values over the range 10-30% break load

Although the stiffness of the modified PET yarn is higher initially, ie before bedding-in, as shown in Figure 3, after bedding-in values are very similar to that of the standard PET material. Part of the permanent re-orientation strain has been removed during processing but working properties are very similar to those of the standard material. This is not the case for the PEN ropes, which are significantly stiffer before and after bedding-in, so this material was used subsequently to examine how stiffness affects mooring line response. However, this example shows the importance of understanding the behavior of these materials, as the relationship between yarn properties and useful rope stiffness can be complex. An initial factor of two between standard PET and PEN is reduced to an increase of around 30% for quasi-static rope stiffness and around 15% for dynamic stiffness at 45% mean load. Dynamic stiffness is strongly dependent on mean load [Fernandes 1999, Davies et al 2002].

In addition to these standard stiffness measurements some additional tests were performed on the full size rope to examine the influence of stochastic loading. Various sequences were defined using mooring line analyses for different scenarios and Figure 7 shows one example, for a production platform in the Gulf of Mexico.

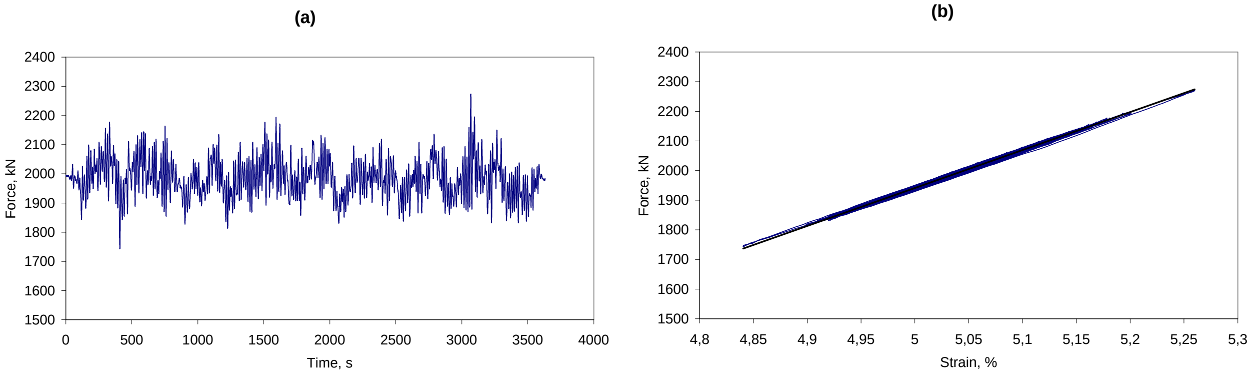

Figure 7. Stochastic loading of 500 ton modified PET rope, mean load 200 tons. a) Sequence applied, b) Measured response.

These results are discussed in more detail elsewhere [François, 2008] but suggest that in a stochastic sequence, the stiffness does not depend on the amplitude of individual cycles, nor on the period of underlying (low and wave frequency) components.

Mooring line analyses

Once the necessary property data had been obtained a number of mooring line analyses were performed to examine how the increased stiffnesses of a rope such as PEN would affect mooring line dimensions. Different supports were considered by the engineering companies participating in the project, for a depth of 2500 meters in two locations, West Africa and the Gulf of Mexico. The *Ariane*™ software was used, together with fatigue analyses.

Material	Quasi-static	Dynamic (function of mean load (ML))
Standard PET	15	18.5 + 0.33 ML
PEN	20	23 + 0.33 ML

Table 3. Values of Kr used in first mooring line analyses.

Then in a second series of analyses, designed to look for the optimal rope properties, parametric studies of the influence of stiffness were performed. These studies generated a large amount of data. Three examples of of results are shown below, for a semi-submersible drilling rig and a production platform, both in the Gulf of Mexico, and for a production barge off West Africa. For analysis, two parameters must be specified, the safety factor T_{max}/Break load, and the minimum allowable tension T_{min}. The choice of values to be taken for a new material clearly has an impact on whether a particular solution is interesting compared to a standard polyester choice. For this test case higher safety factors were taken and a 5% minimum tension was used for PEN, rather than the 2% now usually applied for polyester, taking into account the lack of experience with this product and the uncertainties on load-elongation properties. For the semi-submersible drilling rig with 8 lines and and production rig (a 12 lines system), loop current and hurricane conditions were applied. Tables 4 and 5 show examples of results.

	Material	Polyester	PEN
	Criteria:		
	SF Dyn Intact	1.83	2
	SF Dyn Damaged	1.375	1.5
	T_{min} applied	2%	5%
	Sizing:		
	Diameter	130 mm	144mm
	Break load	542 T	601 T

Table 4. Case study 1, Semi-submersible production platform, GOM 2500 meters depth.

In the first example, the improved behavior of the PEN is clearly occulted by more conservative safety factors and, above all, by the criterion of minimum tension that sets the level of pre-tension in the mooring lines, the level of maximum tensions, hence the size.

	Material	Polyester	PEN
	Criteria:		
	SF Dyn Intact	1.83	2
	SF Dyn Damaged	1.375	1.5
	T_{min} applied	2%	5%
	Sizing:		
	Diameter	246 mm	246 mm
	Break load	1778 T	1778 T

Table 5. Case study 2, Semi-submersible production platform, GOM 2500 meters depth.

It is clear for both examples that with these model parameters there is little to be gained by increasing the line stiffness.

The third example involves a large production barge moored using 16 lines in 2500 meters depth off West Africa. Here the environment is much less severe and the offset criterion is governing the design. Table 6 shows an example of results from this case. The minimum tension criterion was also varied : Figure 8 shows how this affects the rope diameter and weight gain.

	Material	Polyester	PEN
	Criteria:		
	SF Dyn Intact	1.83	2
	SF Dyn Damaged	1.375	1.5
	T_{min} applied	2%	5% / 2%
	Sizing:		
	Diameter	168mm	152 / 144mm
	Break load	782 T	648 / 590 T
	Prétension	150 T	160 / 120 T

Table 6. Case study 3, Production barge, West Africa 2500 meters depth.

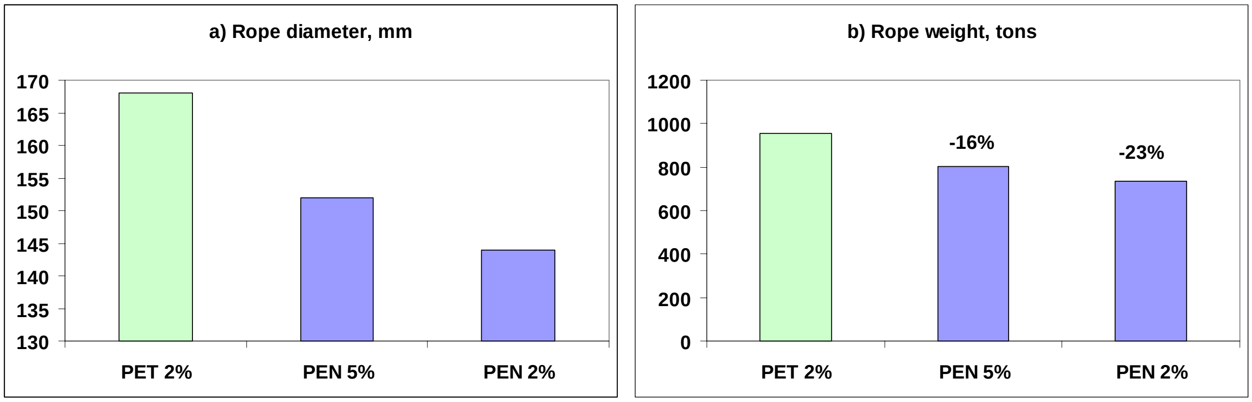

Figure 8. Influence of minimum tension criterion on PEN rope diameter and weight gain.

These results indicate that the use of a higher stiffness material can lead to significant savings, over 200 tons of material here. This reduction may also result in associated savings on account of easier handling of a smaller diameter rope and reduced storage requirements during installation. A further gain is to be found in the line pre-tensions, these are somewhat lower in the PEN line and may allow the use of a smaller tensionning system. It should also be noted that these are all conservative estimates, based on higher safety factors for the higher stiffness material. In order to justify lowering these factors it would be necessary to provide evidence that the long term behavior of the higher stiffness material is at least as good as that of the currently-used polyester ropes.

Long term behavior

Two aspects of the long term behavior of the two materials were considered in this study. This was not intended to be an exhaustive study, clearly further qualification work would be essential if a PEN rope was to be considered for this type of application, but simply to give a first indication of differences compared to the currently-used fiber.

First, creep tests were performed. Several types of test were run; first, constant loads were applied to single filaments and rope yarns for short periods, then sub-ropes were subjected to 3-day creep-recovery cycles, and finally longer creep tests (hundreds of hours) were performed to measure creep rates. Figure 9 shows an example of results for filaments, which indicate no significant difference in creep rates for the two fibers. This suggests that the intrinsic creep mechanisms are similar at a material level.

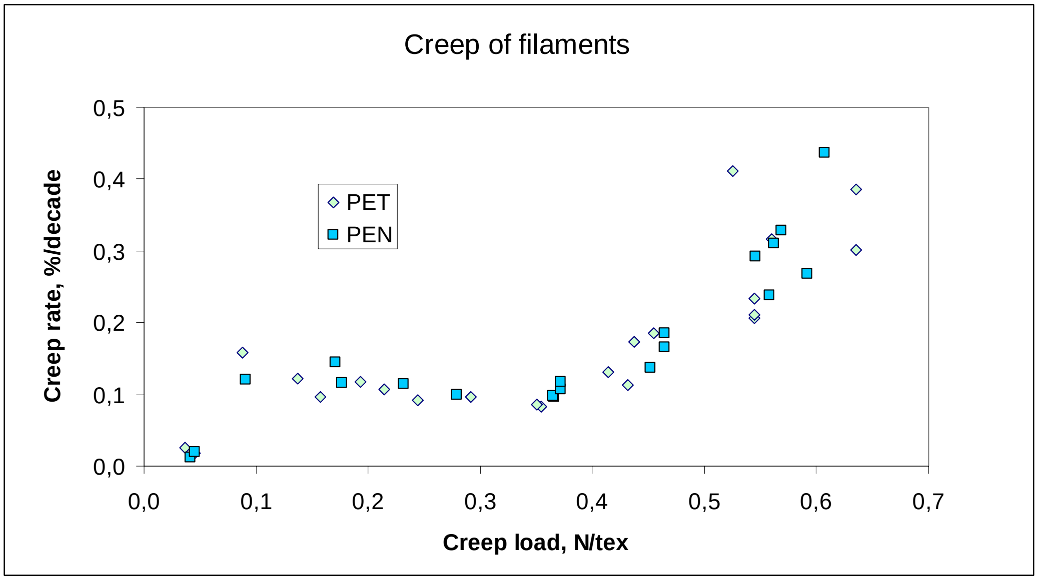

Figure 9. Creep rates from tests on single filaments.

Then sub-ropes were subjected to short term creep/recovery cycles at different load levels, Figure 10, designed to produce the parameters for a creep model developed previously (Davies 2003, Chailleux 2005). This allowed a direct comparison of the strains to be expected for load levels of 10, 30 and 50% break load to be determined. The creep rates are again similar for the two materials, but more importantly the overall strains and the permanent strain after unloading of the PEN ropes are much smaller than those measured on the modified polyester. As the modified polyester has already a significantly lower permanent strain than the standard polyester this indicates that the PEN rope may offer further significant advantages during installation in crowded areas. Finally some longer creep tests were performed, up to 50 days, to check the creep response over a longer period, Figure 11.

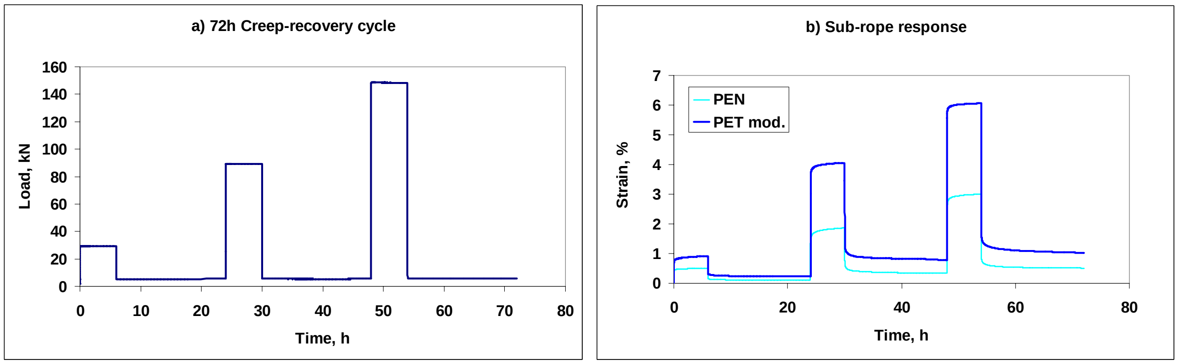

Figure 10. Creep/recovery cycle results for new sub-ropes of modified PET and PEN

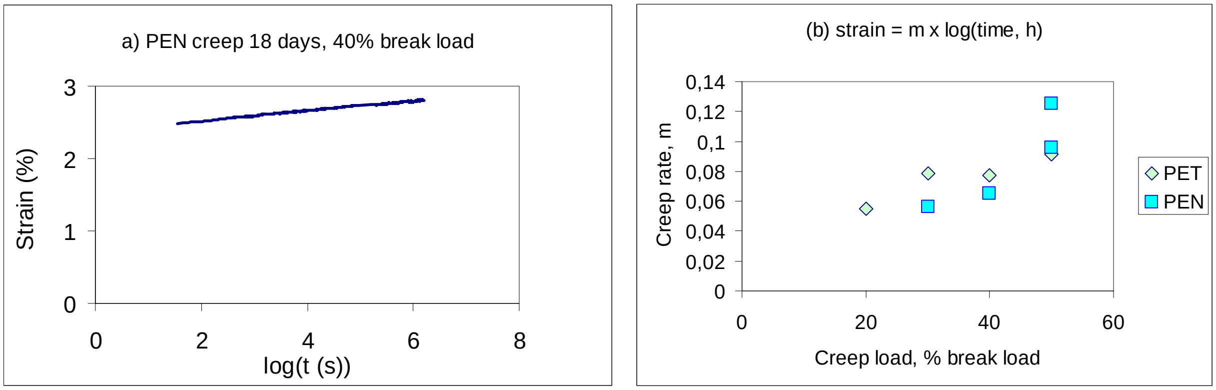

Figure 11. Long term creep on sub-ropes, a) example of plots for 40% break load, b) creep rates versus applied load

The creep of PEN is linear on a semi-log plot, Figure 11a, and creep rates are plotted on Figure 11b. It is apparent from these results and other data generated during the project that the creep rates are very similar for the two materials, and similar to previously-published results for standard PET [Del Vecchio 1992, Davies 2000, Grosjean 2005].

The other property of interest for mooring line applications is fatigue life. It has now been clearly demonstrated by extensive testing that the fatigue life of standard polyester tethers is more than satisfactory [Banfield 2005]. The aim of the present study was not to generate fatigue data, but in order to obtain a first indication of whether fatigue behavior of PEN is significantly different to that of PET fibers two types of test were performed, tensile fatigue on single filaments and yarn-on-yarn abrasion. First, single filament tensile fatigue tests were performed in air at ENSMP. Figure 12 shows an example of the results, which indicate that the intrinsic tensile fatigue behavior of the PEN is very similar to that of the polyester.

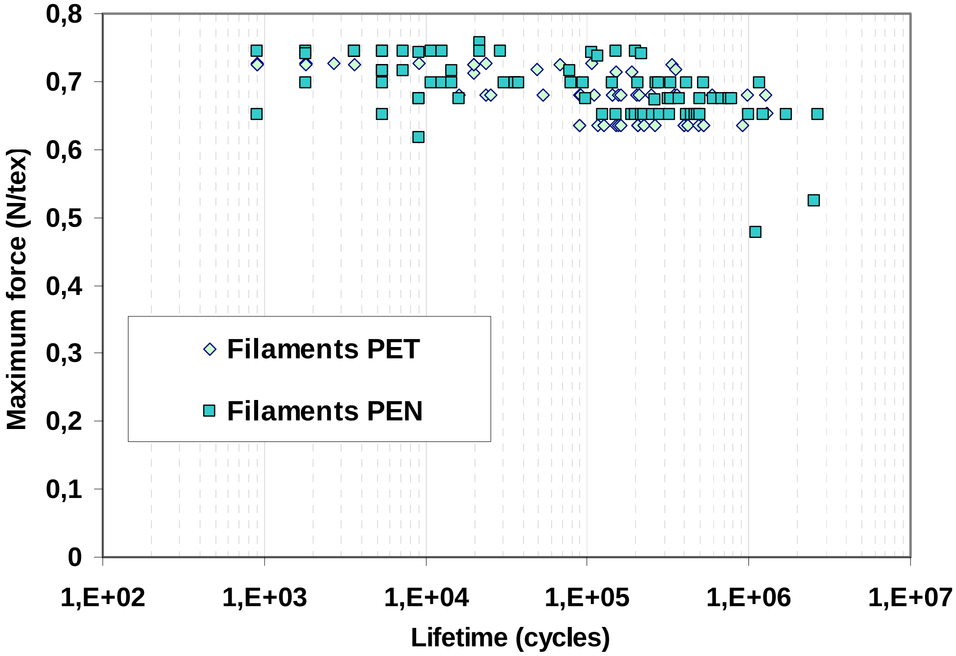

Figure 12. Tensile fatigue S-N curves, zero minimum load, various maximum loads, 50 Hz.

Then yarn-on-yarn abrasion tests were performed in natural sea water at Ifremer according to the standard test procedure [Cordage Institute 2001]. Figure 13 shows results for the two materials compared to the response of a standard yarn. The modified PET behaves in a very similar way to the standard material, the PEN lifetimes are a little lower and close to the recommended values [ISO, 2007]. However, it should be emphasized that whereas the marine finish on the standard polyesters has been developed over many years, the finish for the PEN fibers was not specifically developed for this fiber. Improved yarn-on-yarn abrasion lifetimes could probably be obtained for the latter if further development was carried out.

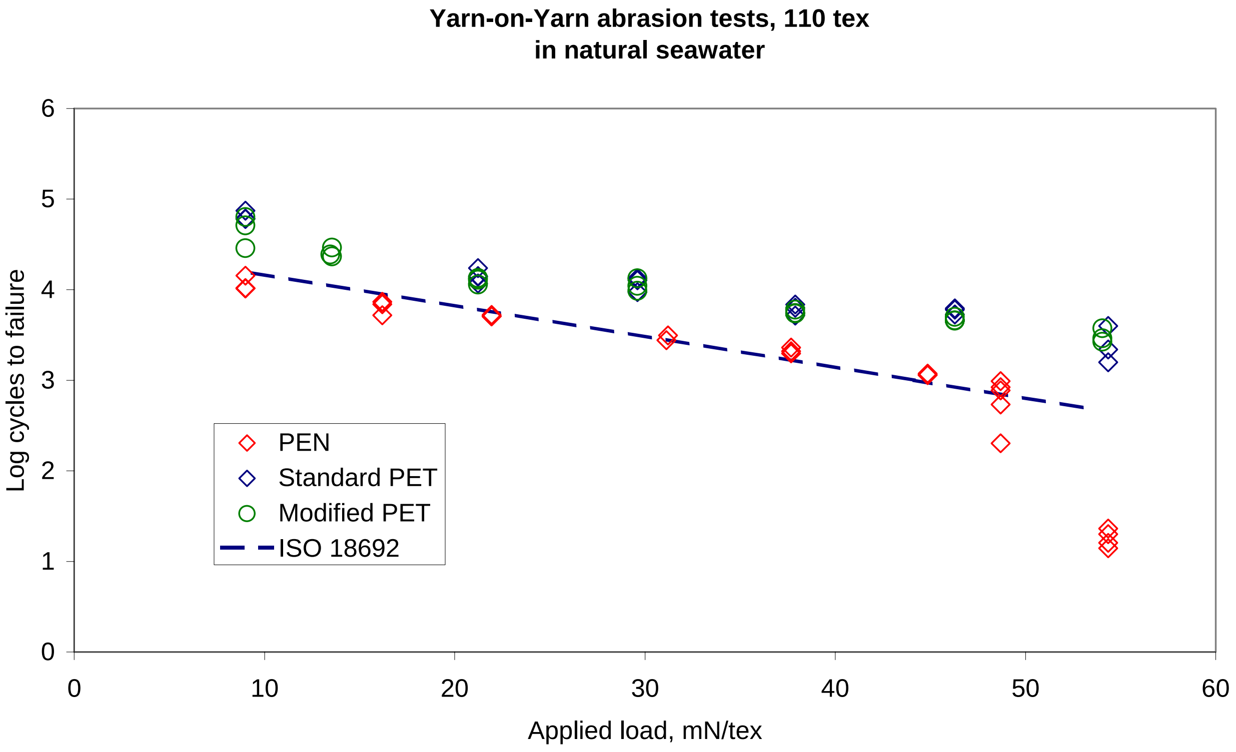

Figure 13. Yarn on yarn abrasion results

Qualification of higher stiffness polyester fiber ropes for mooring lines

These results suggest that the PEN material behavior is similar to that of standard PET fibers, so that additional safety margins, as were considered in the above analyses, could be removed, subject to adequate qualification of fibre and rope. The modified polyester fiber ropes studied here were tested and installed on the *Red Hawk* cell spar [Haslum 2005]. A standard API/ABS test program was performed including full scale break tests and a range of tests on scaled (1:4) ropes including 80000 cycles over a range of 15-45% break load. Those provide confidence in the modified polyester, but, as was shown above, the stiffness properties of the worked rope are very simlar to those of the standard material. For ropes with a new fibre such as PEN or other improved polyester fibre (see below), the process of qualification [Bureau Veritas, 2007] shall focus, besides standard tests, on the two following aspects, as discussed in [François 2005]:

- careful identification of the load elongation properties, that could be made for example by tests on sub-ropes, in addition to standard tests on a full size rope,
- within the qualification of fibre, which is a pre-requisite to rope qualification, assessment of "in-rope properties" of the fibres for long term endurance and capacity to withstand low minimum load under cyclic loading, by tests on small ropes, and a comparison with results for current polyester grades (see [Banfield 2005]) .

Other material options

In the current work PEN was studied, as this is the only fiber in the intermediate range commercially available for rope applications at present. It should be emphasized that this fiber was initially developed for tyre applications and there are potentially a very large range of other PEN fiber properties which could be obtained by appropriate drawing and heat treatment cycles [Wu, 2000]. A lower cost alternative to PEN might be to produce stiffer polyester fibers by drawing and heat treatments, and again development work has shown that polyester yarns can also be produced with a wide range of stiffnesses, up to those of PEN [Parguez, 2004].

While stiffness can be tailored to a particular application the strength of these fibers does not increase with increasing stiffness. However, ongoing research work in Japan has shown that polyester fiber strength can also be significantly improved [Kikutani, 2007] and this may result in an even wider range of possibilities for optimization in the future.

Conclusions

While the polyester fiber grade used extensively today for station keeping ropes has proved very satisfactory, it is only one of a very large family of materials which could be used for this application. In this study the influence of increasing rope stiffness has been examined, and PEN ropes have been used to illustrate how in some locations where offset is the critical design parameter a higher stiffness rope can provide improved performance through smaller diameter lines, weight gain and lower pre-tensions. When strength is the dimensioning factor higher fiber tenacity is required compared to the standard fiber, and the currently available intermediate stiffness fibers do not provide increased tenacity.

This paper has concentrated on the technical advantages of intermediate stiffness fiber ropes. For a particular application the economic benefits of smaller diameter, lower weight ropes, in terms of transport, handling and installation must be offset against the material cost penalty. The latter will depend on the manufacturing route, and in particular on whether the existing polyester route can be modified or if a fiber based on a different molecular structure such as PEN is necessary.

Acknowledgements

This work was performed within Phase 5 of the French Mooring line project. The project, which started in 1996 and was completed in December 2007, involved research institutes (Ifremer, IFP, ENSMP), engineering companies (Acergy, Doris, Principia, Saipem, Technip), the Bureau Veritas and Total. It was performed within the framework of the CLAROM group, the French Club for Research Activities on Offshore Structures.

The authors are grateful to Caroline Muller and René Soenen of Performance Fibers for supplying material samples. The expertise of technical staff at Ifremer (N. Lacotte, A. Deuff, B. Forest, D. Choqueuse and L. Riou) at IFP (J. Bonnaves, P. Hamdoun), at the ENSMP (Y. Favry, C. Teissedre) and at the LCPC (G. LeRoux, B. Philippot) is also gratefully acknowledged.

The views expressed here are those of the authors, and do not necessarily reflect those of their respective companies.

References

Banfield SJ, Casey NF, Nataraja R, (2005) Durability of polyester deepwater mooring rope, OTC 17510.

Bugg DL, Vickers DT, Dorchak CJ, (2004) Mad Dog project: Regulatory approval process for the new technology of synthetic (polyester) moorings in the Gulf of Mexico, OTC 16089.

Bunsell AR Hearle JWS, Hunter RD, (1971) An apparatus for fatigue testing of fibres, Jnl Physics E, 4, 868-72.

Bureau Veritas , (2007) Certification of fibre ropes for Deep water offshore services, NI432R01

Chailleux E, Davies P, (2005) A non-linear viscoelastic viscoplastic model for the behaviour of polyester fibres, Mechanics of Time Dependent Materials, 9, pp147-160.

Cordage Institute standard, Test method for yarn-on-yarn abrasion, CI 1503-00, August 2001.

Davies P, Baizeau R, Grosjean F, François M, (1999) Testing of large polyester cables for mooring line applications, Proc ISOPE, Brest, p360.

Davies P, Huard G, Grosjean F, Francois M, (2000) Creep and Relaxation of Polyester Mooring Lines, OTC 12176

Davies P, Francois M, Grosjean F, Baron P, Salomon K, Trassoudaine D, Synthetic mooring lines down to 3000 meters depth, (2002) OTC 14246.

Davies P, Chailleux E, Francois M, Grosjean F, Bunsell A, (2003), Prediction of the long term behavior of synthetic mooring lines OTC 15379

Del Vecchio CJM (1992), Light weight materials for deep water moorings, PhD thesis University of Reading

De Pellegrin I, (1999), Manmade fiber ropes in Deepwater Mooring Applications, OTC 10907.

Fernandes AC, Del Vecchio CJM, Castro GAV, Mechanical Properties of Polyester Mooring Cables, Int. J. Offshore & Polar Eng., 9, 3, Sept. 1999, pp207-213.

Francois M, Davies P (2000) Fibre rope mooring – a practical model for the analysis of polyester mooring systems, Rio Oil & Gas, 2000.

Francois M, (2005) Fibre ropes for Station-keeping : Engineering properties and qualification procedures, OCEANS 2005 MTS/IEEE - Washington

Francois M, Davies P (2008) Characterization of polyester mooring lines, OMAE2008.

Grosjean F, Davies P, Francois M, (2005) Synthetic Fiber Ropes mooring: technical status and stiffness prediction, Proc CMOO4.

Haslum HA, Tule J, Huntley M, Jatar S, (2005) Red Hawk polyester mooring system design and verification, OTC 17247.

ISO 18692 (2007) , Fibre ropes for offshore station keeping – Polyester.

Kikutani T, (2007) Private communication

Lechat C, Mechanical behaviour of polyester fibres and fibre assemblies for mooring offshore platforms, PhD thesis (in French), Ecole des Mines de Paris, 2007.

Lechat C, Bunsell AR, Davies P, Piant A, Mechanical behaviour of polyethylene terephthalate & polyethylene naphthalate fibres under cyclic loading, Journal of Materials Science, Vol. 41, 2006, pp1745-1756

Paganie D, (2007) Independence Hub breaks records through collaboration, innovation, Offshore, volume 67, issue 12th December,

Parguez O (2004), Private communication

Wu G, Li Q, Cuculo JA, (2000) Fiber structure and properties of poly(ethylene-2,6-naphthalate) obtained by high-speed melt spinning, Polymer, 41, 8139-8150.