Creep as a Design Tool for HMPE Ropes in Long Term Marine and Offshore Applications.

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***Abstract* - HMPE fibers show an elongation and creep behavior that is substantially different from e.g. polyester fibers. Both fibers have a reversible elastic elongation however for polyester it is much higher than for HMPE. Both fibers also show primary creep behavior; for polyester this is the main creep contribution. A very important difference is that only HMPE shows a pronounced secondary creep. This component is irreversible and not only dependent on load but also on temperature. This secondary creep component results in much higher achievable elongations for HMPE based ropes without substantial loss in strength.**

In this paper a model for the creep of Dyneema HMPE on fiber level will be introduced and it is shown that the adaptation of the model for calculations on ropes is possible, regardless of the rope construction.

The calculation model for creep of Dyneema ropes can be used as design tool for long-term conditions that are present in offshore operations.

I. INTRODUCTION

As the offshore industry is expanding their operational window regarding water depths, mooring and station keeping of offshore structures like MODU's (Mobile Drilling Units), production platforms and FPSO's (Floating, Production Storage and Offloading) and all kind of operations on the seabed, demand stress members with improved properties. The maximum water depth mentioned for conventional catenary chain and wire rope configurations is around 1500 meters. This is partly based on material limitations but predominantly on economical considerations [1]. During the last decade a number of alternative mooring systems that use synthetic ropes have been studied and tested to expand this water depth. A number of these systems are still in the test stage, others have been put in use in recent years [2].

Among the man-made fibers that were on the market at the start of these synthetic rope mooring studies, polyester (PES) soon showed to be the preferred fiber as it has good fatigue, stiffness and long term properties. At that time, HMPE (High Modulus PolyEthylene) also referred to as HPPE (High Performance PolyEthylene) fiber production just started and these fibers were not taken into account in these studies. In recent years this new fiber, based on Ultra High Molecular Weight PolyEthylene (UHMWPE), has been studied and tested for these applications. Due to lower weight (ease of handling), lower diameter (easier storage and transportation), higher stiffness (better station keeping, especially at deeper waters and when used as insert lines) and excellent long-term properties (tension- and bending fatigue, UV- and chemical resistance), HMPE fiber has been introduced as an alternative for polyester fibers. Today HMPE ropes are in use for offshore operations e.g. as work ropes, anchor handling, seismic operations, mooring of drilling rigs and under study for pipe laying and ocean towing [3,4,5].

A parameter that with HMPE is clearly different from most synthetic fibers, is creep or cold flow. Attention is given to this property to make this property accessible as an engineering tool in long-term applications. The model and engineering tool to calculate creep will be discussed in this paper.

II. CREEP PROPERTIES OF SYNTHETIC YARNS AND ROPES.

A. General

Polymeric materials, including fibers, show creep under static loading conditions. Fig.1 shows a typical creep curve of a polyethylene and a polyester fiber and one of a polyethylene rope. In this curve the elongation is plotted as a function of time under constant load.

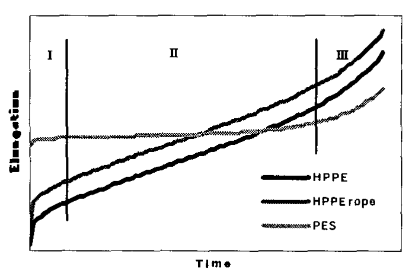

Fig. 1 Elongation under constant load as a function of time.

In such an elongation vs. time curve, as is also observed in many metals [6], three regimes can be distinguished, characterized by a different behavior of the creep rate, viz. the slope of the curve in Fig. 1.

1] *Regime I* is the reversible elastic and delayed elastic elongation. The instantaneous elastic elongation is fully reversible and is certainly no creep. Materials like steel and high performance fibers (HMPE, aramids) have only 1.5 to 3% elongation when loaded to break. Conventional fibers like nylon or polyester give elongations ranging from 10 to 25% when loaded to break.
But next to that, HMPE and PES show a primary creep contribution, characterized by a decreasing creep rate. For HMPE it has been shown that primary creep is fully reversible (delayed elastic elongation).
For all new ropes there is an additional (irreversible) elongation caused by bedding in of the rope structure. This elongation occurs immediately after applying the load and is the main difference between the curves for the HMPE fiber and the rope in Fig. 1.
2] *Regime II*, the creep rate is approximately constant (secondary creep or flow). With HMPE this part is almost completely irreversible. Secondary creep is important in HMPE and not in polyester. With PES it is not fully clear whether this stage should be considered as a very small irreversible additional creep contribution or as just an extremely delayed elastic elongation.
3] *Regime III*, the creep rate increases again, signaling imminent failure (tertiary creep). In this part molecular chains start to break and the fiber or the rope fails. This part is of course irreversible.

To be of practical use in the rope industry a model for creep on fibers, should be translated to ropes. One of the difficulties here could be the fact that the rope construction might have an influence, making it necessary to develop models for all existing rope constructions. However, based on the assumption that a rope is an assembly of single fibers [15], a translation of the fiber model for use in rope applications should be possible.
Together with IKV-RWTH Aachen, Germany [16], DSM started in the 1990s a project in order to translate the fiber creep model to ropes. The creep characteristics of the laid and braided samples were found to be identical, confirming the assumption that a rope acts as a bundle of assembled fibers.
So, as shown in Fig. 1, the elongation of a HMPE rope can be described as parallel to that of the fiber, provided that the comparisons are made with identical levels of load per unit weight. However it should born in mind that creep of a rope usually is specified for a certain fraction of its breaking load. It is well known that the breaking load of a rope is significantly lower than that of the aggregated strength of its constituent yarns. As a consequence a yarn in a rope, is only loaded to a certain fraction of its rated breaking load, feels only a proportionally lower load and the creep rates will be considerably lower.

III. CREEP MODEL FOR DYNEEMA HMPE FIBERS

A. Determination of parameters influencing creep.

Fig. 2. and 3 illustrate the typical elongation behavior of Dyneema HMPE fiber for regime I and II. After a short initial phase (Regime I – elastic and delayed elastic elongation) the fibers exhibit a linear increase in elongation upon prolonged exposure to static loading conditions (Regime II - secondary creep or flow). It should be emphasized that the creep behavior of HMPE fibers is not only related to the polymer feedstock that has been used, but depends also highly on the processing of the material.

It is evident from the figures that the creep rate of the fibers strongly depends on the stress level and on the temperature. This temperature dependency is different from polyester fiber, which does not show a large effect of temperature in the normal working range of offshore applications.

For the modeling it is important to determine exactly the transition point from regime I to regime II. This is hardly possible from the diagrams as shown in Fig. 2 and Fig. 3. In Sherby-Dorn plots it is much easier to find the transition from regime I to regime II [10,11,12]. See Figure 4. Regime II is represented by

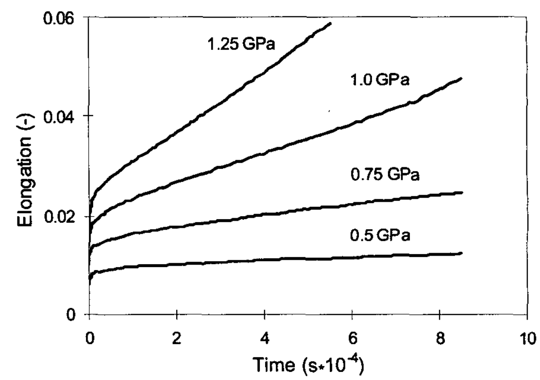

Fig. 2. Creep of a gel-spun fiber (Dyneema) for various loads at a temperature of 30°C [8].

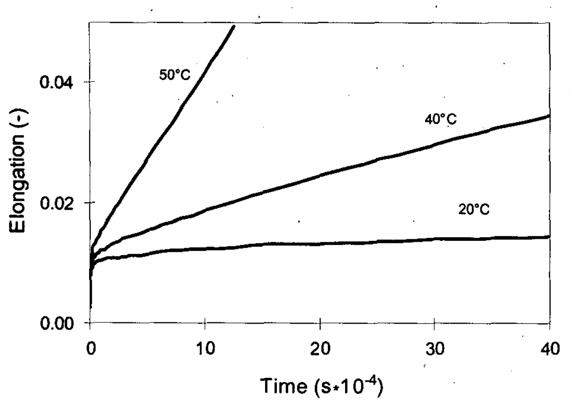

Fig. 3. Creep of a gel-spun fiber (Dyneema) at various temperatures, stress: 0.6 GPa [8].

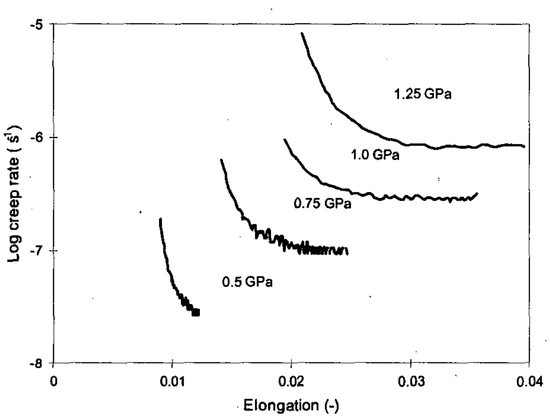

Fig. 4 Sherby-Dorn plot for the creep data of Fig. 2, reproduced from [12].

the horizontal part of the line. As can be seen determination of creep rate for regime II only can be done after regime I has become insignificant. The time required for this depends on load and temperature.

B. Modeling fiber elongation due to creep.

Up to now regime I, II and III have been pictured as three processes acting one after the other. However, the total elongation is due to three molecular processes that act parallel in time [14]:

- I. the stretching of non-crystalline chain segments,
- II. the slip of molecular chains,
- *III. chain rupture.*

All three processes occur at the same time and start acting directly after load is applied with reversible stretching of non-crystalline chains dominating in the beginning of the experiment, irreversible molecular slip of chains on the long term and chain rupture close before break.

Govaert et al. [13] performed creep recovery experiments, in which they measure elongation after the load has been removed in order to separate the reversible and irreversible regimes quantitatively. The reversible part (Regime I - delayed elastic elongation) is well described by a linear relationship between the logarithm of time and the elongation, for the irreversible process (Regime II - secondary creep or flow) they found a linear relationship between time and elongation. The secondary creep is therefore characterized by a constant creep rate (see also Fig. 4) and behaves as a flow process; it is therefore often referred to as flow creep. Experimental data used for modeling have been limited to those conditions where chain rupture is negligible.

Based on these findings, Govaert et al. [8] developed a model to describe the creep of polyethylene fibers as a function of time, load level and temperature. Jacobs [14] adapted and optimized this model for commercial (Dyneema) fiber grades.

Table 1 gives a qualitative relationship between the parameters that determine elongation in HMPE and polyester fibers: time, load and temperature.

TABLE I

Elongation as a function of load, temperature and time for HMPE and PES fibers.

HMPE fiber	Regime I	Regime II	Regime *III*
Parameter	Delayed elastic	Flow	Failure
Time	Log time	Proportional	Not modeled
Load	Proportional	Non-linear $ó^{3.7}$	
Temp.	Weak:0->50 °C: < 30%	Exponential X3.5-4/10°C	

PES fiber	Regime I	Regime II	Regime III
Parameter	Delayed elastic	Flow	Failure
Time	Log time	Very low or not present	Not modeled
Load	Proportional	n.a.	
Temperature	Weak	n.a.	

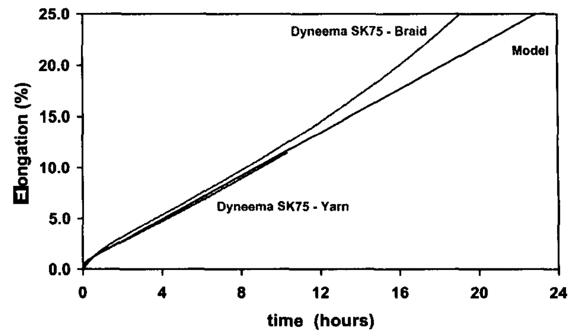

Fig. 5 Comparison of Dyneema SK75 data with predictions of the model (70 °C, load 0.5 N/tex)

IV. MODELING HMPE AND POLYESTER ROPES.

It should be stressed that the Dyneema Creep Model presented here, has been developed for HMPE fibers in general but the quantitative data presented describe Dyneema SK75 fibers only. The initial research has been performed on Dyneema SK60 type yarns but meanwhile Dyneema SK75 is becoming the most important fiber grade for use in engineered ropes. The model recently has been updated for the latest developments of Dyneema SK75 type yarns which are 25% stronger compared to SK60.
As mentioned before the creep characteristics of HMPE fibers are strongly dependent on molecular weight of the polymer and on the production process. It should be emphasized that Dyneema fibers have the lowest creep rate of commercially available HMPE fibers.

The model will be demonstrated during the presentation. Fig. 5 shows a comparison of the calculated creep of a Dyneema SK75 braid with practical measurements on yarn and braid. Conclusions:

- Creep of rope and yarn are essentially identical
- Up to 10% elongation the experimental data and the model data are identical.
- The deviation above 10% elongation can be attributed to tertiary creep (Regime III)

As an extension from the work presented by Elizabeth Huntley at Oceans [17] on polyester, Whitehill Mfg. also tested a Dyneema SK75 three-strand rope and compared this with the Dyneema Creep Model. See figure 6. During this creep experiment temperature varied starting at 72 °F (22 °C) and gradually changing to 55 °F (13 °C). The experimental data fall in-between the calculated lines for the extreme conditions.

For practical use in offshore industry the comparison between a polyester and a Dyneema rope is essential. A number of publications are available on creep in polyester ropes; an overview has been presented by Huntley and Whitehill [17]. The data for a polyester rope described there are used as a reference to compare the performance of Dyneema SK75 ropes as calculated with the Dyneema Creep Model. Figure 7 shows the performance of a polyester rope compared with that of a Dyneema SK75 rope. It is clear that initially the elongation of the polyester rope is much larger due to the higher elastic elongation (Regime I). The creep rate during loading is higher for Dyneema SK75 (Regime II). This higher elongation of HMPE ropes during creep opens the opportunity for HMPE ropes to monitor creep and performance through length measurement during use. HMPE ropes that have an elongation due to creep of approximately 10% still have the same strength as a new rope. See Fig. 8.

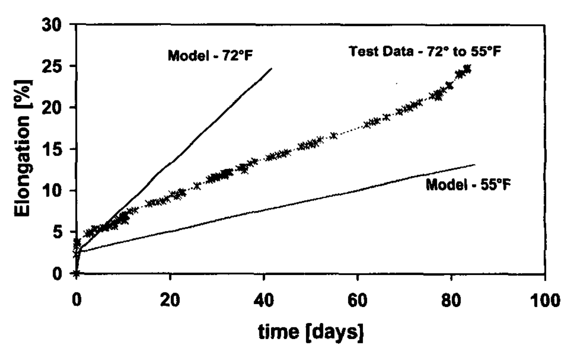

Fig. 6. Dyneema SK75 creep test.
Temperature range: 72°F gradually decreasing to 55°F - Load 11.19 g/den (Courtesy Whitehill Mfg)

In the mean time creep measurements are performed by several rope makers and in several joint industry projects. Results will be published in due time.

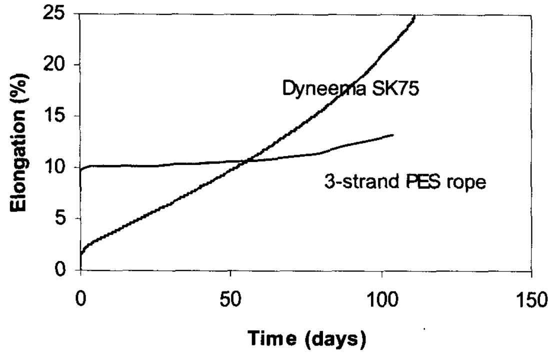

Figure 7 Creep of a Dyneema SK75 rope (model) compared with that of a PES rope (ref 17) at approx 0.6 N/tex.

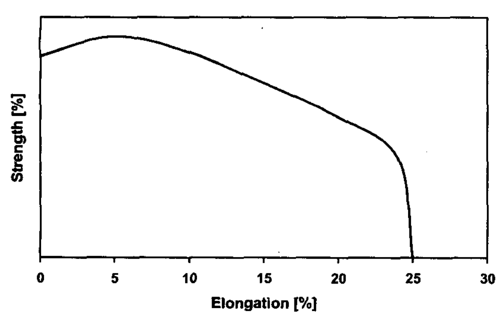

Fig. 8 Schematic relationship between elongation due to creep and residual strength

V. CONCLUSIONS

Although elongation due to creep can be an undesired phenomenon, especially in static applications (making re-tensioning during use necessary), creep of HMPE fibers is certainly not prohibitive for the use of Dyneema ropes in offshore industry. This has been shown in practical use and is supported by model calculations. Creep can even result in phenomena, which work out positively in rope applications:

1] Increased strength
Due to creep, length differences introduced during rope production can be equalized due to the fact that the shortest fibers, which see the highest load, will elongate most. This results in a more favorable load distribution over the fibers, resulting in ropes with higher efficiency (= higher break loads). Several tests including OCIMF's TCLL test have demonstrated this effect.

2] Discard criterion
HMPE ropes that have an elongation due to creep of approximately 10% still have the same strength as a new rope. See Fig. 8. Depending on load history, ropes part at an elongation of approximately 25%. So discarding the rope at 10% elongation secures that no strength loss will occur due to creep.

3] Heat setting
HMPE ropes can be heat set. In heat-setting, the length differences of the yarns are reduced, partly as a result of optimizing the construction of the rope and partly because length differences between fibers are reduced through creep. Heat setting of ropes results in higher strength per unit weight. Heat-setting at elevated temperatures is a more gentle process than the creep process at ambient temperatures. Significant chain rupture only occurs at a much higher elongation.

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