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Analysis, Design and Installation of Polyester Rope Mooring Systems in Deep Water

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Abstract

The purpose of this paper is to describe the authors' recent experience with the analysis, design, and installation of polyester rope mooring systems for deep water applications. Among the latest research activities, this article describes a series of full-scale tests performed on polyester rope provided for several spread moored systems offshore Brazil and West Africa. One of the main purposes of the performed tests was to determine non-linear stiffness characteristics of the rope; but other parameters used in the design and optimization of the polyester rope mooring system were also investigated.

Introduction

The past decade has seen a steady increase in the number of polyester rope deep-water mooring system for oil and gas exploration, especially floating production facilities. Brazil has always been in the frontier of the application of synthetic mooring ropes. Industry forecasts point to a strong increase in the number of such systems, considering the latest deepwater discoveries made offshore Brazil. Due to the past and present history of success in the use of polyester rope for the mooring of deep water floating system offshore Brazil, it is a general consensus that this trend will continue into the future and expand to other producing regions such as The Gulf of Mexico and West Africa as it can already be observed.

There are many obvious advantages in using polyester ropes on deep water mooring systems. We could mention a few of them such as: lighter weight, desirable elastic characteristics and superb fatigue performance; on the other hand when engineering and installing such a system there are specific issues to be appropriately dealt with by the designer and the installation personnel. This paper will discuss some of the peculiarities associated to the design; analysis and deployment of polyester rope mooring system for deep water applications.

The main topic of discussion in this article is a practical way to model the elastic stiffness of polyester mooring ropes in order to have a simple and reliable model that produces reasonably conservative extreme mooring loads and vessel-offsets. Such numeric model describing the elastic behavior of the polyester ropes have a significant impact on mooring system for floating facilities for deep water applications, with a specific application to the mooring of FPSO's.

Typical Polyester Rope Mooring System for Deep Water FPSO Applications

Fig.1 depicts a typical deep water FPSO spread moor system. Each anchor leg is constituted by two segments of chain, one located at the bottom and the second close to the surface; joined by a single or multiple segments of polyester rope. In case of the mooring system shown on Fig.1 we can see three (3) segments of polyester rope joined by two (2) short segments of chain.

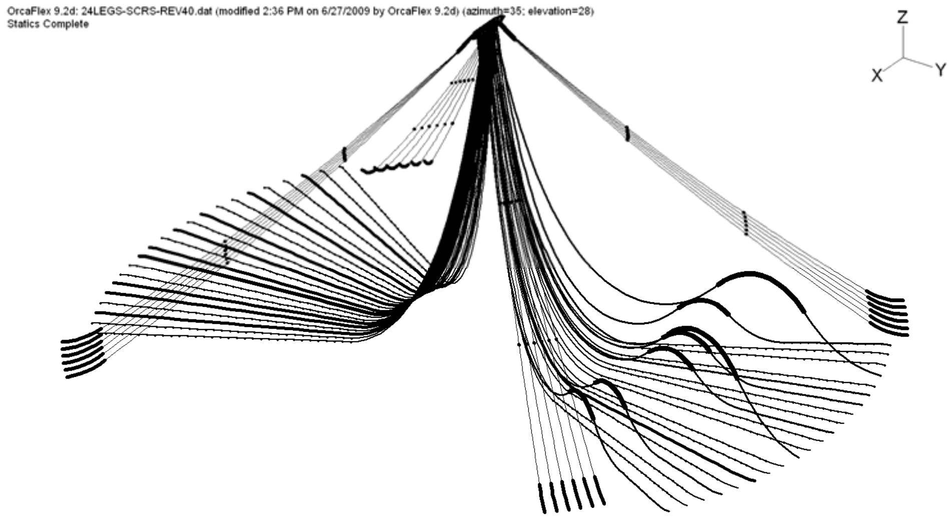

Fig. 1 – Typical deep water spread moor system

As indicated in Fig. 1, for each anchor leg the polyester section is the longest and the most compliant of the components, therefore the mooring system's horizontal stiffness and its dynamic behavior are highly dependant upon the polyester's rope elastic behavior.

A proper representation of the polyester rope's stiffness will allow for an adequate estimate of vessel-offsets and mooring line loads and will allow therefore for an optimized mooring system, eliminating unnecessary cost associated to an overly conservative mooring system design.

Modeling Polyester's Elastic Behavior

One the single most important activities during the design of polyester rope mooring system is the analyses to determine the dynamic behavior of the coupled mooring-vessel system. In that sense the polyester stiffness plays a very important role in the dynamic behavior of the system, therefore a proper numerical representation of the elastic behavior of the polyester rope is of paramount importance as it has a direct and significative influence in extreme vessel-offsets and loads on mooring lines.

Based on extensive research conducted on the elastic behavior of polyester ropes and on past research studyies (Del Vecchio, 1992); the rope stiffness can be numerically modeled assuming the following mathematical model:

$$k = k_0 + k_1 L_m - k_2 L_a \qquad \text{Eq. 1}$$

Where:

k – Polyester rope instantaneous stiffness
k_0 – Static stiffness
k_1 – Mean load stiffness coefficient
k_2 – Varying load stiffness coefficient
Lm – Mean load level
La – Amplitude of dynamic loading

As indicated in the equation above, the instantaneous rope stiffness depends on a combination of mean load level and the magnitude of the dynamic component of the loads the system is exposed to. As shown in Del Vecchio the stiffness is a logarithmic function of cycle period but this is a secondary effect and is accounted for in the dynamic loading. Creep and constructional elongation effects are not included in the elastic model discussed along this paper. However, the effects are addressed by modifying the polyester rope length by the required amount.

The tests conducted for several of the polyester rope systems the authors have designed and deployed, indicate that the effect of mean line loads in the augmentation of the polyester rope stiffness is not instantaneous. The rope structure becomes stiffer as the rope is continuously loaded until a stiffness plateau is reached.

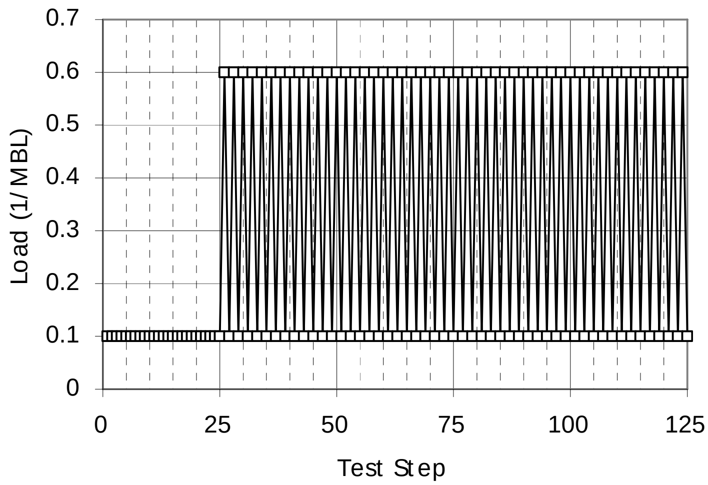

Fig. 2 - Periodical Loading on Polyester Rope

To illustrate, Fig. 2 exemplifies the loading scheme imposed to a typical mooring polyester rope with fixed mean load equal to approximately 35% of the polyester rope breaking load and a dynamic load amplitude equal to 25% of the rope's breaking load, the test was performed on a new worked rope. If instantaneous polyester rope stiffness values are calculated along the different test steps; we can observe an asymptotic increase in the rope stiffness as the test progresses until it reaches a determined plateau level. Fig. 3 is for illustrative purposes only and do not correspond to an actual test. Note how the initial stiffness of about 12 times the rope's MBL increases contiuously until a plateau at about 26 times the MBL is reached. According to Fig. 3 it took approximately 75 cycles for this plateau to be reached.

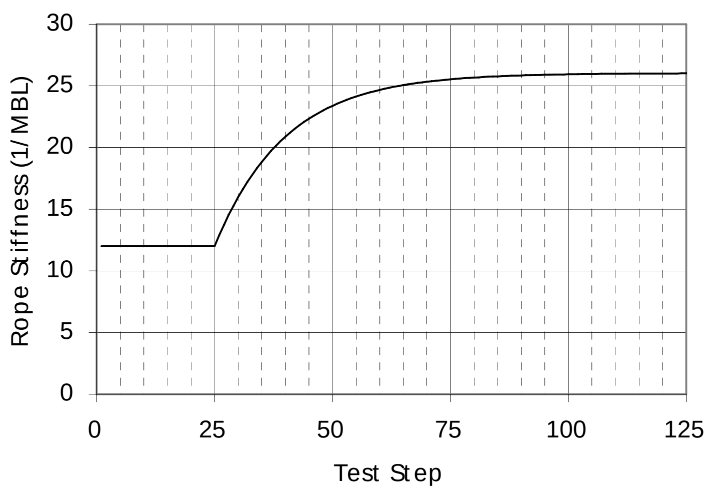

Fig. 3 - Instantaneous polyester rope stiffness

The longer the polyester rope is subject to a steady dynamic load regimen the stiffer it becomes until a certain maximum stiffness is reached, a plateau which level depends on the mean load on the line and the actual amplitude of the dynamic loading, as indicated on Eq.1.

Typically, it has been a design practice to assume the plateau level as the reference stiffness for the calculation of mooring loads for design; however, when the actual behavior of polyester mooring system subject to realistic extreme environmental conditions is observed; the chances of the maximum stiffness plateau to be reached are very small. In reality, not only mean line loads vary greatly as the vessel slow-drifts around the mean vessel-offset position, the dynamic component of the loads also vary in amplitude.

Polyester Rope Stiffness Curve for Design

In practical terms, we could say that the instantaneous polyester rope stiffness is a combination of two stiffnesses; the first component is the static stiffness, which is constant and the second component is the dynamic component of the rope stiffness that depends on the mean load; the amplitude of the dynamic loading and the number of cycles at that specific mean load level and amplitude.

In order to avoid unnecessary conservatism associated to the design of the mooring system; the authors have conducted a series of full-scale tests to determine a practical stiffness curve for the design of polyester rope mooring system. This curve would allow for an adequate combination of static and dynamic effects on determining the stiffness characteristics of the polyester rope. It was decided that the rope would be loaded in a way that resembles conditions observed offshore; especially loading regimen that typically occur when the mooring line is about to experience an extreme loading associated to second-order vessel motions combined with first-order wave induced motions. We shall call this test the "Design Stiffness Test".

The "*Design Stiffness Test*" simulates the conditions experienced by the rope in the field. The load signal is comprised of an increasing or decreasing mean load coupled to a wave frequency component of approximately 5% of the rope MBL. In accordance to industry code; a typical safety factor applied to the design of polyester rope for mooring system is in the order of 1.88; which corresponds to a maximum load no greater than 55% of the certified minimum breaking load (MBL) of the rope.

Fig. 4 shows the actual loading sequence from which the polyester rope stiffness curve was obtained. For that specific polyester rope; the breaking load was approximately 900 metric tons; therefore the maximum peak load the rope was subjected to during the test, 600 tons; corresponds to 67% of the rope's certified MBL; the mean load level of 540 tons corresponds to 60% of the MBL.

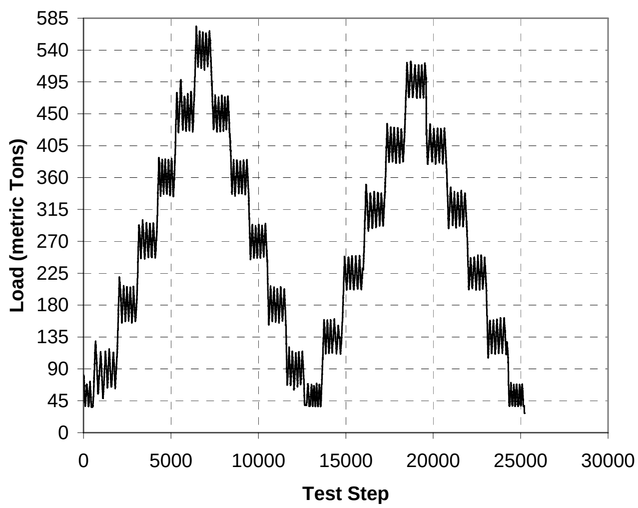

Fig. 4 - Load Sequence – Design Stiffness Test

The Fig. 5 through Fig 10 show a combination of load-elongatino plots obtained for 6 different mean load levels: 10%, 20%, 30%, 40%, 50% and 60% of MBL from the "*Design Stiffness Test*" presented on Fig.4. The whole test sequence was subdivided in test blocks called Test 1, 2, 3 and 4. Elastic modulus from each test is presented on Table 1.

For each of the plots the slope defined by a linear curve fitted through the points will be the polyester rope stiffness at that given mean tension load. For each one of the graphs presented in Fig. 5 through 10 a linear regression fitting was performed; each graph shows the actual rope stiffness obtained from the linear fitting. As an example: the first graph presented in Fig. 5 generates a slope equal to 10.99 meaning that the rope stiffness recorded for that test is approximately 11 times the rope MBL.

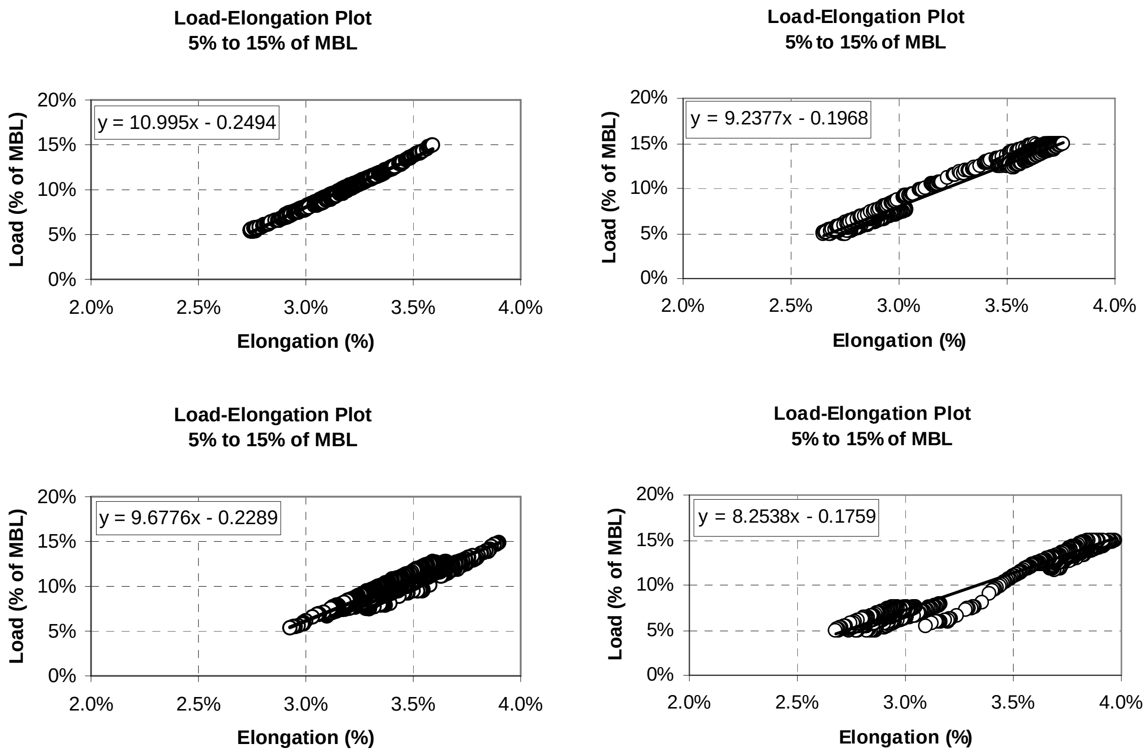

Fig. 5 - Load-Elongation (10% of MBL)

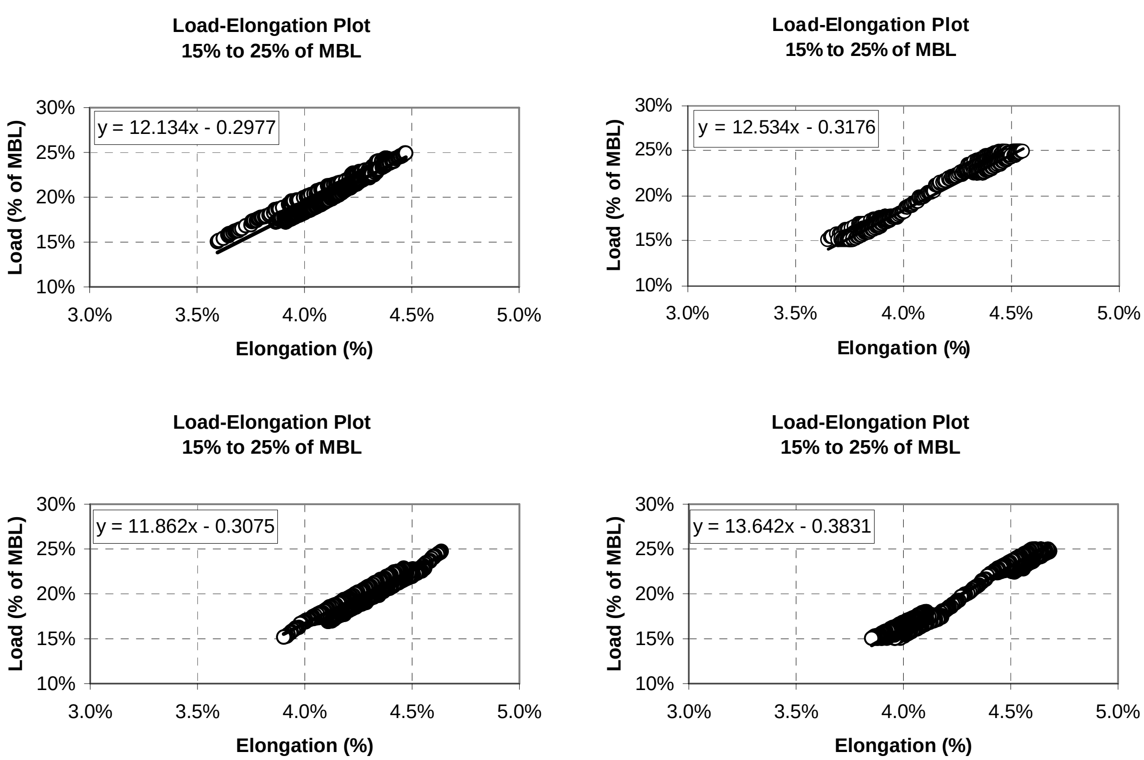

Fig. 6 - Load-Elongation (20% of MBL)

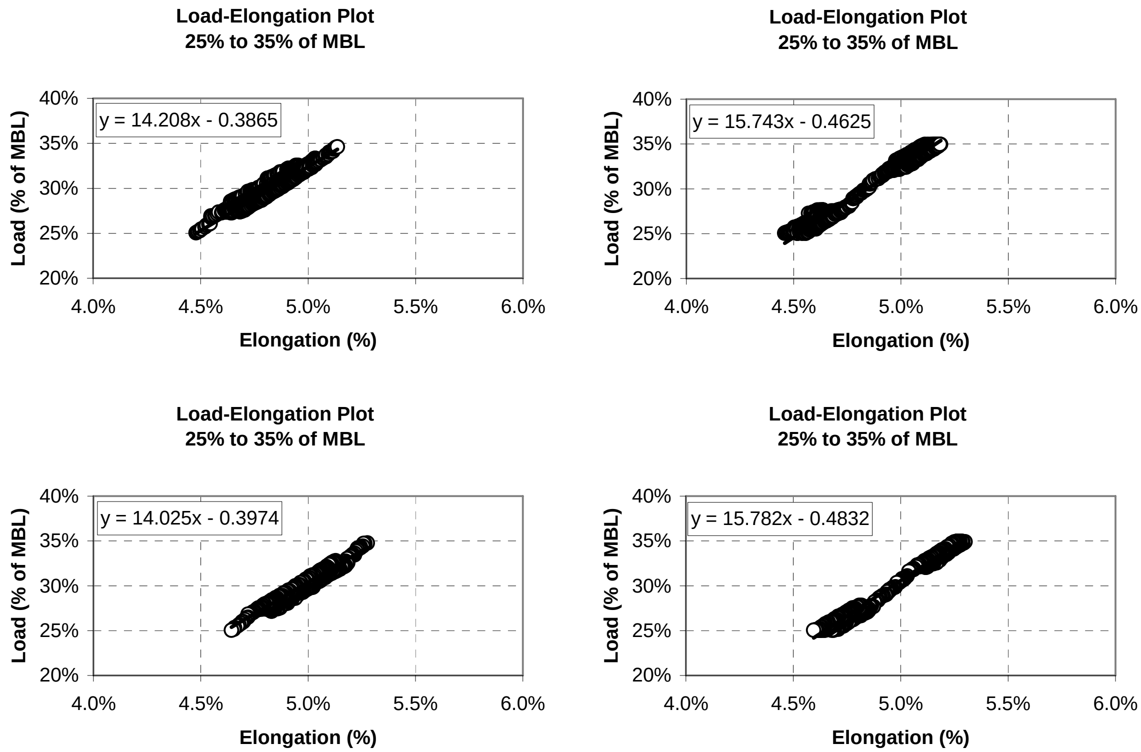

Fig. 7 - Load-Elongation (30% of MBL)

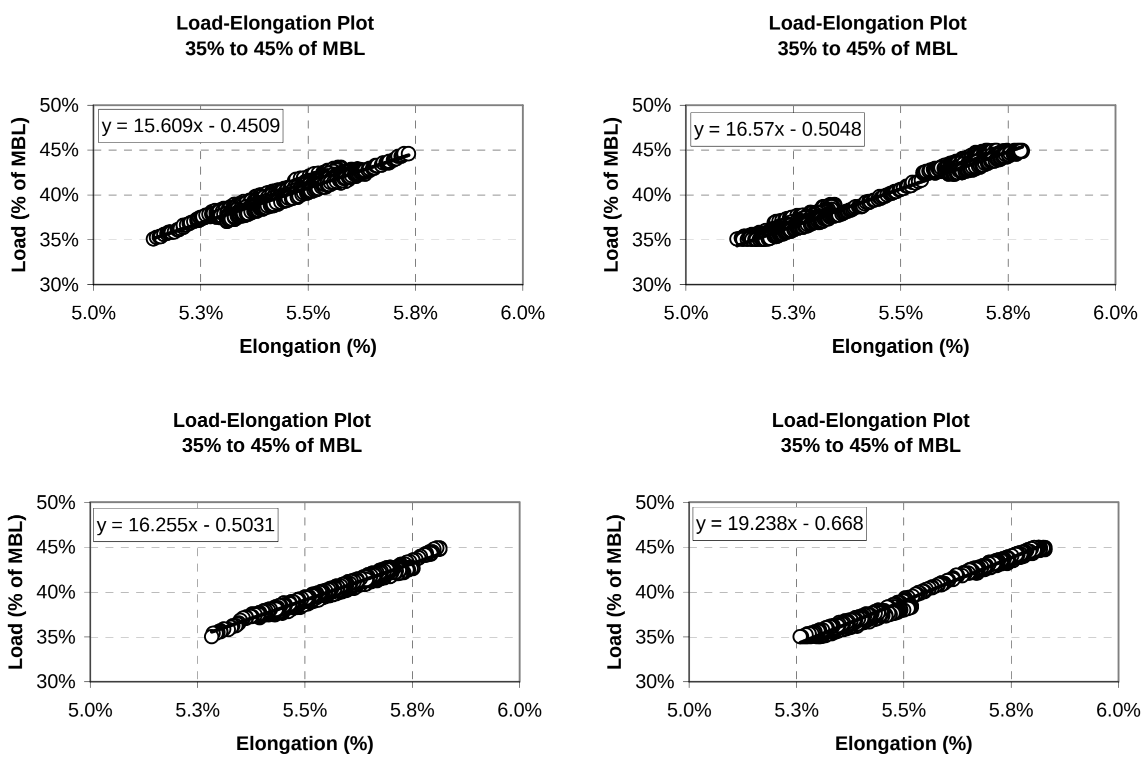

Fig. 8 - Load-Elongation (40% of MBL)

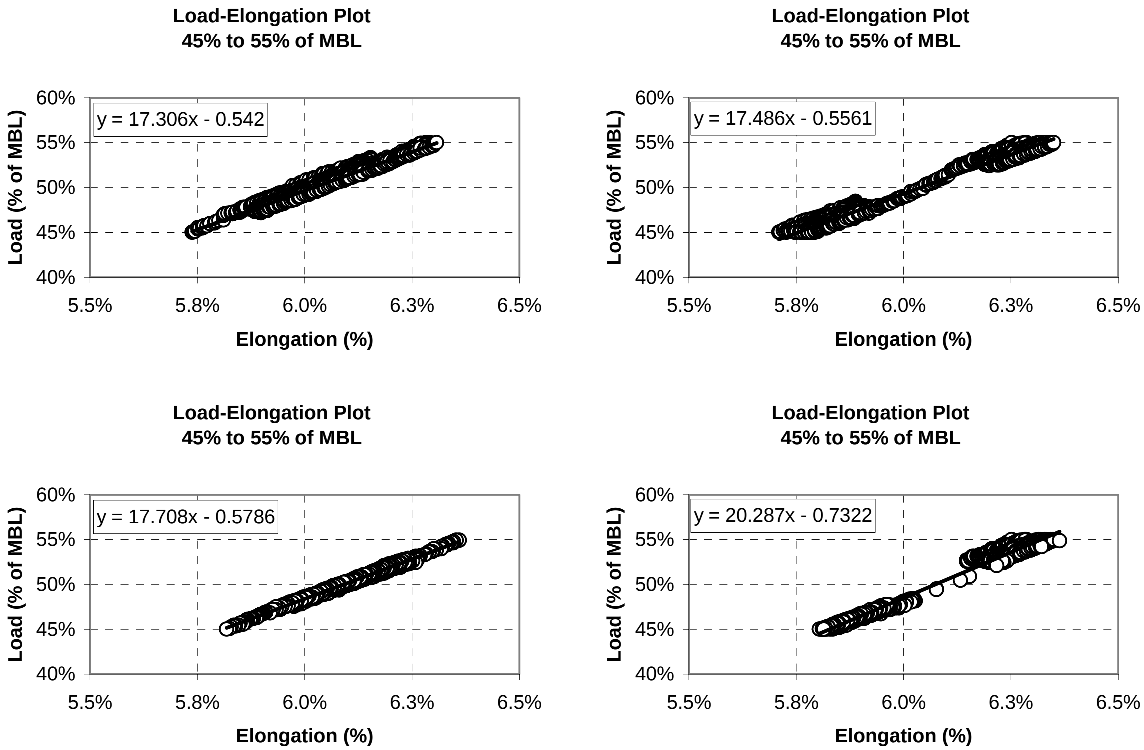

Fig. 9 - Load-Elongation (50% of MBL)

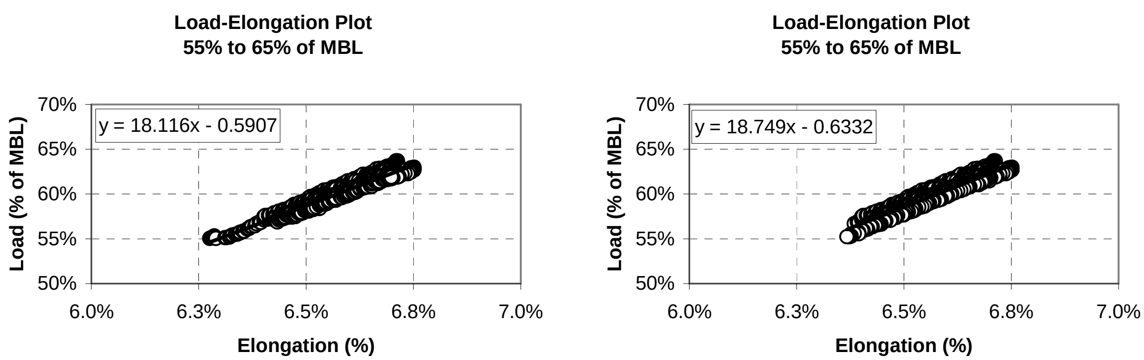

Fig. 10 -

Load-Elongation (60% of MBL)

Table 1 and Fig 11 present a summary of the test results shown in Fig. 5 through 10. As indicated in Table 1, for each of the 6 mean tension levels, 4 tests were performed, except for the last mean tension level (60 % of MBL). The rope stiffness obtained from each of the 4 tests is presented on the columns: Test 1 through Test 4. The maximum of the 4 stiffness obtained is presented on the column "Maximum" and plotted on Fig. 11 as function of the mean load on the rope.

Fig. 11 also serves as a comparison between the stiffness curve obtained from the "*Design Stiffness Tests*" performed for the polyester rope and the actual polyester rope stiffness curve adopted for the design of mooring systems. The adopted *Design Stiffness* curve is slightly stiffer when compared to the test stiffness curve defined by the test data as a means to produce reasonably conservative loads.

Fig. 11 indicates that the actual stiffness curve adopted for the calculation of extreme loads to be used in the design of the polyester rope is approximately 20% stiffer when compared to the elastic modulus obtained from the conducted "Design Stiffness" testing.

Table 1 - Rope Stiffness as function of Mean Load Level

Load (% of MBL)	Rope Stiffness (MBL^{-1})				
	Maximum	Test 1	Test 2	Test 3	Test 4
0%	10.0	-	-	-	-
10%	11.0	11.0	9.2	9.7	8.3
20%	13.6	12.1	12.5	11.9	13.6
30%	15.8	14.2	15.7	14.0	15.8
40%	19.2	15.6	16.6	16.2	19.2
50%	20.3	17.3	17.4	17.7	20.28
60%	18.8	18.1	-	-	18.75

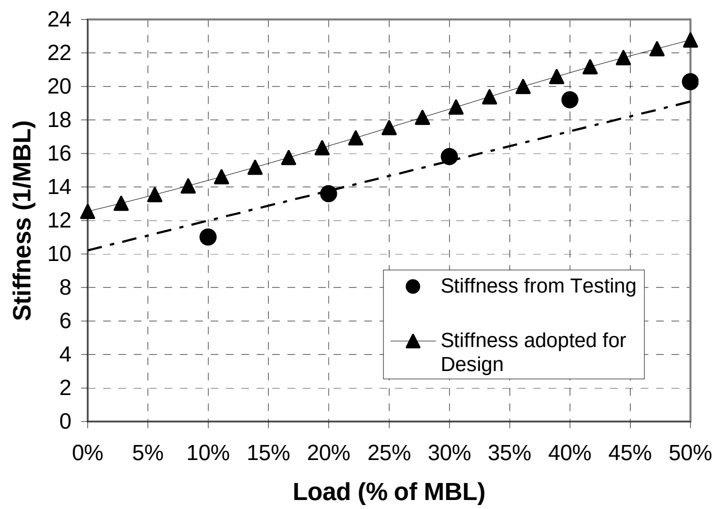

Fig. 11 – Testing vs. Design Stiffness curves

A Comparison between the "Dynamic" And the "Design" Stiffness

As previously discussed, typically the stiffness characteristics of polyester ropes adopted for the calculation of extreme mooring loads are determined by means of cycling the polyester ropes at different mean levels until a stiffness plateau is reached, normally a number of 100 oscillations around a mean load level is prescribed as a reasonable number of cycles for the plateau to be reached. Fig. 12 depicts an actual full-scale test performed by the authors for a 900 metric tons MBL polyester rope. From the test data presented in Fig.12 the rope "*dynamic*" stiffness was determined as presented on Table 2.

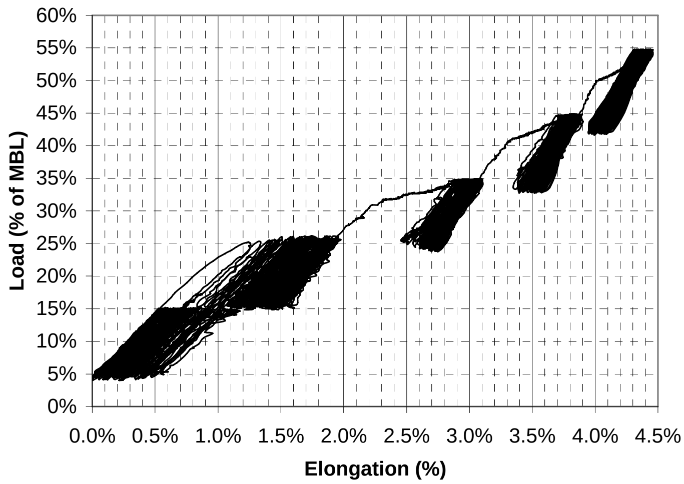

Fig. 12 – Typical Dynamic Stiffness Testing Curves

For sake of clarity this article will refer to this type of testing as "*Dynamic Stiffness Testing*" as opposed to the "*Design Stiffness Testing*", the difference between these two tests being the load regimen the rope is subject to, resulting in different stiffness for the same mean load level. Between the *"Dynamic"* and the "*Design"* stiffness, the first will always be higher.

Table 2 - Rope Stiffness Comparison – Dynamic vs. Design Stiffness

Rope Stiffness Test Comparison		
Mean Load (% MBL)	**Dynamic Stiffness (MBL^{-1})**	**Design Stiffness (MBL^{-1})**
10%	18.2	14.5
20%	24.4	16.5
30%	30.6	19.0
40%	36.8	21.0

The data presented on Table 2 shows a comparison between the rope stiffness obtained from the "*Dynamic Stiffness Test*" compared to the "*Design Stiffness Test*" curve adopted for the design of the mooring system. The differences can be significant and this is expected.

It is known, from the extensive tests the authors have performed for polyester mooring rope; that stiffness resulting from a *Quasi-Static* loading on the rope is quite lower than rope stiffness induced by the dynamic component of the vessel motions. Typically when the polyester rope is subject to a monotonic crescent loading a linear relationship between loading and elongation is clearly observed and constant rope stiffness can be derived from this relationship. In the plot shown on Fig. 13, the rope stiffness when subject to a *Quasi-Static* loading is represented by a flat line at approximately 14 times the MBL.

A proper *"Design Stiffness"* model will be somewhere in between the *"Quasi-Static"* and the purely *"Dynamic"* stiffness as the final load the rope is subjected to both regimen of loads. If the higher elastic modulus obtained from the "*Dynamic Stiffness*" test should be used for the design of the mooring system without any special considerations; overly conservative loads would be determined, which will lead to bigger, stiffer ropes and even larger extreme loads; starting a self-feeding design loop that would result in overly designed ropes and consequently will impact other components of the mooring system, this would heavily penalize the mooring system without any improvement in performance.

The stiffness curve obtained from the *"Dynamic Stiffness"* test reflects the rope stiffness when subject to continuous dynamic load cycling, as opposed to the "*Design Stiffness*" curve that recognizes that the load will be subject to a combination of *quasi-static* and *dynamic* loading.

Fig. 13 indicates the difference between the 3 stiffness types. It is clearly seen that the *Dynamic* stiffness is higher than the *Quasi-Static* stiffness and that the *Design Stiffness* is situated in between the two (*Quasi-Static* and *Dynamic*) combination between the two.

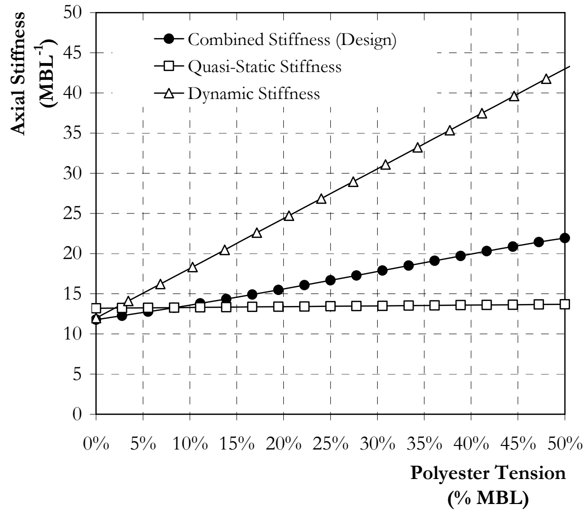

Fig. 13 – Stiffness Comparison – Dynamic, Quasi-Static and Combined Stiffness (Design)

A Comparison between the Combined Stiffness and the Combined Load Approach.

In order to show evidence that a combined stiffness curve is an adequate approach for the calculation of extreme mooring loads and vessel offsets, the authors performed a set of mooring analyses using the three different polyester rope stiffness curves, as indicated in Fig. 13:

1. *Quasi-Static Stiffness*
2. *Dynamic Stiffness*
3. *Design Stiffness* (Combination of *Quasi-Static* and *Dynamic Stiffness*)

The mooring loads calculated with the *Quasi-Static* and the *Dynamic Stiffness* are combined and compared against the loads determined using the *Design Stiffness* approach to show that the resultant mooring loads from the combination of the *Quasi-Static* and the *Dynamic Stiffness* loads are quite similar to the loads calculated using the combined *Design Stiffness* curve.

The following formula shows how the loads calculated using the *Dynamic* and *Quasi-Static* stiffness curves are combined:

$$Load = ML_{Quasi-Static} + LF\ Max_{Quasi-Static} + WF\ Max_{Dynamic}$$

- $ML_{Quasi\text{-}Static}$ = Mean line load. Calculated using the *Quasi-Static* polyester stiffness curve.
- $LF\ Max_{Quasi\text{-}Static}$ = Low-frequency extreme line loads caused by second order slow drift vessel motions. Calculated using the *Quasi-Static* polyester stiffness curve
- $WF\ Max_{\text{Dynamic}}$ = Wave frequency extreme line loads caused by first-order wave induced vessel motions. Calculated using the Dynamic polyester stiffness curve.

The load calculated using the formula indicated above will allow us to determine whether or not the *Design Stiffness* curve is adequate for the calculation of the extreme mooring loads.

Loads presented on Table 3 are fairlead loads at one the mooring lines of a typical deep-water polyester rope mooring system; we selected the most loaded line to serve as a basis for comparison; the most loaded line among all 20 anchor legs comprising the mooring system.

This study was performed using a load case matrix relative to the survival environmental conditions. Table 3 presents extreme mooring lines at the fairlead for 10 representative load-cases. Since this is a comparative study, we decided to limit the amount of data presented for sake of objectivity. Loads presented on Table 3 are a summary of mooring loads calculated using the two different methodologies. It can be observed that the mooring loads are quite similar, even though the *Dynamic* stiffness is much higher than the *Design (*combined) stiffness; that indicates that the combined stiffness approach is adequate for a correct estimate or mooring loads. The loads presented in Table 3 are combination of the maximum low and wave frequency loads. The difference is quite small less than 3% for the most loaded case.

It is important to mention that currently most time-domain simulation tools used for mooring design do not take in consideration the load regimen the rope is subjected to when determining the stiffness of the polyester rope. It is up to the designer to create a "*Design Stiffness*" curve that will be adequate to the loading regimen the mooring system will be subjected to. Moored floating facilities will be subjected to *Quasi-Static* and *Dynamic* loads and the stiffness test must take that in consideration.

Table 3 – Loads Comparison – Design vs. Dynamic + Quasi-Static Stiffness Loads

Load Case	Design Stiffness Loads	*Quasi-Static* + *Dynamic* Loads	Difference (%)
1	281.6	287.5	2.12%
2	425.7	422.2	-0.82%
3	452.4	464.6	2.69%
4	237.6	240.7	1.32%
5	368.1	363.3	-1.29%
6	411.3	416.2	1.19%
7	355.8	353.4	-0.69%
8	405.8	405.1	-0.17%
9	310.0	308.7	-0.42%
10	343.6	340.8	-0.80%

Random Loading Test

In addition to the above listed tests for constant dynamic cycling amplitude, a single modulus test was performed for a load signal with a random character. The time history was replicated for about 350 seconds, while during the test because of the limitation of the testing equipment the duration of the tension history was about 3500 seconds. Fig. 14 shows the original tension time history, which was obtained from time domain simulation performed as part of the mooring analysis. Fig. 15 shows the load time history of the test machine.

The random load signal test was performed to test the hypothesis that a constant stiffness will be a good approximation of the axial stiffness of the polyester rope in service. This hypothesis is based on the idea that during a storm there will be a continuing variation in mean load and at each mean load level the rope is exposed to only a few load cycles, the same idea explored during the *"Design Stiffness Test"*

Fig. 16 shows the strain as a function of load during the random signal test. From this figure it can be seen that there is not a large variation of the slope of the curves during the test.

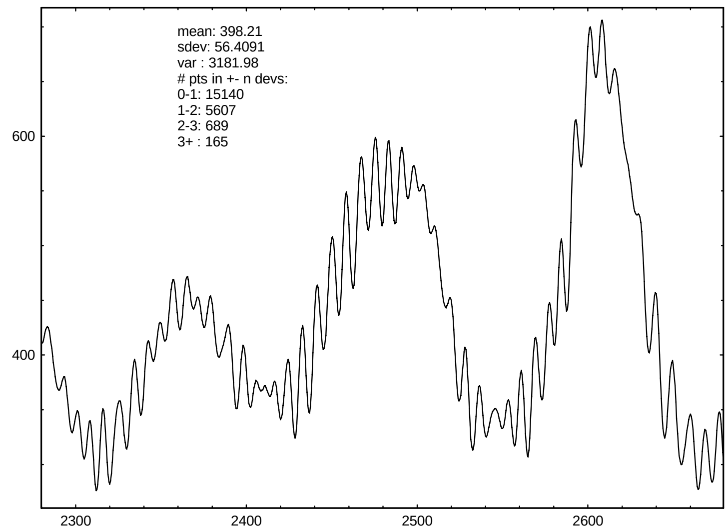

Fig. 14 – Random loading time history

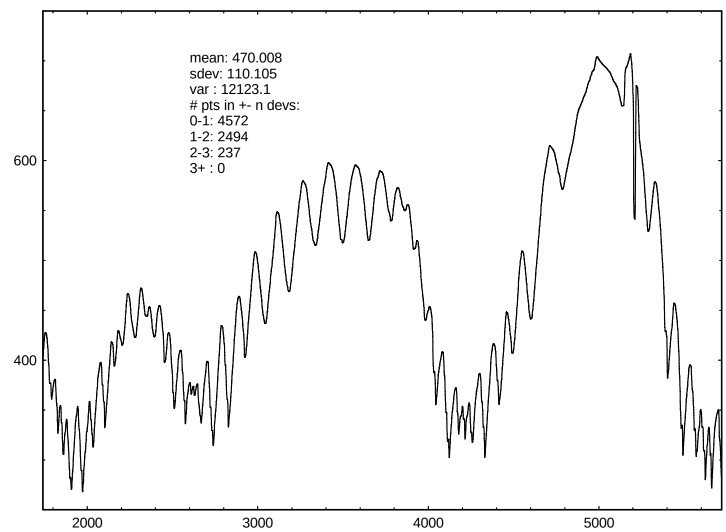

Fig. 15 – Test machine loading time history

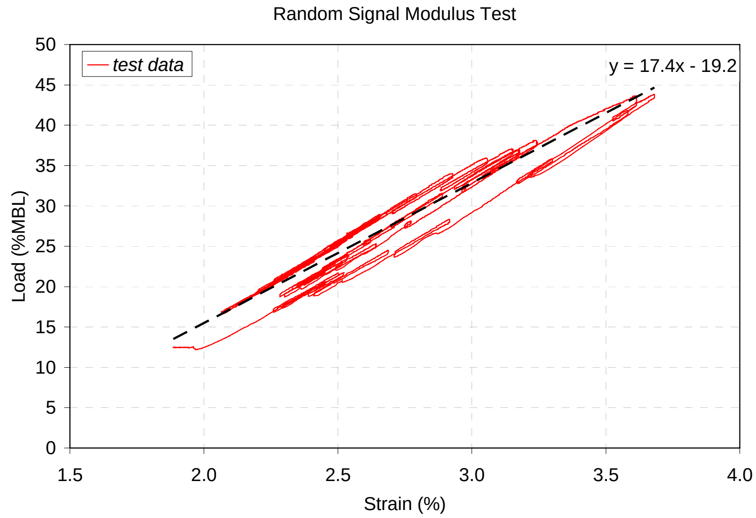

Fig. 16 – Load-Elongation Curve

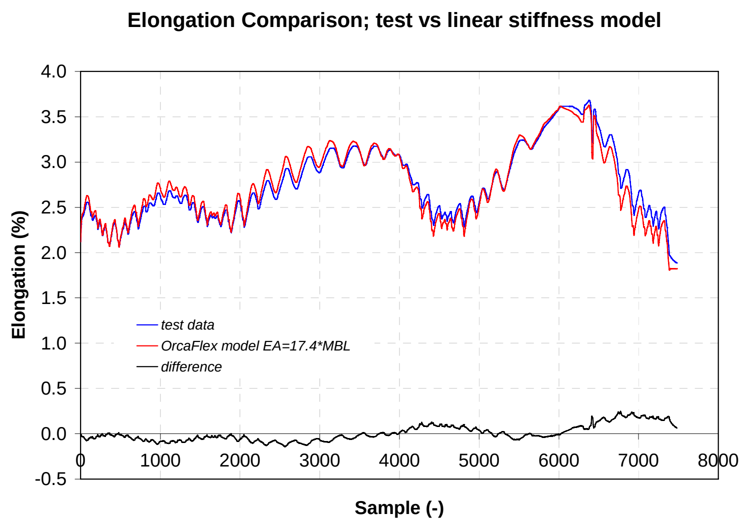

Fig. 17 – Load-Elongation Curve

The random load signal test was simulated using the time domain program Orcaflex, and the result of the analysis is shown in Fig. 17. The figure shows that when a constant axial stiffness is used equal to 17.4 times the MBL, the error in elongation is not greater than 0.25%.

According to Fig. 13, a stiffness level in the order of 17.5 times the MBL is achieved when the rope reaches a mean load of approximately 30% of MBL. Fig. 16 also shows that the mean load level for the random loading presented in Fig. 14 is approximately 30% of MBL. Therefore a good correlation between the tests can be observed, even though the tests refer to different ropes testing in different occasions at the same facility.

The Random Testing data support the idea that using constant rope stiffness for the polyester rope will not compromise the estimates of extreme mooring line loads and vessel offsets and can be used *in lieu* of a more sophisticated elastic model in case data is not readily available.

Important Design Considerations for Polyester Rope

There are several issues that designers of polyester rope mooring system have to pay close attention to during the design phase to ensure an adequate design; amongst those we could mention:

- Marine growth
- Length measurement and control during fabrication

- Constructional elongation
- Creep
- Handling during installation
- Contingency plans in case of damage of polyester rope
- Ingress on soil particles in the rope

This article will discuss in details some of the issued listed above.

Marine growth

Polyester rope is susceptible to damage when exposed to marine growth; in order to prevent this condition it is common practice to require the the top end of the polyester to be at a certain minimum depth; this depth varies and in general it is a depth that ensures that the amount of light to reach the polyester in insignificant and the chances of damages imposed to the polyester rope due to marine growth is kept to a minimum.

The actual depth in which the top end of the polyester rope will be depends on several factors that have an intrinsic uncertainty associated to it; such as water depth at the anchor location, inaccuracies related to anchor and vessel positioning; variations in the length of mooring components but most importantly, the depth of the top end of the polyester rope will depend on polyester stretch.

Typically the stretching due to the bedding-in of the polyester fibers in the rope structure and the long term creep are the factors that contribute the most with uncertainties associated to the length of the polyester segments, which are typically the longest elements in the composition of the anchor leg and therefore will have a greater impact on the final depth of that first referred connection between the top of the polyester and the top segment of the anchor leg.

Fatigue

The industry has come to a consensus that polyester fiber has fatigue superior fatigue characteristcs when compared to other commonly adopted components such as chain, shackles, H-links and spiral-strand work wires. On mooring polyester ropes normally the rope splicing is the fatigue-prone area, therefore the adopted splicing methodology has tp be qualified by means of fatigue testing of sample ropes. For a qualified splicing methodology, it can be assumed that if a chain of similar breaking load capacity is able to withstand the fatigue loading on the anchor leg, the polyester rope will have at least the same capacity and therefore will be fit for purpose.

Installation of Polyester Rope Mooring System In Deep Water

Pre-stretching using installation vessels

In preparation for the deployment of polyester rope from the installation vessels it may be advantageous to perform a pre-stretching of the polyester rope using an additional auxiliary installation or service boat. This is a practice common put in place in order to prevent excessive future adjustment of the anchor leg pre-tension due to the stretch experienced by the polyester rope after the initial service time, especially after the floating installation has experienced rough environmental conditions.

Most of the time, polyester ropes are transferred from shipping reels to the working drums on installation vessels. Since transportation reels are not designed to withstand large hold-back tensions, this operation is normally performed with the polyester rope under relatively low tension that causes the wrapping around the working drums to be very loose. In case the polyester rope wrapped on the working drum under low-tension is deployed into service; most likely the rope will bury itself in the lower wrapping layers and the resulting friction between adjacent ropes can cause permanent damage to the polyester rope jacket and even damage the sub ropes protected by the external jacket; therefore such practice is to be avoided.

Using an auxiliary vessel as a hold back vessel, the polyester can be re-spooled into the work-drum under an appropriate tension and this operation can contribute to an accelerated accommodation (bedding in) of the polyester fibers, i.e. a portion of the permanent constructional elongation can be imposed to the polyester rope which will lead to a lower incremental permanent elongation after the initial installation. Fig. 14 illustrates the use of two Anchor Handler Vessels performing such a pre-stretching operation for a spread moor system offshore Brazil. One of the Anchor Handler Vessels (AHV) was serving as service boat performing all the logistic operations between the shore base and the installation location. When the Anchor Handler Vessels performing the installation of the anchor leg were ready to deploy a new segment of polyester rope; the selected rope was transferred from the “service” tug into the installation vessel under tension. Typically this operation was performed under a bollard pull of approximately 60 metric tons; which corresponds to less the 5% of the rope MBL. Even though this is not sufficient to impose on the rope all the expected permanent stretch/constructional elongation it is the author’s experience that such ropes have experienced as much as 2/3rds of the total permanent elongation as a result of such an operation.

Fig. 14 – Using two anchor handlers to pre-stretch the polyester rope

The permanent elongation tests performed for the polyester ropes the authors have designed and put in service, indicate that a typical 3% increase in rope length due to constructional elongation is expected after the polyester rope experience more severe environmental conditions.

Pre-installation of polyester rope mooring systems

A common practice in order to expedite the deployment of floating production facilities is the pre-installation of mooring lines. The pre-installation of the anchor legs can be done with surface buoys that will buoy offthe anchor line on the surface allowing for a quick recovery once the floating facility arrives in the location.

Among the disadvantage of buoying off the anchor legs on the surface, the cost associated to the design, construction and deployment of such buoys can be mentioned. Another disadvantage is the possibility of failure of the buoys, what would lead to potential damage to the anchor leg, especially the sensitive polyester ropes.

Laying an anchor leg on the seabed is the preferred option due to its simplicity and lower cost. One point for concern however is the ingress of sand or clay particles in the polyester rope; what would lead to abrasion and rapid /accelerated degradation and consequential failure of the polyester fibers, strands and/or sub-ropes.

The ingress of soil particles can be minimized and effectively avoided by the use of cloth filters just beneath the rope’s jacket. The filtering capacity of such cloths vary depending on the filter type and number of wrapping layers around the sub-ropes; therefore analysis of the particle distribution size of soil samples collected from the area can serve as a good indicator when specifying filtering systems for polyester mooring ropes. Typically these filters can capture particle sizes that vary from 5-20 μm.

The authors have worked on the development of a pre-deployment strategy of a polyester rope anchor leg system in order to expedite vessel hook-up after arrival, the mooring system was an 18 mooring legs spread mooring system offshore Brazil.

Initially the laying pattern presented in Fig. 15 was proposed as an effective way of pre-deploying and recovering the anchor legs, as the installation vessels would be very close to the floating facility once the anchor leg is recovered.

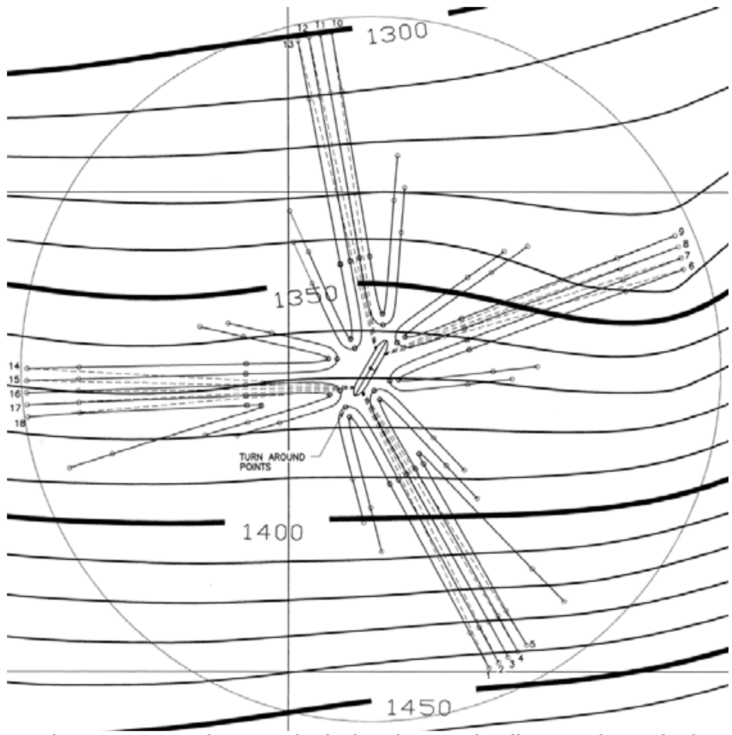

Fig. 15 –Proposed Pattern for laying the mooring lines on the seabed

The disadvantage of laying the anchor legs using the pattern indicated in Fig. 15 is the fact that the region around the turning points are low tension areas and consequently any torsion induced to the rope during installation can cause the rope to twist at those specific low-tension areas.

It is the author's experience that indeed some torsion can be induced on the polyester rope during the pre-deployment of the polyester mooring line. In order to avoid such problems, a change in the polyester laying pattern was proposed and in the new pattern the anchor legs were deployed outwards of the mooring circle.

It is our recommendation that during operations in which the polyester rope is to be laid on the seabed, a close inspection by ROV is to be performed at the touch down location during the whole laying operation. In case the polyester anchor leg is not laid on a straight line pattern low tension areas should be avoided in order to prevent possible twisting of the polyester ropes.

In addition to the previous recommendation, the use of low friction swivels when deploying the mooring lines can be useful in removing any eventual torsion introduced in the system.

Conclusions

The adoption of a reasonable model for the numerical representation of the polyester's elastic behavior has a significant impact on the predicted extreme vessel-offsets and mooring line loads when the dynamic behavior of deep water mooring system is under scrutiny. A reasonably conservative estimate of loads will lead to a more rational and practical design representing substantial savings in the procurement and installation costs associated to a deep water polyester mooring system. The tests performed with the polyester rope supplier to determine in detail the elastic behavior of polyester ropes have proven invaluable tools for the optimization of the mooring system. Taking in consideration the large water depths and massive number of mooring lines required in such developments, the tests performed resulted in significant cost savings and therefore a more attractive solution from a commercial point of view. At the same tyme it allowed for the design of a fit-for-purpose mooring system in accordance with international guidelines and regulations. As indicated on Table 3, the use of a single "*Design*" stiffness curve produces similar extreme loads when compared to the method of calculating the *"dynamic"* and *"quasi-static"* load components separately and them combining. Installation of polyester ropes requires very detailed planning and engineering. Polyester stiffness, stretching; marine growth and rope handling during installation are key issues that have to be carefully looked after by the design and during installation.

Definitions

This is a summary of the terminology used in this paper; even though the authors tried to use terminology in accordance to the current industry practice, we recognized that there is not universal agreement, therefore this section is for the reader's benefit as it will support the correct understanding of the concepts presented here:

Constructional elongation – Also known as permanent elongation or permanent stretch. This is the permanent non-recoverable elongation experienced by the rope due to the structural accommodation (bedding in) of the rope fibers.

Dynamic Stiffness **–** The polyester rope's *Dynamic Stiffness* is obtained by cycling the polyester rope at a given combination of mean load and load variation amplitude until the rope instantaneous stiffness reaches a plateau level; it stabilizes. The plateau level is the rope's *Dynamic Stiffness* for that given mean load.

Design Stiffness – Similarly as to the *"Dynamic Stiffness"*, the polyester rope's "*Design Stiffness*" is obtained by cycling the polyester rope at a given combination of mean load and load variation amplitude, however the number of cycles is reduced.

Dynamic Stiffness Test – The Dynamic Stiffness Test is designed to subject the rope to a continuous load cycling at a constant mean load and amplitude. The purpose of this test is to determine the peak rope elastic stiffness for that specific mean load level and load amplitude.

Design Stiffness Test – The Design Stiffness Test is very similar in concept to the Dynamic Stiffness Test; the difference is the number of cycles the rope is subject to, at each mean load level. Instead of cycling the rope until the elastic modulus is stabilized at a given mean load level the number of cycles will resemble what the rope would experience when in operation.

References

1. Del Vecchio CJM (1992) "Light weight materials for deep water moorings", PhD thesis, University of Reading
2. ABS, Guidance Notes on the Application of Synthetic Ropes for Offshore Mooring (1999)
3. API, RP 2SK Design and Analysis of Stationkeeping Systems for Floating Structures; 3rd edition 2005
4. ISO, 18692-Fibre ropes for offshore stationkeeping Polyester, 2007