Load-elongation characteristics of high tenacity polyamide yarns

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Abstract

Synthetic fibre ropes are extensively used in a number of applications related the production of oil in deep and ultra-deep water, for example in moorings and in the installation of equipment on the sea floor. The ability to build a tether with quasi-static and dynamic load-elongation characteristics that best suits each application is used by the engineer to optimize the performance of the system being designed. Tether properties can be estimated based on yarn properties and the geometric construction of the tether. Since the basic constituent of the ropes, that is the yarns, are non-linear viscoelastic, cyclic load-elongation properties are a function of frequency, mean load and load amplitude. The paper describes the load-elongation behaviour of high tenacity nylon yarns in cyclic conditions relevant for deepwater moorings and for the connection of two deepwater units one to each other by means of these tensile elements. Load control and elongation control, including slack conditions are reported.

Keywords: fibre rope, nylon, load-elongation, mooring, deep water.

1 Introduction

The use of synthetic fibre ropes is well established in deep water moorings [1] (% YBLWet). The ability to tailor load-extension characteristics to the required response of the tether is the most important characteristic of fibre ropes. For example, the use of high efficiency polyester ropes suits very well the taut leg mooring of Floating Production Units [2].

Typical deepwater mooring ropes have breaking loads ranging from 5MN to 20MN. The basic building unit of these ropes is an industrial yarn with breaking load of the order of 100N and rope making consists of a sequence of twisting and/or braiding operations.

Properties of ropes are derived from the properties of their constituent yarns and of the geometry of the construction. High tensile efficiency ropes are obtained by using quite long twisting and/or braiding pitches and high tenacity yarns.

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Tenacity is the standard way of assessing the strength of textile products such as yarn and fibre ropes. Tenacity is measured by dividing the breaking load of the component by its mass per unit length and is expressed in N/tex in the International System of Units. Tex is a mass per unit length of 1g/km. In textile practice modulus is also presented normalized by mass per unit length (in N/tex) instead of by cross sectional area as usual in other engineering areas.

Table 1 shows typical properties of some industrial yarns used for rope making [2]. As mentioned above the choice of a yarn to make a mooring rope is decided considering several characteristics of which load-extension properties and cost are probably the most important.

Table 1: Typical properties of most widely used rope making yarns

Material	Tensile Strength (GPa)	Tenacity (N/tex)	Failure strain (%)	Density (g/cm^3)	Moisture Absorption (%)
nylon 6	0.9	0.81	23	1.14	4.5
nylon 6.6	1.0	0.88	19	1.14	4.5
Polyester	1.1	0.82	11.0	1.38	0.4
Aramid	2.8	1.95	3.6	1.44	7.0
HMPE	2.6	2.65	3.5	0.97	0.0

Offshore moored Units respond to mean environmental load by offsetting horizontally from their base position until the mooring system generates restoring force to balance these loads, but their response to waves and the dynamic components of wind and current is more complex. For the sake of better understanding one can consider the dynamics of the vessel as consisting of a low frequency resonant response excited by currents and winds and a high frequency response to waves.

The limits, both static and dynamic, for these movements is typically given by what it is acceptable for the pipes that connect the Unit to the seafloor bringing or taking fluids from various equipments such as wellheads, manifolds, etc. Since hydrodynamic forces from waves are of a cyclic nature and very strong to be restricted by a deepwater mooring system, in general a mooring system should be compliant to these loads.

All steel mooring systems draw their compliance from the catenary shape they assume in their free length. Fibre ropes can be designed, in deep water, to use their axial compliance for this purpose. However the non-linear viscoelastic behaviour of yarns and consequently ropes interacts with the loading on the moored Unit in a quite complex way making the design of mooring systems based on fibre ropes substantially different from the design of systems base in all steel components.

A Full understanding of the behaviour of fibre ropes is essential for the design of the mooring system since the response of the system is a function of load-elongation characteristics. On the other hand rope must be fit for the long term response in fatigue, creep as well as environmentally assisted degradation.

The application envisaged presently is the use of fibre ropes to link two offshore units moored in deep water at an approximate distance of 50m. The ropes restrict relative movement making it viable to have a foot bridge and a bundle of flexible pipe jumpers between the units.

This is a new application for fibre ropes and the combined system consisting of the two units show other responses in addition to the individual response of each moored unit as described above.

Preliminary design exercises for this application have shown that high efficiency polyester fibre ropes are too stiff, resulting in very high fatigue loads and in the ropes becoming slack. It was then decided to study the use of high efficiency nylon ropes. Another option would be to use ropes made of Polyester fibres with lower modulus.

Load extension properties of mooring size ropes in high efficiency constructions can be estimated from yarn characteristics, therefore this paper presents a study of the load-extension characteristics of some high tenacity nylon yarns relevant to this application.

2 Materials and methods

It was decided to evaluate three high tenacity yarns, two of them are nylon 6.6 and one is a nylon 6 yarn. All yarns are manufactured by Polyamide High Performance Fibres. Table 2 shows basic data for them.

Table 2: Linear density and breaking properties of polyamide yarns studied

Manufacturer Identification	Type	Linear Density tex	Tenacity (dry) N/tex	Elongation at break (dry) %	Tenacity (wet) N/tex
140HRT	6.6	210.5	0.832	19.8	0.765
142HRT	6.6	211	0.95	18.0	0,867
540T	6	190	0.768	23.5	0.711
HPPIY Spec.AA	PET	111	0.700	22.0	0.700

Tensile tests were performed in the yarns after 12 hours immersion to characterize their wet breaking strength, since in the application ropes will be wet and it is well known that nylon yarn behave differently in the wet condition. Table 2, above, also shows breaking tenacity measured for the wet yarns.

For load-elongation measurement yarns were terminated by gluing with epoxy resin between acrylic tabs. Free length between tabs was 190mm. This was considered the gauge length.

Tests were performed in a 100kN MTS load frame using a 2500N load cell. The load cell was verified with dead weights to check its calibration and stability since loading was between zero and 91N. Extension was measured with the 150mm range LVDT mounted in the servo-hydraulic cylinder. This is acceptable since all fixtures in the load path are at least two orders of magnitude stiffer than the yarns tested.

Since loading in the application envisaged sometimes is controlled by force and sometimes is controlled by extension test were performed both in load and in displacement control. This allowed the determination of the yarn characteristics in the slack condition.

For the sake of comparison a limited number of tests were performed in a high tenacity low modulus polyester (PET) yarn manufactured by Zhejiang Unifull Industrial Fibre Co., which has similar breaking tenacity and elongation. Basic properties of this yarn are also shown in Tab. 2.

All load-extension measurements were performed with the yarns wet after immersion for 12 hours. For tests performed in load-control minimum load varied from 2 to 40% of the wet breaking load of each yarn (YBLWet) and maximum load varied between 10 and 50% of YBLWet. Yarns were cycled at 0.1Hz, which is a typical frequency for the response of the current application. Since the response varies substantially in the first few cycles, results are presented for a single cycle after 50 to 100 cycles, as needed to obtain a steady response.

3 Results

Figure 1 shows a typical plot of load versus strain after 100 cycles, in the form of a hysteresis loop. The graph gives us an idea of the non linear behaviour of the yarn as well as the significant amount of energy dissipated in each cycle.

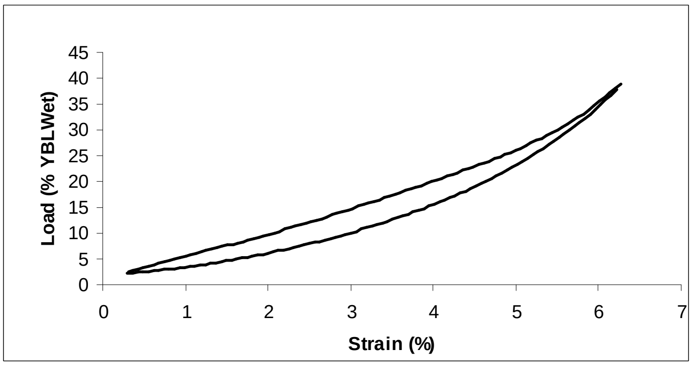

Figure 1: Load versus strain plot of a nylon 142HRT yarn cycled between 2 and 40% of the average wet breaking load of the yarn at 0.1Hz (100^{th} cycle)

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Table 3 shows the secant modulus for each loading condition, for tests performed under load control respectively for yarns 140HRT, 142HRT and 540T.

Table 3: Secant modulus for nylon yarns after 100 cycles

Load Limits (%)	140HRT Modulus (N/tex)	142HRT Modulus (N/tex)	540T Modulus (N/tex)
2 - 10	2,34	2,45	1,83
2 - 20	3,12	3,34	2,49
10 - 20	5,10	5,77	4,79
2 - 30	3,88	4,21	3,50
10 - 30	5,77	6,50	5,22
20 - 30	7,89	9,24	7,42
10 - 40	7,36	7,24	6,48
20 - 40	8,61	9,77	8,75
30 - 40	10,36	12,02	10,40
10 - 50	7,43	7,98	7,11
20 - 50	9,64	10,35	9,20
30 - 50	11,07	13,20	11,10
40 - 50	12,75	15,83	12,71

Table 4 shows yarn modulus normalized by YBLWet. These figures were obtained by dividing the secant modulus (in N/tex) by YBLWet (in N) and multiplying by the mass per unit length (in tex).

This is another way of normalizing modulus which it is quite useful for the designer of the mooring system. It represents the force, in number of times the breaking load, one must apply to the component to double its length. It provides a direct way to compare modulus of components that have the same breaking load.

Figures 2 and 3 show the result of cycling yarns 142HRT and 540T up to 30% of YBLWet from the unloaded condition. It can be seen that load-elongation characteristics are similar if the yarns had the same breaking load. However the higher hysteresis presented by the 142HRT yarn is noticeable.

Table 4: Secant modulus of nylon yarns presented as load/strain normalized by the breaking load of each yarn

Load Limits (%)	140HRT Modulus (N/N)	142HRT Modulus (N/N)	540T Modulus (N/N)
2 - 10	3,05	2,83	2,57
2 - 20	4,08	3,85	3,50
10 - 20	6,67	6,66	6,75
2 - 30	5,07	4,86	4,92
10 - 30	7,54	7,50	7,35
20 - 30	10,31	10,66	10,44
10 - 40	9,62	8,36	9,13
20 - 40	11,25	11,28	12,31
30 - 40	13,55	13,87	14,63
10 - 50	9,71	9,21	10,00
20 - 50	12,61	11,94	12,95
30 - 50	14,47	15,23	15,62
40 - 50	16,67	18,26	17,88

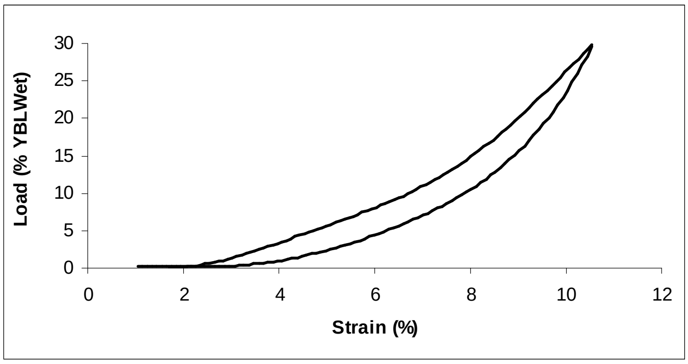

Figure 2: Load-strain plot of a nylon 142HRT yarn cycled between a slack condition and 30% of the average wet breaking load of the yarn at 0.1Hz (50^{th} cycle)

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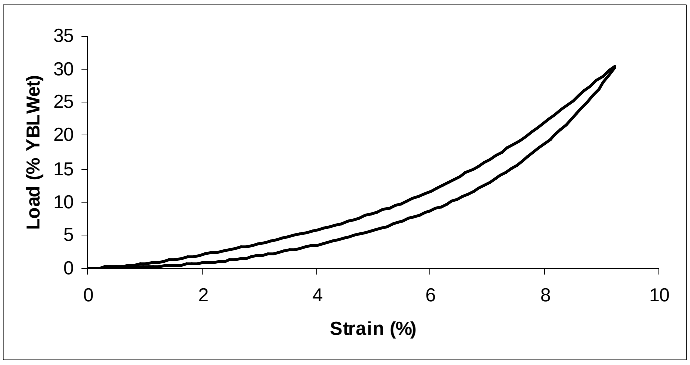

Figure 3: Load-strain plot of a nylon 540T yarn cycled between a slack condition and 30% of the average wet breaking load of the yarn at 0.1Hz (50^{th} cycle)

4 Discussion

It was possible to characterize the load-extension behaviour of nylon yarns that are good candidates for making ropes to be used to connect floating units moored in deep water.

A usual way of translating yarn modulus is by a linear regression in terms of load range and load range (peak to peak). Tab. 5 shows the coefficients of such regressions for the three nylon yarns studied, as well as the square of the coefficient of correlation (R^2). The fit selected forces the intercept to be at the point (0, 0, 0).

Table 5: Regression of Modulus (N/tex) as a function of Mean load (% YBLWet) and Load range (% YBLWet)

Yarn	Mean load coefficient	Load range coefficient	R2
140HRT	0.297346	-0.021043	0.9963
142HRT	0.367327	-0.064195	0.9973
540T	0.302957	-0.042311	0.9982

Modulus of high efficiency fibre ropes can be estimated based on the modulus of their constituent yarn and rope geometry. Typically moduli of such ropes vary from 0.75 to 0.8 of the modulus of the yarns for high tenacity PET fibre. Its is reasonable to expect that high tenacity nylon yarns such as those tested show a similar behaviour. Verifying this hypothesis is one of the subjects of ongoing work.

Figure 4 shows results (raw data) for yarns 142HRT, 540T and the PET yarn cycled between the slack condition and 30% of YBLWet plotted together. Although the PET yarn has failure strain in the same range of the nylon yarns it can be seen that the near zero load is very different. The nylon yarn show an almost asymptotic behaviour to the X axis and one would expect that a high efficiency rope made with this yarn shows no impact when being loaded from a slack condition. On the other hand, a PET rope of a similar construction will certainly show impact loading in the same condition.

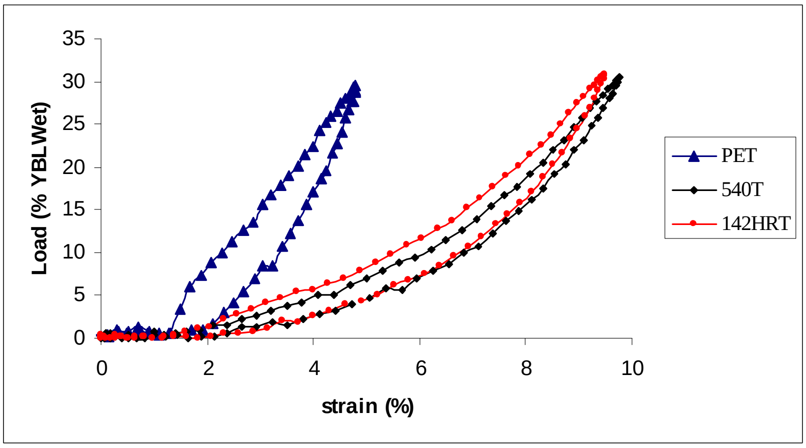

Figure 4: Load-strain plot of nylons 540T and 142HRT yarns and of the high elongation PET yarn cycled between a slack condition and 30% of the average wet breaking load of each yarn at 0.1Hz (50^{th} cycle)

5 Conclusions

High tenacity nylon yarns showed load-extension behaviour, characterized by the secant modulus after some 100 stabilization cycles, that can be represented as a linear function of mean load and load range. Mean load is the dominant factor, the influence of load range being one order of magnitude smaller.

It is reasonable to expect that high efficiency ropes made with these yarns show modulus between 0.75 and 0.8 of the modulus of the yarns used. This approximation can be used for preliminary design analyses.

All nylon yarns showed asymptotic behaviour as loading approaches zero, as opposed to the typical behaviour of PET yarns. Considering that rope constructional stretch adds tensile compliance to the yarn it can be concluded the high efficiency nylon ropes should not show impact when loaded from the slack condition. This characteristic is very interesting in the application of connecting two units moored in deepwater.

6 Further work

The time history of the movement between two units moored in deepwater, connected by cables, is random in nature, therefore its computer simulation would be much easier if load-extension behaviour of the connecting ropes could be represented by a single curve giving an instantaneous modulus at each load. The assembly of such a “master curve” is the subject of present ongoing work.

Load-extension behaviour must be characterized in ropes in order to verify how modulus varies with rope construction and to check the hypothesis that rope modulus is in the range of 75 to 80% of yarn modulus. It is believed that this can be done on model ropes with breaking loads of a few tens of kN.

Preliminary computer simulations have shown that cycling amplitudes are substantial in the application envisaged, therefore fatigue performance of the candidate ropes shall be obtained and compared with the service load history. Although this could be addressed initially with small ropes, some testing in full size ropes will be required. To the best knowledge of the authors, no such data is available in the literature for high tensile efficiency ropes based on high tenacity nylon yarns.

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