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CHARACTERIZATION OF POLYESTER MOORING LINES

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ABSTRACT

Fibre ropes are extensively used in marine applications. One critical area of interest is their application as mooring lines for floating offshore platforms, for which primarily polyester is now employed in various regions (offshore Brazil - now for 10 years, West Africa, Gulf of Mexico). Evaluating the response of the system requires a description of the load-elongation properties of the rope.

A practical model involving two sets of stiffness data is currently used, and procedures for their measurement are available. This paper presents an overview of this model, then focuses on recent work on the quasi-static stiffness of polyester ropes. This is addressing the variations of the mean tension in the lines, at a very slow rate, under changing weather conditions.

Extensive tests were performed, principally on polyester sub-rope samples. Some tests were also performed on a full size 800-ton MBS rope. Besides standard tests, specific tests were performed over an extended range of loading, to cover the situations that may be found in a wide range of systems and design conditions. The factors (measurement accuracy, test conditions, etc…) affecting the values are discussed along with the presentation of tests and results.

Results are interpreted to provide practical data for mooring analysis, in the form of a quasi-static load-elongation characteristic. These results also give a better insight into the visco-elasto-plastic response of polyester fibre ropes.

For the dynamic stiffness of polyester ropes, an overview of recent and earlier test data is presented. The dependence of dynamic stiffness on testing parameters is discussed, highlighting mean load as the principal parameter under real stochastic loading, and confirming the current practice for modelling dynamic stiffness in design.

1 INTRODUCTION

Fibre ropes are extensively used in a number of marine applications. One critical area of interest is their application as mooring (anchoring) lines for the station-keeping of floating offshore platforms in deep-water. Following a development period, and now ten years after the first installations of floating production systems by Petrobras in Brazil, this technology has reached a stage of maturity: fibre rope station keeping systems are now employed commonly offshore Brazil, and also in other regions around the world (in West African waters, in the Gulf of Mexico, …). Polyester, the material primarily used in this application, is addressed in this paper.

Evaluating the response of the system, and then the adequacy of maximum offset and line tensions with the relevant acceptance criteria, requires a description of the load-elongation properties of the rope. However, these properties are rather complex to evaluate and specify, in comparison with the linear elastic behaviour of equivalent steel components, as they are non-linear and time dependent. Besides, the loading regimes of a rope in an anchoring line are quite specific with respect to usual service conditions of fibre ropes.

A first insight into the load-elongation properties of fibre rope lines was given in [1]. Within the French CLAROM fibre rope projects, since 1997 [2], extensive testing has been carried out. This resulted, in 2000, in a practical (Engineering) model for the load-elongation characteristics of polyester ropes, that was presented and documented in [3] and [4], and is currently in use within several State of the Art mooring analysis and line dynamics software packages. Tests performed since on other materials [5] have generally confirmed the applicability of this model.

In the meantime, testing procedures have been developed for rope qualification (see [6]), that are now available with the ISO standard for rope qualification [7] and the BV Guidance Note [8]. The model for engineering and analysis of fibre rope mooring systems and the testing procedures in these documents define rope properties in a consistent manner. This model involves a separation into several terms. One of these terms is the "Quasi-static stiffness", that is the focus of the present paper.

The tests were performed principally on polyester sub-rope samples. Some tests were also performed on a full size parallel construction 800-ton MBS rope. In addition to the standard tests, an extended series of test sequences was performed, to get an understanding of rope behaviour under a wider range of load and elongation, and to cover the particular situations that may be found in some systems or design conditions.

Besides the interpretation of results to provide practical data for analysis, these results also gave a better insight into the visco-elasto-plastic response of polyester fibre ropes. As correct measurement and interpretation of test data are essential for platform safety, the factors affecting the values are discussed (measurement accuracy, test conditions, …) along with the presentation of tests.

For the dynamic stiffness, a discussion on the dependence of dynamic stiffness on testing parameters is made, based on the comprehensive data from recent tests and on earlier data.

2 FIBRE ROPES LOAD-ELONGATION PROPERTIES AND MODEL

Issues

The load-elongation properties of fibres and fibre ropes exhibit a non-linear and time dependent (visco-elasto-plastic) behaviour. This is primarily the result of the load and time dependence of the materials forming the filaments (a complex assembly of long chains of organic molecules), and to a lesser extent from the effects of rope construction [9]. As a result these properties cannot be reduced to a load-elongation "characteristic", even a non linear one, and particularly, NOT to the load elongation curve of a new sample under monotonic loading (as obtained from a standard breaking test).

In the lines of a station-keeping system, once the system is deployed/installed and set under tension, the rope will be maintained under a sustained tension for months, even years or decades in the case of a deep-water permanent mooring, then subjected to the random loads induced by the environment (wind, waves, current). It is then convenient for the evaluation of system response, as proposed in [8], to separate the response into three terms, related to the time scale of actions, and matching the typical steps of a mooring analysis (be it frequency or time domain) :

- Mean elongation (system pretension, permanent load),
- Visco-elastic response to slow variations of mean load under changing weather, modelled by the quasi-static stiffness, as further discussed in sections 3 and 4 below,
- Response to dynamic actions (both low frequency and wave frequency) modelled by the dynamic stiffness (see section 5 below).

A particularly important aspect, quite specific to fibre ropes, is the modification of the properties of a rope during the first loading(s) and during the early stages of rope service. This process, called "bedding in", is primarily due to changes at a molecular level within fibres. It results in a stabilisation of the rheological properties of the rope, and in an essentially permanent - not recoverable - elongation with respect to the rope initial length at the time of manufacturing. The length of a finished rope is thus defined in [7] as a bedded-in length at a specified tension.

Besides, as a noteworthy consequence of time dependence, it is important to consider in the definition of test sequences and the derivation of engineering data that the time scale of actions on a test bench is much smaller than for a line in-situ: this time dependence (also bedding-in) will thus affect somewhat differently the response.

Quasi-Static stiffness

Following the concept proposed in [1], a "quasi-static stiffness" was defined, ten years ago, in order to model the visco-elastic response of ropes to slow variations of mean load, under the effect of changing weather conditions, i.e. a time scale of several hours or days, where the tension in the line, initially the line pre-tension, increases (in the "windward" lines) or decreases (in the "leeward" lines), at a very slow rate.

In this test (see [7], [8] and below), after a proper bedding-in, the rope is cycled between two tension levels, with a constant load plateau at each level, during which creep or recovery is measured. Several cycles are needed to get rid of the initial condition of the rope on the test bench (which is not representative of actual conditions), and to obtain stabilised results. Typically, 3 cycles of twice ½ hour each are used, keeping the duration of the test within a practical time frame.

In order to get a stiffness that is more representative of the real loading duration of the events intended to be modelled (see below), cycles of longer duration can be simulated as follows from test results (load and elongation versus time).

1) The elongation $L(t)$ along each creep (or recovery) plateau can be written, by a three parameter fit (see [8]), as :

$$L(t) = L(t_p) + a_c \cdot \log [1 + (t - t_p) / t_a] \quad (1)$$

This fit (on a_c , t_a, and $L(t_p)$) is independent of time unit and origin, and the result does not depend on the selection of t_p, the time at any point along the load plateau.

2) From $L(t)$, the elongation $L\tau$ at the end of each ½ cycle of duration τ can be obtained as :

$$L\tau \approx L(t_p) + a_c \cdot \log [\tau / t_a] \quad (2)$$

3) The (linearised) quasi-stiffness is then taken as a secant stiffness between the end points of the last successive ½ cycles of duration τ . Normalising loads by rope MBS, the non-dimensional quasi-static stiffness KrS is obtained.

The two load levels are normally taken as 10% and 30% of MBS, and the duration τ is normally taken as 12 h, providing values for typical storm conditions. Different levels or durations could apply to some design or metocean conditions (e.g. a damaged system, a loop current event). The tests presented in this paper were performed to get an understanding of rope behaviour under a wider range of load and elongation, and in order to provide data for such conditions.

3 ROPE TESTING

General :

The CLAROM French Mooring Line project has been working on fibre rope moorings over the last ten years and has generated a large database of material properties. Tests have been performed at scales from single filament [9] up to 800-ton break load ropes [10], including the intermediate yarn, assembled yarn and sub-rope levels. Here only results from the sub-rope and full scale ropes will be discussed, but it is important to underline that by working on filaments and yarns the material and rope construction contributions to overall rope behaviour can be quantified and modelled. This provided also some light on the underlying mechanisms at molecular level, if not yet a definitive interpretation.

Experimental set-up

Sub-rope tests were performed at the IFREMER test facilities in Brest. A 9-meter long 100-ton capacity test frame was used, equipped with a 1.5-meter course hydraulic piston (see Figure 1). A programmable controller enables loading sequences to be pre-programmed, so that long, complex test sequences lasting several days can be defined and run. Full size rope tests were run at the LCPC test laboratory in Nantes, on the 2400-ton test frame (see e.g. [10]).

Figure 1 . Sub-rope on test frame

Both series of tests used the same instrumentation to measure strains in the central rope section away from the splices : wire transducers clamped to the rope for stiffness measurements and digital cameras linked to an image analysis system for break tests and to check wire transducer measurements. The tension in the rope is measured by the strain-gages load cell system of the test frame. All measurements are recorded, at a high data acquisition rate (up to 5 Hz for dynamic stiffness), and stored on a PC for subsequent analysis. Accurate and continuous time series of load and elongation are thus available for analysis.

Materials

The tests described here were performed on 8-strand braided polyester sub-rope samples, with a 70 t breaking strength, and on test lengths of a full size (800 t MBS) parallel construction rope based on the same sub-ropes. The fibre is a standard high tenacity grade with marine finish. Oliveira Sá, Portugal supplied all samples.

Test sequences

The standard test to measure quasi-static stiffness described in [7] consists of three 1-hour load-unload cycles between 10% and 30% (of the break strength), applied to a rope which has been fully bedded-in (i.e. an initial loading to 50% , with the load maintained constant for 30 minutes, then 100 cycles between 10 and 30%).

In order to widen the scope of this characterisation, an extended quasi-static stiffness test was developed : As shown in Figure 2, a series of load-unload cycles is applied, similar to those of the standard test, all with the same 20% range but at different sets of load levels, starting and ending with a set of cycles at 10-30%. Four cycles are applied at each load condition, in order to verify stabilisation.

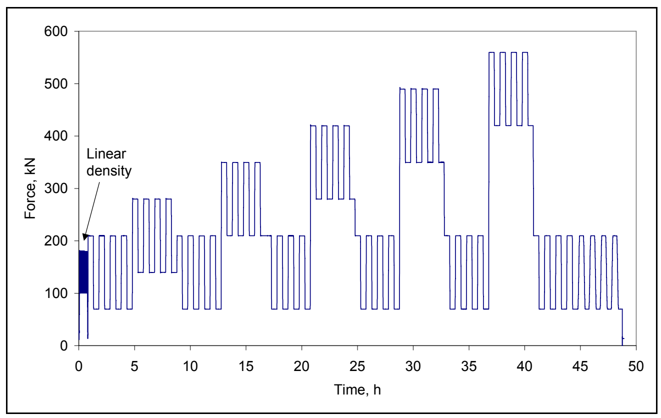

Figure 2 . Extended quasi-static stiffness sequence Force versus time applied to sub-rope samples 3 and 4

On two samples , an extended sequence was applied to a rope that has been previously subjected to bedding-in cycles following the standard procedure quoted before, or equivalent (on one of them). On two other samples, a sequence was applied to a rope with a lower degree of bedding-in cycles, obtained by applying instead the procedure defined in [7] for the "linear density test" (i.e. an initial loading to 20%, then 100 cycles between 15 and 25%, ending at a 20% load). Samples were then loaded to failure. A fifth sample was used for dynamic stiffness measurements (see section 5 below).

Test results - stiffness

Figure 3 shows an example of the resulting force-strain plot during the extended quasi-static stiffness test (continuous record over 48 h).

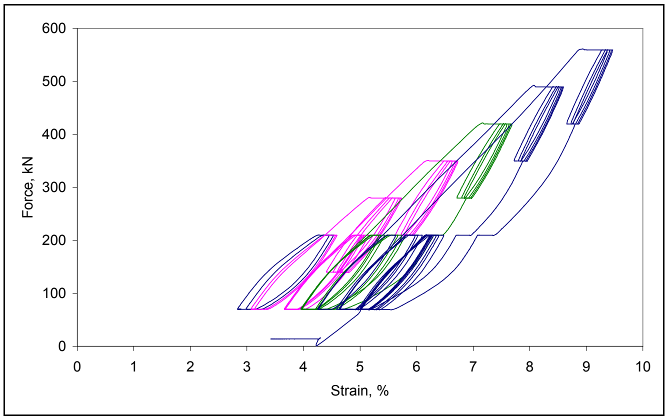

Figure 3 . Extended quasi-static stiffness sequence, sub-rope samples 3 and 4.

From the elongations at the end of the last two half cycles, a secant stiffness is obtained (without extrapolation at this stage). The quasi-static stiffness is found to be increasing with mean load, with a trend similar to that of the dynamic stiffness (see Figure 5). As shown in Figure 4, there is a close match between the results of all four samples, and a very limited effect of previous bedding-in : stiffness for the samples with mild bedding-in are only marginally lower than for well bedded-in samples, the lowest point corresponding to the very first load set after measurement of L_{20} .

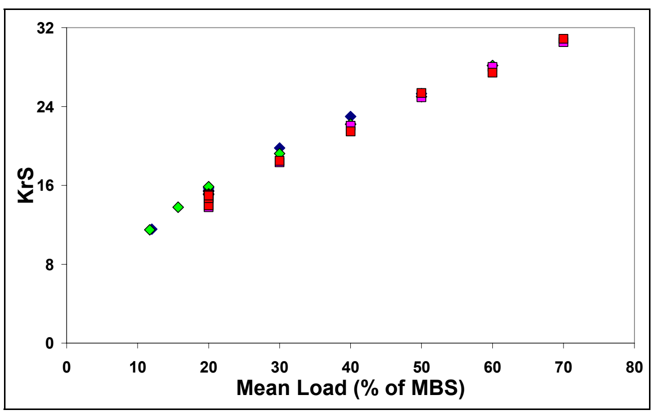

Figure 4 . Quasi-static stiffness versus mean load, all four samples.

Comparing (see Figure 5) the results of the measurements performed on sub-ropes with those from full size 800 ton break load ropes, an excellent agreement is found for both the quasi-static and the dynamic stiffness when expressed in tenacity unit (N/Tex), as on Figure 5. Same result would be found if these stiffnesses are expressed as a non-dimensional Kr, using a normalisation by MBS of the full size rope (see [8]).

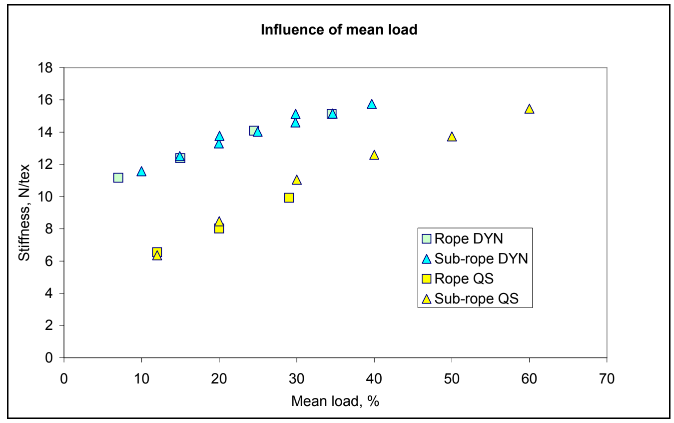

Figure 5 . Correlation between results for sub-rope and full size ropes; quasi-static and dynamic stiffness.

Test results - mean elongation

The tests also provided information on the mean elongation of the rope, and its dependence on the loading history.

On the samples to which the “linear density test” sequence was applied, the elongation at a 20% load, at the end of the sequence provides the reference length L_{20} for rope purchasing, according to the length measurement method in the standard [6].

Besides, a mean elongation at 20% can be obtained from each set of 10-30 cycles (indeed taken as the mean between the elongation at the end of the last 10% and 30% ½ cycles), or inferred from the fully relaxed condition (see 4 below). As shown in Figure 6, a very good agreement between the results of each group of two ropes is found.

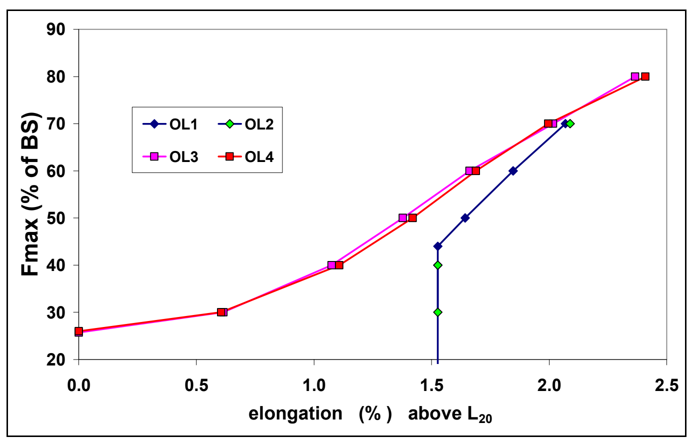

Figure 6 . Mean elongation at a 20% load all four samples.

The mean elongation of well-bedded-in samples is stable, about 1.6% higher than L_{20}, for all loads up to 40%. For higher maximum loads, further (delayed) permanent elongation is observed, increasing almost linearly until 70% (the maximum load for these two samples).

For the samples with a milder bedding-in, the elongation increases quickly when the load exceeds the maximum seen during bedding-in, confirming that L_{20} is a lower-bound of the installed length, and is always lower than for well bedded-in ropes, up to 70% load. Given the time frame of the test (within 48h of the very first loading of the rope, i.e. much less than the time required to install a system and to have it actually operating) the resulting permanent elongations may be also considered as a very lower bound.

4 INTERPRETATION

QS stiffness

From the fitting of creep and recovery plateau's (greatly facilitated by the very good accuracy of load control) and the extrapolation of last cycle plateau's, the elongation's for different levels and duration's can be obtained : the standard duration of 12h and 7 days, that would be more representative of slowly growing events, such as loop currents, are considered here. When normalising loads by full size rope MBS and elongations by the length at 20%, including permanent elongation), the quasi static stiffness for the standard levels (10 and 30%) is found, , to be about 14.5 for 12h (i.e. 17% less than for the 1/2h duration in test), and about 12.5 for 7 days, i.e. 12 % lower than for 12h. This decay is consistent with earlier findings, as shown in Figure 7 .

Q-S PRACTICAL characteristics

For other loads, a stiffness between two levels could be calculated in the same way, but this is not very representative of the situation in a station-keeping system, where line tension will generally not oscillate between such levels : Together with vessel offset, the tension will gradually increase (or decrease) more or less monotonically in most cases, and over the same period of time, from initial tension to a maximum (or minimum) value which will be different in each line.

Then, by considering the relevant points, a practical characteristic for the specified loading time can be obtained, that is shown in Figure 8. This characteristic was derived from data from the different samples: a very consistent behaviour was found.

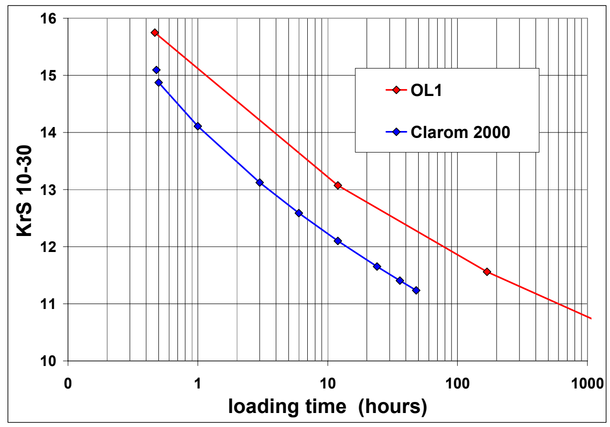

Figure 7 . Q-S stiffness $KrS_{10\text{-}30}$,
blue : data from reference [3] (corrected).

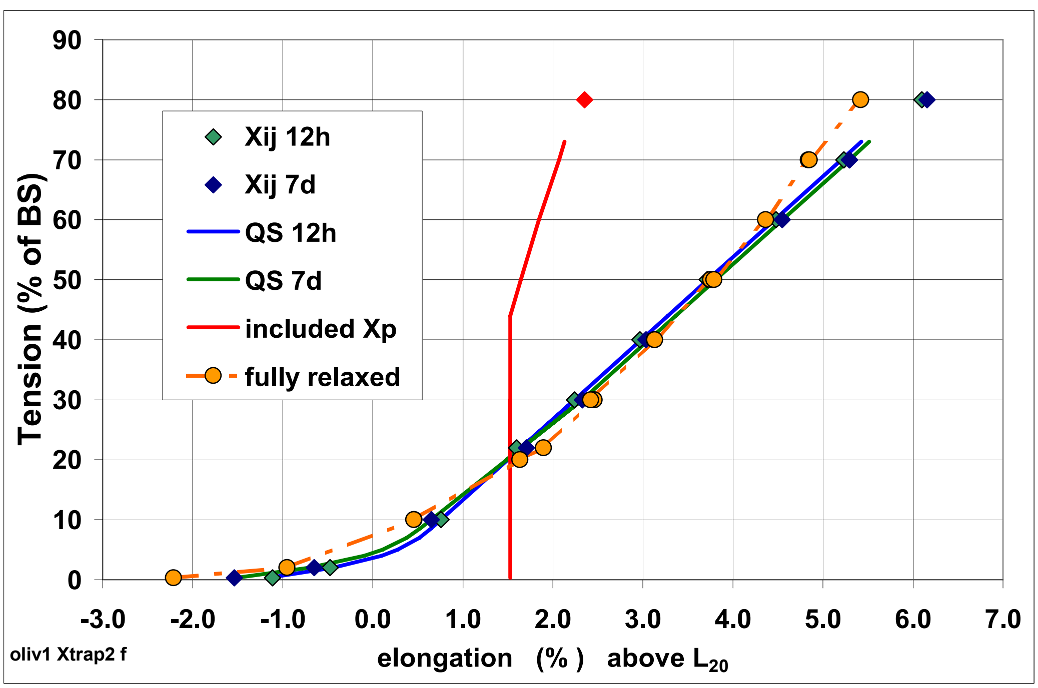

Figure 8 . Q-S PRACTICAL characteristics
included Xp, and fully relaxed characteristic (see text)

A first observation is that, for the 12h (standard) loading time, this characteristic is almost linear, i.e. the standard quasi-static stiffness derived from tests between 10 and 30 % is valid over a large range, from about 7 to above 70%.

For the 7 days loading time, the slope of the characteristic (dX/dT = 1/Kr) is higher between 10 and 30 % (as per the lower stiffness noted above) but, above 30%, is the same as for 12h.

Taking the pre-tension T_0 as a start point, this characteristic (elongation versus load) can be written as :

$$X(T) - X(T0) = (T - T_0) / Krs_\tau \quad \text{for } T \text{ between 10 and 30\%} \qquad (3)$$

$$X(T) - X(T0) = (30 - T_0) / Krs_\tau + (T - 30) / Krs_{12h} \quad \text{for } T \text{ above 30\%} \qquad (4)$$

where Krs_τ is the 10-30 stiffness for loading time considered (12h or 7 days).

For tensions below 10%, there is a clear increase of compliance with decreasing load. From a fitting between available data points, the characteristic may be taken as :

$$X(T) = X(10) - 10 / Krs_\tau * (u + 1.8 * u\text{\^{}}3.6) \quad \text{where } u = 1 - T / 10 \qquad (5)$$

In a system working at low tensions in leeward lines, this effect will have a similar effect as the catenary effect in weighty components of the line.

Fully relaxed condition

During the test, at a given load, either creep can be observed, or recovery from a larger elongation. There should be a stable point in between. As discussed below, this point can be obtained by extending the loading duration **τ** to t_∞, the time at the intersection point of elongation versus (log) time of two ½ cycles terminating at same level, and correcting for the permanent elongation (when applicable).

Taking t_∞ as 4 10^7 s , i.e. about 15 months, all points converge to a single curve, that is the non linear, but elastic (reversible) fully relaxed characteristic, i.e. the characteristics ***Xrx(T)*** for "infinitely slow" rate of loading , also shown (round dots) on Figure 8.

Arriving at or approaching a point on the fully relaxed characteristic in a shorter time than t_∞ is possible, but requires some specific test sequences.

Discussion - Toward a rheological model

Based on the above fully relaxed characteristic *Xrx(T)*, the load-elongation relation around this condition could be written as follows in order to address, if needed, more complex cases than the practical QS characteristic presented above can handle:

$$L= L_{20} * (1 (+ Xpe) + Xrx (T_0)) \qquad (6)$$

$$X(T) - X(T_0) = Xrx(T) - Xrx(T_0) + Xdpe - \mathbf{Xv} \qquad (7)$$

In this equation, *Xpe* is the permanent elongation at T_0, if not included in *Xrx*, and *Xdpe* is the delayed permanent elongation :

$$Xdpe = Xpe (T_{max}) – Xpe(T_0) \qquad \text{if } T > T_0 \text{ else } 0 \qquad (8)$$

where *Tmax* is the maximum between tension T and the maximum reached before (since last re-tensioning).

Xdpe for a well bedded-in rope (maximum 0.8% at 80%) is indeed included in the practical characteristic above. It could be that for particular situations a lower initial bedding-in level, thus higher Xdpe, needs to be considered, but as discussed before, considering data from the samples with milder bedding-in would be unduly over-conservative.

The term ***Xv*** is the (remaining) un-developed visco-elastic elongation : ***Xv*** is positive in a situation where the rope tend to creep, i.e. *X* is lower than *Xrx*, and negative in the opposite case (relaxation).

For the 12h standard duration, the amount of *Xv* (also included in the practical characteristic above) is below 0.2% but, towards low tensions, is going from - 0.2% to - 0.5% for loads going from 20 to 2%. The values for 7 days are 40% lower.

On the other hand, if neither cycling nor load holding time was applied in the tests, *Xv* would have been of the order of 0.5 to 1%, or more : this highlights the importance of time scale in such tests.

For a constant load, i.e. creep or recovery, *Xv* could be modelled as the response of a non-linear spring and damper system. With an adequate (argsinh) damper function, a solution can be found, that can be approximated by:

$$Xv = a_c \log (t_\infty / \tau) \quad \text{for } \tau << t_\infty \qquad (9)$$

$$Xv = 0 \quad \text{for } \tau >> t_\infty$$

(with a transition over one or two decades around t_∞).
where a_c is the creep (or recovery, then < 0) per decade. This supports the method above to determine t_∞ . However a_c is not an intrinsic material constant but depends on load history, and the spring and damper model suggested above does not fully address the growth of *Xv*. Besides, a closer look at time traces shows that *Xpe* is not only a function of *Tmax*, but depends also on the time under load (as also shown by Figure 6), so *Xp* and *Xv* are likely not fully separable.

The characteristics above are thus given for the Designer, as PRACTICAL Q-S characteristics. Development of a true "time domain" rheological model still requires further effort.

5 DYNAMIC STIFFNESS

The "Dynamic stiffness" is modelling the near-elastic response of the rope to cyclic actions (both low frequency and wave frequency) induced by the environment.

In tests (see [7] and [8]), after bedding-in, the rope is cycled around a pre-set mean tension. For harmonic (constant amplitude, sinusoidal) loading, at least 100 cycles are typically used today and, as the load-elongation graph converges to a fairly linear relation, a stiffness can be defined. This is taken as the mean slope over several cycles at the end of the sequence (i.e. 500 data points, in the results below). Normalising loads by rope MBS, the non-dimensional dynamic stiffness KrD is then obtained.

In order to complement the characterisation work performed earlier (see [3]), a number of dynamic stiffness tests were performed, on the same sub-ropes and full size ropes as those above. Similar tests were also performed on another full size rope with a different polyester fibre (see [11]). Results will be briefly summarised, together with a discussion of the dependence of dynamic stiffness on testing parameters.

Cycling period

A series of tests was performed with the same mean load and amplitude, and cycling periods from 12.5 s to 500 s. Results confirmed that the effect of this parameter on dynamic stiffness is negligibly small (1.4% variation over the above range). This is in accordance with earlier findings from bi-harmonic loading, and those of stochastic loading below.

Load history

During tests with harmonic loading, at a constant mean load, the stiffness quickly increases in the first cycles, then tends to stabilise (at least apparently), and 100 cycles minimum are typically used today to obtain results in a practical time frame. There is however some effect of previous load history affecting the results. Indeed, the increase of stiffness during cycling is quite linear with log of time, as is the variation of mean elongation (be it creep or recovery) over the same time: From different tests, it seems that the stabilisation of the dynamic stiffness (toward the maximum stiffness for applied mean load) and that of mean elongation (towards the fully relaxed condition) are closely related.

Load range, stochastic loading

From a series of tests under harmonic loading, with different mean load and range, the effect of both parameters can be identified. Figure 9 shows the influence of load range, with the dynamic stiffness normalised by the value at a 5% range (obtained from a fit of data) . The dynamic stiffness is clearly decreasing when range is increased, more sharply towards higher amplitudes and lower mean loads. This may be due, at least in part, to the increase in rope temperature observed during such tests (see [12]).

However, the real loading is not harmonic. Series of tests were thus performed on the two full size ropes, using 1-hour time series obtained by mooring analysis (i.e. a wide band signal, with realistic low frequency and wave frequency contents), and different combinations of mean load and amplitude. Figure 10 shows an example of applied time series and resulting load-elongation plot. It is noteworthy that the load-elongation is very close to a single overall linear relation (linear regression over 18000 points). A closer look to signals clearly shows effect of neither the amplitude of individual cycles, nor the period of underlying (low and wave frequency) components.

Besides, from different tests it is apparent (see Figure 9) that this stiffness is almost independent of the overall (min to max) amplitude of the signal, and is slightly higher (within -1 to +5%) than the stiffness under harmonic loading at a 5%

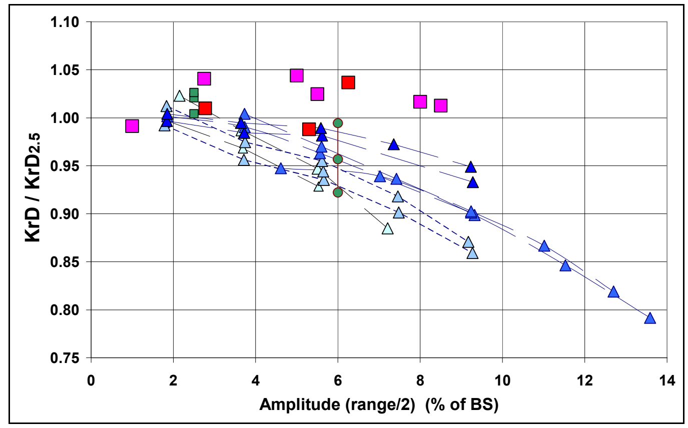

Figure 9 . Influence of load range on dynamic stiffness harmonic loading (10 , 20, 30, 40% light to dark blue), stochastic loading (red and pink)

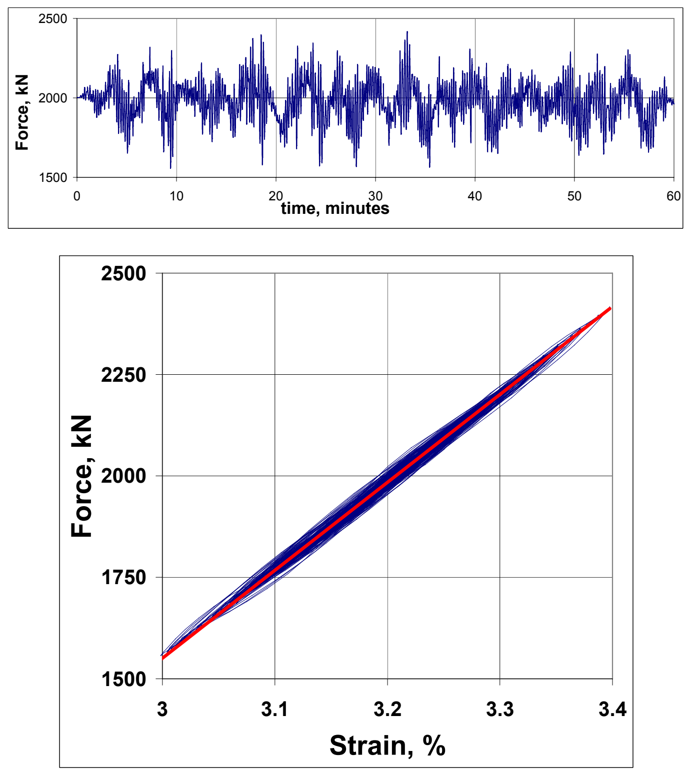

Figure 10 Example of stochastic loading (1h)
a) time trace;
b) resulting load-elongation and linear regression

range. In this respect, it must be observed that in such realistic stochastic signals, the energy, being related to the standard deviation of the signal, is 5 to 10 times lower than in an harmonic signal having the same range. Besides, it seems that a better stabilisation, i.e. closer to real conditions, was achieved by these sequences.

Thus, there is no point in taking into account an effect of load range in analysis.

Mean Load

Mean load has been identified before as the dominant parameter affecting the dynamic stiffness, and a linear relation is currently used. As an update of [3] (where a comparison with the relation in [1] and those by other authors was shown), Figure 11 shows the variation of dynamic stiffness with mean loads, for 11 different ropes from 6 rope manufacturers, including the results of recent tests.

Besides the overall trend for an increase of stiffness (about linearly) with mean load, some scatter is observed that can be attributed to several reasons. A first set is the effect of the parameters noted above : load range (10% maximum on this figure), load regime and effect of previous history/stabilisation. There is also some small effect of measurement inaccuracy and small discrepancies between the testing laboratories (three, in addition to IFREMER), along the measurement and data processing chain.

The principal reason is, however, the differences between the ropes themselves (material and construction), that are reflected in the dynamic-stiffness-at-end-of-bedding-in Krebi. For the ropes in Figure 11, Krebi (shown by bigger marks, at 20% mean load) is in the range of 18.5 to 23, i.e. the range of a "normally stiff" rope according to A1-5.7 in [8].

Normalising data by Krebi, for each rope, significantly reduces the scatter, but does not lead to a single relation, due to the other reasons quoted.

Values for Analysis.

As shown in Figure 11, all data points are lying within the envelope formed by the design (upper-bound) stiffness and the minimum stiffness, as proposed in [8] :

$$KrD = 18.5 + 0.33\ ML \qquad (design)$$
$$KrD_m = 15 + 0.25\ ML \qquad (lower\ bound),$$

where *ML* is mean load (in % of MBS).

Only a few points are marginally outside.

Towards low mean loads, results now available confirm that stiffness is decreasing, and that the linear relation is on the conservative side. Therefore, the minimum value proposed earlier has been dropped. Towards higher mean loads, there is a trend for the stiffness to increase less than predicted by the linear relation. This was attributed to an insufficient number of cycles in earlier test procedures, and does not appear in some results, therefore was not considered.

The envelope given above is thus adequate for the design of a mooring system, i.e. typically some significant time in a project before a particular product is selected and manufactured. This envelope covers the possible range of stiffness of a "normally stiff" rope. Then the standard measurements during rope qualifications will confirm that the purchased product has properties within the range used for Design. This envelope should be adjusted if stiffer ropes are considered. Besides, for some cases (e.g. a site assessment) where the rope is already known, a more accurate relation could be defined. This will however require that further measurements are made, e.g. using stochastic loading, and that due care is taken is the derivation of engineering values, that cannot be simply taken as the raw results of a few tests.

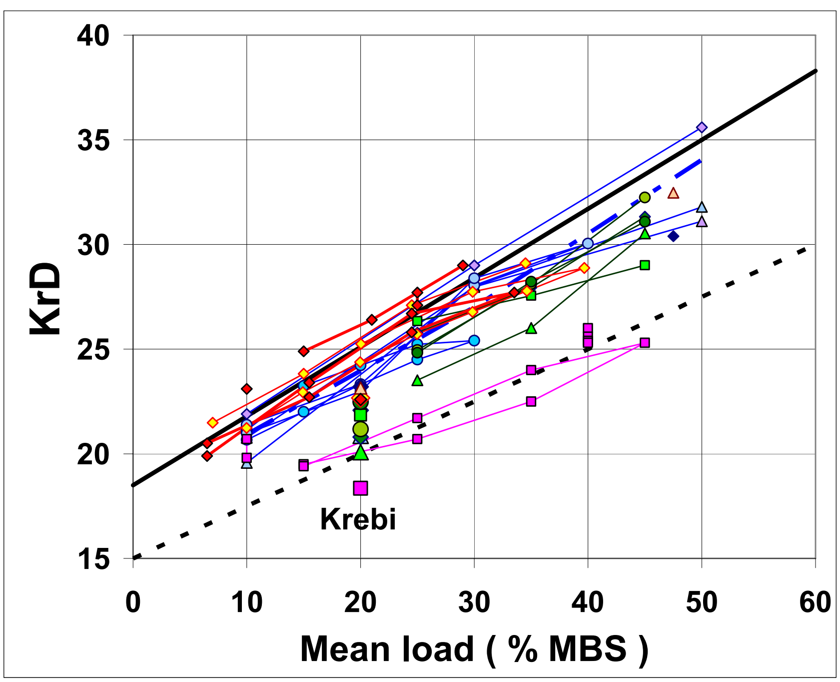

Figure 11 . Dynamic stiffness as a function of mean load : test data from [3] (blue and green), recent (red and pink), and relations in ref [8]

CONCLUSION

Within the French CLAROM fibre rope project, tests have been performed to confirm and complement the currently used practical engineering model that was derived from earlier work. This work focused principally on the response of ropes to slow variations of mean load, under the effect of changing weather conditions, usually modelled by the "Quasi-static stiffness". In addition to the standard tests described in [7], extended test sequences were defined. From these specific sequences, and the number of data points provided, an interpretation can be given that overcomes the discrepancy between the time scale of tests (one or two days), and the real world.

Tests reported in this paper were principally performed on sub-ropes. Some full size rope test results are also reported. The scalability of results, an already known fact, was shown. Due attention was given to the accuracy of load and elongation measurement methods. Continuous time traces were obtained : this is also an important factor for interpretation of test data.

Based on the interpretation of test results, a practical Q S characteristic can be defined, addressing monotonic changes of line mean load, from around the line pre-tension. This characteristic is an extension of the current Quasi-Static stiffness KrS. Two characteristics are proposed for the 12h (standard) loading time, and for 7 days, a loading time more appropriate for some other design conditions (e.g. the effect of a loop current). Both are scaleable by KrS.

A first observation is that, for the 12h loading time, the quasi-static stiffness (Krs_{10-30}) derived from standard tests is valid over a large range of tensions, from about 7 to above 70%, i.e. the characteristic is linear over this range.

Another significant observation is that, for tensions below 10%, the characteristics show a clear increase of compliance with decreasing load : this should be considered for systems working at low tensions in leeward lines.

As background to the above characteristics, further separation of the rope response is presented, based on the derivation of a fully relaxed characteristic (the characteristic for "infinitely slow" rate of loading), and two additional terms : a permanent (non recoverable) elongation, and a (remaining) un-developed visco-elastic elongation, modelling the effect of loading rate. Nevertheless, development of a true "time domain" rheological model and a definitive understanding of underlying mechanism will require further effort.

For the dynamic stiffness, the discussion of the dependence of dynamic stiffness on testing parameters, based on recent data, highlighted mean load as the principal parameter under real stochastic loading. This confirmed the adequacy of current practice in the analysis of a system, of modelling the dynamic stiffness as a linear function of mean load only. Besides, for a particular rope, it is important to note that load history and other effects will always affect the test results, thus due care is to be taken in the derivation of engineering values that cannot be simply taken as the raw results of a few tests. Using stochastic loading time series for the testing appears an efficient method in this respect.

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