

Predicting the Creep Lifetime of HMPE Mooring Rope Applications

M.P. Vlasblom, R.L.M. Bosman ^a

Abstract—Under constant loading HMPE fibers and ropes show an irreversible deformation (creep) behavior that is strongly dependent upon load and temperature. This paper presents an updated model that seeks to accurately predict the creep rate at various temperature ranges and to estimate creep life of HMPE on fiber level, and demonstrates the apparent validity of this model to rope applications regardless of rope construction. The model may thus serve as design tool for long-term loading conditions as are found in offshore mooring operations.

INTRODUCTION

High Modulus Polyethylene fibers (Dyneema[®] ^b Spectra[®] ^c) are introduced in synthetic rope mooring as an alternative to steel or polyester because of their lower weight (ease of handling), smaller diameter (easier storage and transportation), higher stiffness (better station keeping) and excellent long-term properties (tension and bending fatigue, UV and chemical resistance).

It is known, however, that the creep behavior of HMPE is clearly different compared to most synthetic fibers. Since the ultimate failure mode of a rope under a long-term constant load is creep rupture, the design-load in any system intended for long-term use should be such that this takes a large number of years [1]. A prediction of rope creep during service life is then needed, and proper data or a creep model is indicated as a necessity for qualification of the fiber and a type approval [2].

To be able to do this the prediction of the creep deformation should be within a certain accuracy and a failure criterion should be defined, indicating that the material is breaking or weakened such that it is losing its strength properties.

To predict creep rate on Dyneema[®] SK75 yarn, DSM Dyneema is using the creep model of Jacobs [3]. In a multi-year research program, the creep characteristics of Dyneema[®] yarns have been determined in a wider temperature and load range. This model has been updated accordingly to predict the creep rate more accurately under a given set of circumstances. Extensive research on creep rupture also makes this property now accessible for the design of long-term loaded applications.

This article will first give an overview on the characteristics of HMPE creep. The outcome of creep rate measurements on Dyneema[®] yarns will then be given and the model describing the creep rate will be discussed briefly, and then checked on

several rope creep experiments. The second part of this article describes yarn creep rupture experiments and the creep rupture criterion by which the creep lifetime can be estimated. This criterion will then also be checked on rope creep experiments. The last part of this article discusses a practical discard criterion for creep-loaded HMPE ropes and the resulting time to discard when using a certain HMPE yarn.

I. HMPE CREEP

Creep Regimes of HMPE

Under constant loads HMPE fibers will elongate. Figure 1 shows a typical creep curve of HMPE, where the elongation of a fiber is plotted as a function of time. The logarithmic creep rate of this experiment, which is the slope of this curve, is shown in figure 2. Three regimes can be clearly distinguished characterized by a different behavior of the creep rate [3], [4].

Regime I “primary creep”: In this regime the amorphous realignment takes place. The creep rate reduces to a plateau level. The elongation is reversible with the use of an elastic and delayed elastic component.

Regime II: “steady state creep”: In this regime the sliding of molecular chains takes place. The creep rate increases slightly. The elongation is what we define as plastic creep, which is irreversible.

Regime III: “tertiary creep”: In this regime molecular chains start to break. High strains will start to cause necking in the filaments (figure 3) and will increase the local stress that further accelerates the strain until breakage.

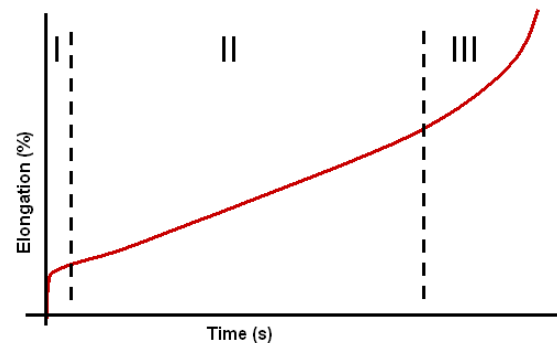


Figure 1. Typical HMPE creep curve

^b Dyneema[®] is a registered trademark of Royal DSM N.V.

^c Spectra[®] is a registered trademark of Honeywell International Inc.

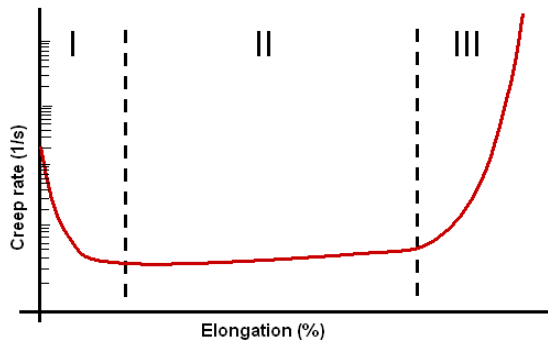


Figure 2. Typical HMPE creep rate curve

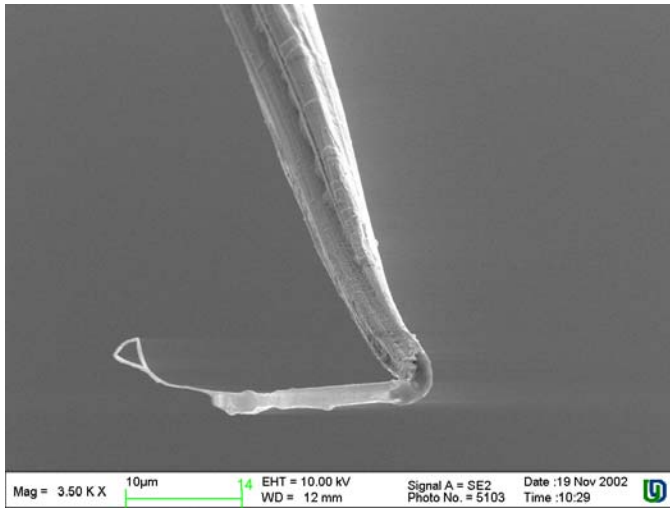


Figure 3. Reduced cross section on the tip of a broken, creep-loaded HMPE filament [5]

The transition of creep regime II and III, indicated by an acceleration in the creep process, can be used to mark the end of the safe working life. Since higher creep resistant materials do not show a creep regime II, it is difficult to estimate the residual creep lifetime for ropes made of these materials.

Figure 2 also indicates that initially the creep rate is high but decreases with increasing elongation and levels off at an elongation of a few percent to the lowest value, marking the end of creep regime I: the plateau creep rate. For extrapolations over longer times, creep tests should at least be carried out up to this plateau in the creep rate, but preferably to the start of regime III.

A schematic illustration of the variation of elongation with time during a creep test is shown in Figure 4. At time $t=0$ the load is applied. The total elongation is a result of three components: (1) an immediate elastic elongation, which is instantaneously recovered upon removal of the load, (2) a delayed elastic elongation, which is reversible but over a longer period of time and (3) a permanent or irreversible elongation, which occurs at an approximate constant rate during loading.

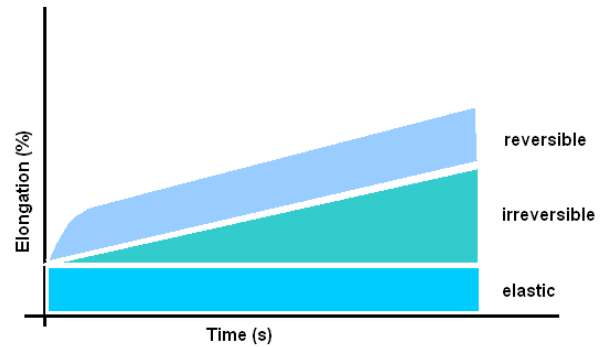


Figure 4. Elongation of regime I and II as a function of time

Modeling creep

Polymer fibers consist of filament bundles, each containing both crystalline and amorphous regions. The crystalline regions consist of highly structured molecule stacks, whereas the amorphous regions consist of unstructured tangles of molecules. HMPE fibers are highly crystalline (max. 85%) and highly oriented (>95%) in the fiber axis direction, giving the fibers their unique properties.

The total elongation of HMPE under constant loads relates to three molecular processes that occur simultaneously in time, but dominate at different stages of the experiment. Reversible stretching of non-crystalline chains dominates in the beginning of the experiment, irreversible molecular slip of chains in the long term and chain rupture just before break, see table 1. The reversible component (Regime I) can be illustrated by a linear relation with the logarithm of time. The irreversible, or plastic creep component (Regime II) can be described by a linear relation with time, a strong non-linear relation with the applied load and an exponential relation with temperature.

Based on this, the creep model for Dyneema® SK60, developed by Govaert [6], optimized and adapted to Dyneema® SK75 by Jacobs, has recently been further adapted to Dyneema® SK78 and is upgraded to perform lifetime estimations as a function of fiber grade, time, load level and temperature.

TABLE I
ELONGATION AS A FUNCTION OF LOAD, TEMPERATURE AND TIME AS USED IN THE CREEP MODEL

	Regime I Delayed elastic	Regime II Flow	Regime III Failure
Time	Log time	Proportional	Not modeled
Load	Proportional	Non-linear	
Temperature	Weak	Exponential	

Test Equipment and Procedure

The yarn creep tests for the update of the creep model were performed in a creep test facility, in which the air temperature can be controlled between 10 and 70°C. The creep experiments on slip free clamped yarn samples of 200 to 1000 mm length run fully friction free. The creep load is applied by a dead weight (up to 38 kg) which is hooked up on the lower axis connected to the yarn. The yarn is preloaded in a fully automatic manner by an elevator that applies the load on the yarn for a preloading phase of 30 seconds, after which the load is taken off for yarn relaxation for a period of 10 times the preloading time. At the end of this relaxation phase the sample length is determined automatically.

The actual creep test starts by once again applying the load. The elevator continuously senses and follows the position of the dead weight at some distance. At each displacement of the elevator the position (in millimeter) and time (in seconds) is registered. The measurement can be performed with resolutions up to 12.5 micrometer. A maximum of 120 mm elongation can be determined before the weight hits the floor.



Figure 5. Fully automatic creep data logging

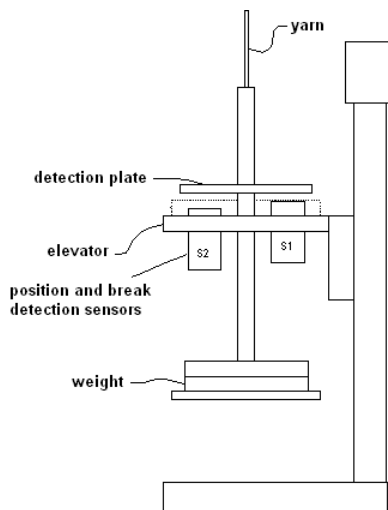


Figure 6. Measurement of displacement

Yarn Creep Rate Measurements

In order to be able to predict the creep deformation, the creep rate of the material under a certain temperature and load condition should be determined first. Since the raw material feedstock, production methods, strength and modulus are known to have an influence on the creep characteristics of HMPE types, several types have been included for reasons of comparison, see table 2a and 2b.

TABLE 2a
TYPICAL PROPERTIES OF HMPE YARN SAMPLES [7], [8]

	Titer (dtex)	Tenacity (GPa)	Modulus (GPa)	Strain at break (%)
Dyneema® SK75	1760	3.4	110	3.5
Dyneema® SK78	1760	3.4	110	3.5
Spectra® fiber 900	5333	2.18	67	3.9
Spectra® fiber 1000	417	3.0	103	3.1

TABLE 2b
TABLE 2B MEASURED PROPERTIES OF USED HMPE YARN SAMPLES

	Titer (dtex)	Tenacity (GPa)	Modulus (GPa)	Strain at break (%)
Dyneema® SK75	1736	3.4	109	3.8
Dyneema® SK78	1745	3.4	111	3.6
Spectra® fiber 900	5315	2.3	72	3.9
Spectra® fiber 1000	422	2.9	116	3.0

In 75-100 creep experiments per product type over a wide temperature range (10-70°C) and load conditions (175-1400 MPa) the characteristic creep properties of different grades of Dyneema® were determined. Figure 7 and figure 8 show the output of one of the creep experiments. A rapid increase in creep rate can be determined in figure 8, which marks the entrance of creep regime III that is also known as the start of creep failure. The time at which this occurs is determined in figure 7.

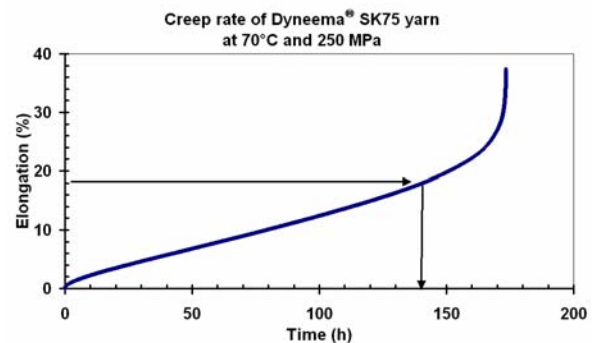


Figure 7. Measured creep elongation as a function of time

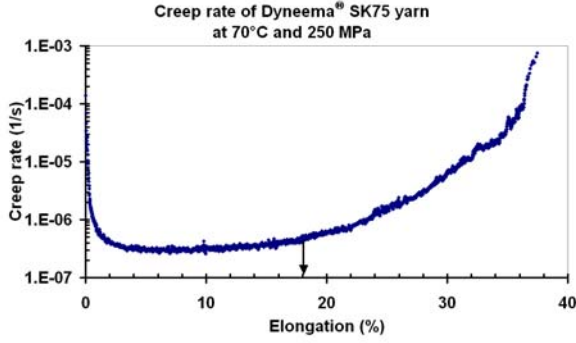


Figure 8 Measured logarithmic creep rate as a function of elongation

The creep rate of HMPE yarns is dependent upon the applied load and temperature. In other words: for each grade, each temperature/load condition will have a characteristic creep rate. Figures 9 and 10 depict the creep rates of the experiments on the regular Dyneema® SK75 and the offshore mooring grade Dyneema® SK78. To make this data more practical, the following general rules for the creep rate can be used:

- (a) At room temperature, Dyneema® SK75 yarns loaded with 10% break strength show a creep rate of 0.2% per week, while Dyneema® SK78 shows a creep rate of 0.2% per month.
- (b) A temperature increase of 20°C increases the creep rate by a factor of 10.
- (c) At room temperature, a reduction of the load by a factor of 0.6 reduces the creep rate by a factor of 10.

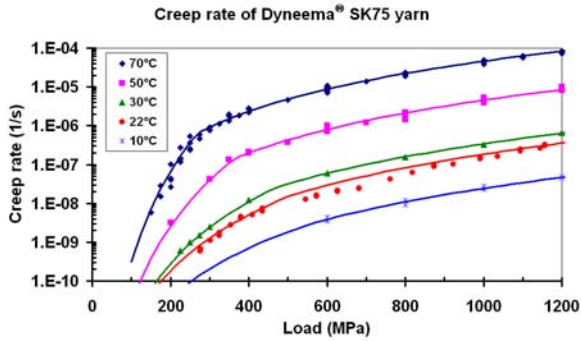


Figure 9. Measured creep rate of Dyneema® SK75 yarn

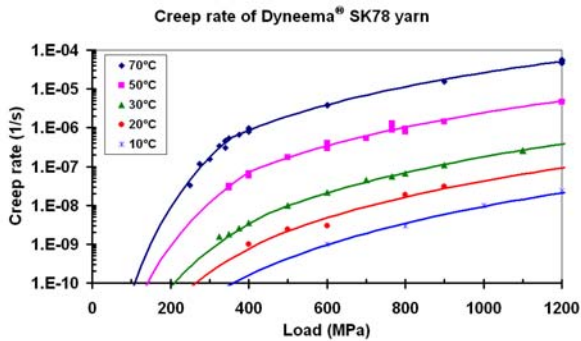


Figure 10. Measured creep rate of Dyneema® SK78 yarn

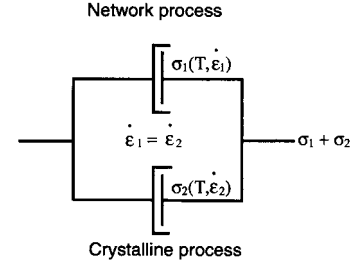


Figure 11. Two-process model for irreversible deformation [3]

Two-Process Creep Rate Model

It is assumed that irreversible deformation is caused by molecular chain slip. The non-linear experimental irreversible deformation data can be represented as two thermally activated processes acting in parallel, each characterized by a different flow resistance with its own activation volume and rate constant [9]. The mathematical description of the creep model for Dyneema® yarn is described in depth in [3]. This model can be represented schematically in figure 11.

However, this creep model is only accurate in a limited deformation range. Over a larger deformation range, the creep rate is not constant but increases gradually, leading to an increasing stress level on the yarns. When a yarn elongates under a creep load, the titer or specific weight (the weight per meter length) is reduced whereas the stress level (force / titer) increases. In order to predict creep deformation up to creep regime III within a certain accuracy, in the updated model this increase of the creep load is taken into account in the calculation time steps.

$$\sigma_2 = \sigma_1 \cdot (1 + \epsilon_1) \quad (1)$$

σ = stress in MPa
 ϵ = elongation in %

Creep Prediction Using the Model

The large dataset allows better creep rate fitting, but also allows statistic analyses to estimate creep rate and lifetime variations. Besides new creep rate fits, the creep model also includes the above-described impact of creep elongation on the stress level, causing the creep curve to gradually increase, as is seen in creep experiments. The observed lifetime variations are common for creep and fatigue experiments.

Figures 12 and 13 show a creep prediction with its 95% accuracy boundaries (t-value = 2) based upon the updated creep rate model.

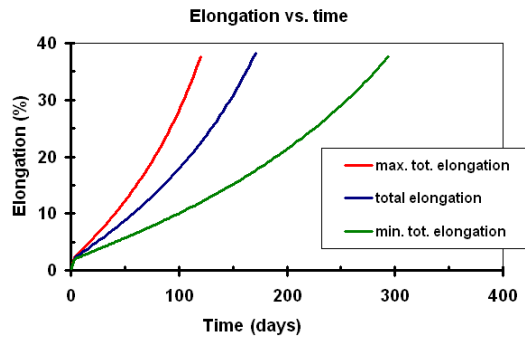


Figure 12. Predicted creep elongation as a function of time

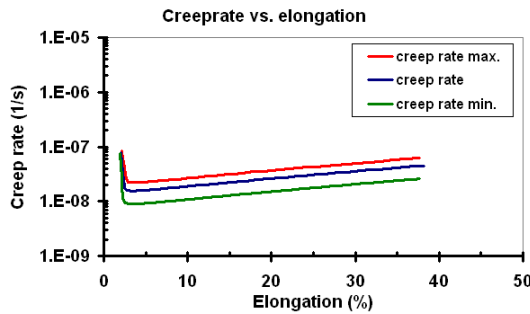


Figure 13 Predicted logarithmic creep rate as a function of elongation

Predicting Rope Creep Rate

The stress level on the material determines the creep rate. Rope construction appears not to have an influence on this, as is hypothetically concluded from measurements with yarn and rope samples showing the same creep rates when stress levels are the same. An offset of the elongation, however, can be seen in the rope creep data depending upon the amount of pre-loading (figure 14). This is known as constructural elongation (the setting of the rope). In this figure the two elongation curves run parallel, indicating that the creep rates are the same for the rope and yarn creep experiments while the same stress levels are applied.

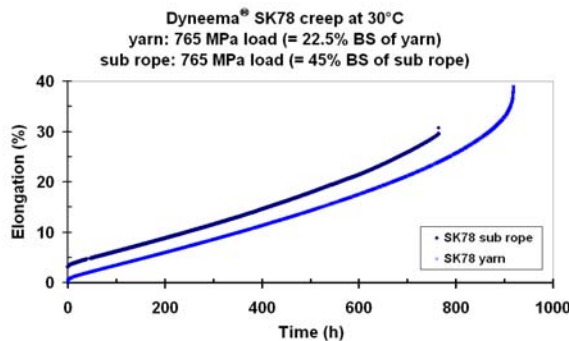


Figure 14. Measured creep elongation of Dyneema® SK78 rope and yarn sample

In comparing fiber and rope creep data on a relative load basis, a conversion factor, or realization factor must be taken into account [10].

$$L_{\text{yarn}} = L_{\text{rope}} \cdot f_{\text{rope}} \quad (2)$$

L_{yarn} = yarn load in percentage break strength of yarn

L_{rope} = rope load in percentage break strength of rope

f_{rope} = conversion factor

To illustrate this:

A rope with a tenacity of 1.4 kN/(g/m) made from Dyneema® SK75 under a constant load of 20% break strength at 20°C shows a creep rate of 0.1% per month. This rope is loaded at 270 MPa.

A Dyneema® SK75 yarn with a tenacity of 3.5 kN/(g/m) under a constant load of 20% break strength at 20°C shows a creep rate of 9% per month. This yarn is loaded at 680 MPa

If the fiber and rope are loaded with the same stress levels (e.g. MPa), a direct comparison, without conversion factors, is possible.

$$\sigma = \rho \cdot L / w \quad (3)$$

σ = stress in MPa

ρ = material density in g/dm³ = 970 g/dm³ for HMPE

L = load in kN

w = specific weight in g/m

Rope Creep Rate Measurements

Properties of rope samples can be derived from tests on sub ropes, as was illustrated in [11] with the dynamic modulus. In line with this, it is assumed that creep properties of rope samples can also be derived from yarn samples. In an effort to test this hypothesis, several creep experiments on (sub)rope samples were performed at DNV in Norway and Ifremer in France [12]-[16]. It shows that there is no significant difference in yarn and rope creep rate (figure 15). The ability to predict yarn creep rate implies that this is also applicable to (sub)ropes loaded under the same conditions.

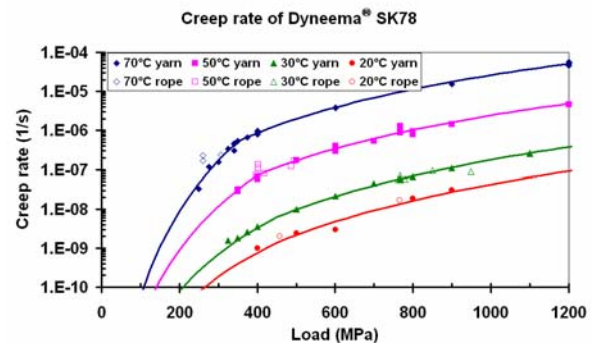


Figure 15. Measured creep rate of Dyneema® SK78 rope and yarn samples with modeled fit lines

II. CREEP RUPTURE

Yarn Creep Rupture

A model capable of predicting the creep rate of HMPE yarns and ropes can only be a valuable tool when an end of creep lifetime (e.g. break elongation under creep load) is known. In the typical HMPE creep rate curve of figure 2 three regimes can be distinguished. The creep regime III “tertiary creep” is also known as the failure regime. The molecular chains start to break, causing the local stress to increase and the creep process to accelerate until total breakage occurs. To be able to estimate creep lifetime on HMPE yarns the start of creep regime III was taken as a criterion. It is a conservative approach since there is time left till total breakage.

HMPE type specific creep properties

The start of creep regime III is dependent upon the applied load and temperature (figure 16). At low and very high stress levels the elongation at entering this creep regime III is low (figure 17), but the low load elongations refer to the higher lifetimes measured in the experiments. The raw material feedstock, production methods, strength and modulus have an influence on this point in time and elongation. Under the same stress levels, Dyneema® SK78 enters creep regime III at lower elongations but after a longer time compared to Dyneema® SK75.

In figures 18 and 19 creep measurements are shown for two temperature and load conditions of four HMPE yarns, as mentioned in table 2b. It illustrates that there is no single creep performance factor between one and the other yarns that is valid for each load condition. What can be concluded, however, is that Dyneema® fibers seem to outperform Spectra® fibers, and that Dyneema® SK78 shows to have the best creep properties under the same conditions.

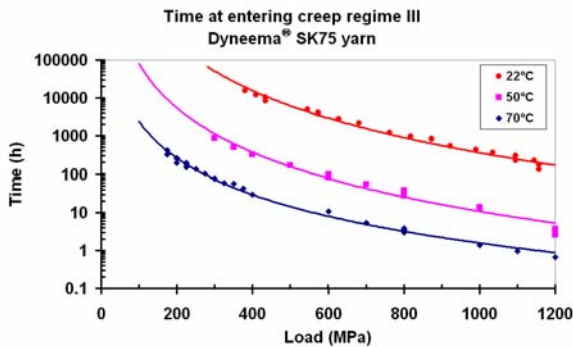


Figure 16. Measured time at entering creep regime III of Dyneema® SK75 yarn samples

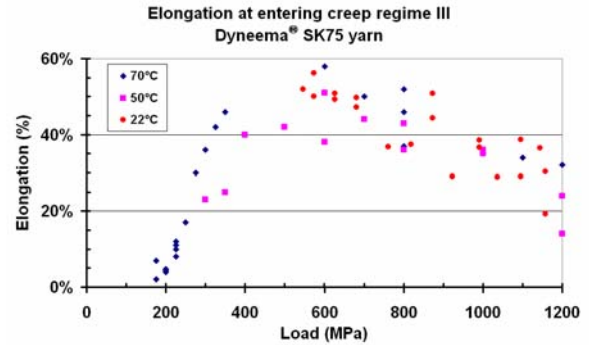


Figure 17. Measured elongation at entering creep regime III of Dyneema® SK75 yarn samples

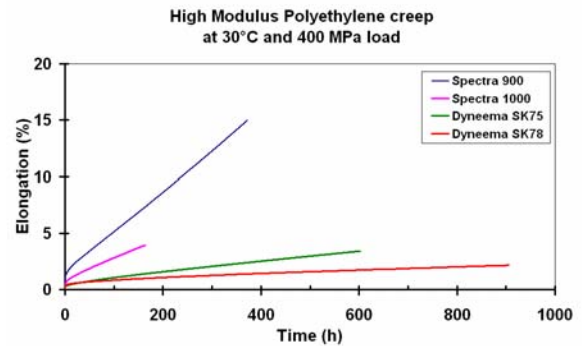


Figure 18. Measured creep of four HMPE yarn types at 30°C and 400 MPa load (none to breakage)

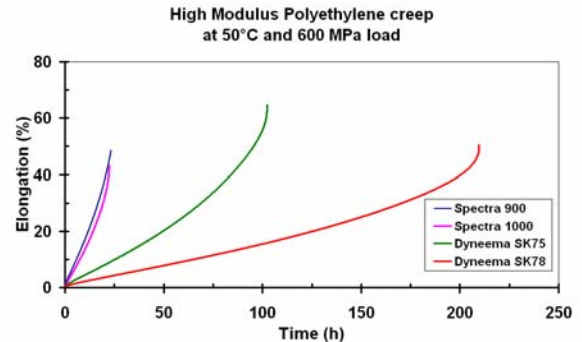


Figure 19. Measured creep of four HMPE yarn types at 50°C and 600 MPa load (all except Spectra® fiber 900 to breakage)

Yarn Creep Rupture Model

Each HMPE grade has its own creep characteristics, making it necessary to perform creep rate and creep rupture measurements on each individual grade. For creep lifetime estimations the creep model makes use of fit curves describing the load - and temperature - dependent elongations at entering creep regime III. To illustrate the capabilities of the creep model, the yarn creep data and simulation result with 95% accuracy boundaries are shown for one of the experiments in figures 20 and 21: the measured yarn creeps at a rate between the predicted average and the minimum creep rate.

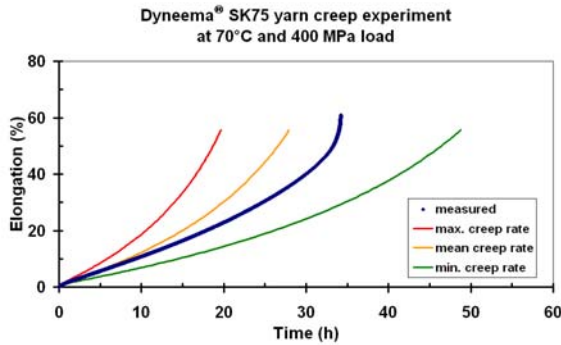


Figure 20. Simulated and measured creep elongation of Dyneema® SK75 yarn sample

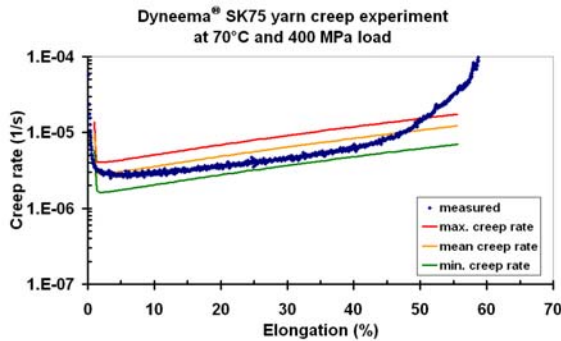


Figure 21. Simulated and measured creep rate of Dyneema® SK75 yarn sample

Rope Creep Rupture Measurements

The applicability of the yarn creep model for rope applications was checked with static loads only on a total of 15 sub rope samples made from Dyneema® SK78; 14 braided samples were tested at DNV in Bergen, Norway and 1 laid rope sample was tested at Ifremer in Brest, France. Figure 22 illustrates the applicability of the creep model for rope creep estimations in one of the test conditions: the measured rope follows the predicted average creep rate of the test condition.

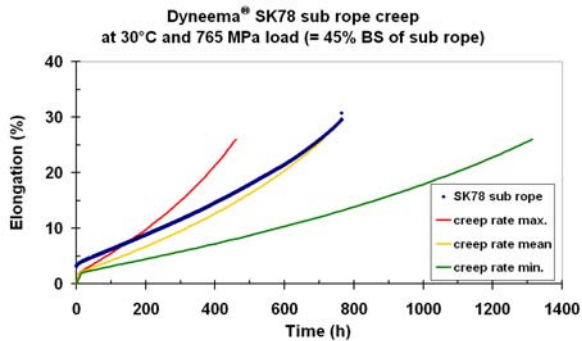


Figure 22. Simulated and measured creep rate of sub rope sample made from Dyneema® SK78

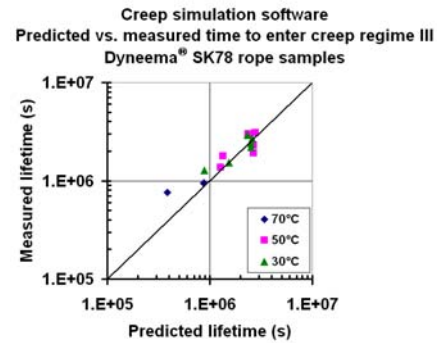


Figure 23. Predicted versus measured creep lifetime of sub rope samples made from Dyneema® SK78

Although the mathematical description of the start of creep rupture is not based on the same scientific approach as the creep rate model, the use of fit curves through the empirical maximum elongation datasets has proven sufficiently effective for estimating creep lifetime. Figure 23 illustrates this for the tested Dyneema® SK78 rope samples. For a perfect model, where lifetime turns out to be exactly what is predicted, all points would be on the diagonal line. The graph shows some positive deviation to this: the measured lifetime was slightly higher than estimated.

III. CREEP DISCARD CRITERION

Retention Strength

Because chain rupture dominates at creep regime III, in this regime the retention strength (the residual strength after exposure to loading) of a yarn or a rope will be reduced rapidly. In regime II, however, the retention strength is only slightly reduced. A few experiments on a braided sample (16x1 construction) were performed to illustrate this (figure 24) [4]. Note that the experiments were performed at elevated temperatures to increase the creep process.

Initially the strength increases due to optimization of the braid structure that reduces the length differences introduced during braiding. This results in a more favorable load distribution over all fibers, resulting in a braid with a higher tenacity. As a function of creep elongation the strength reduces slightly. The retention strength of rope samples is expected to follow the trend shown in the experiment using the small braid.

A discard criterion on retention strength for creep loaded rope made from Dyneema® is not preferred because the retention strength only reduces much after entering creep regime III. Since the loading condition determines the amount of elongation under which a rope enters creep regime III (see figure 17), another discard criterion is necessary.

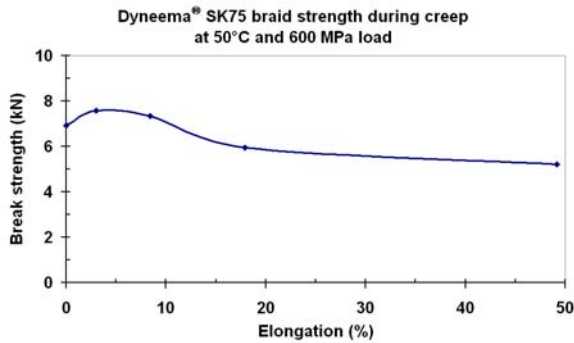


Figure 24. Dyneema® SK75 braid strength during creep

Time

The time after which an HMPE rope subjected to a creep load should be discarded is dependent upon the load, the temperature and the rope tenacity. The industry guidelines and customer rope specifications tend to describe only creep rate tests and are unable to extrapolate these to creep rupture. Guideline API-RP 2SM states that creep rupture calculations should be performed on rope creep data, based on the annual cumulative rupture damage derived similar to the miner's rule for fatigue analysis. Besides this, a large safety factor on creep lifetime is specified [17]. But performing rope creep measurements under realistic (relative low loads at low temperatures) offshore conditions would not only involve high costs but would not lead to a large set of lifetime data within a practical time frame. Furthermore, a large safety factor is reasonable for rope materials on which no in-depth studies on creep rupture have been performed. This study on the creep lifetime performance of Dyneema® yarns shows that creep rate of ropes is comparable to yarns under the same stress levels, and creep lifetime can be estimated sufficiently within certain boundaries.

Elongation

When taking the creep model as a basis for predicting the creep lifetime, a retirement criterion is still necessary. Based upon the retention strength tests and the practical use in mooring lines, a discard criterion of 10% permanent elongation is suggested. As can be seen in figure 17, only in some very low loading conditions is creep regime III entered before reaching this discard, although this takes a very long time (figure 16). For mooring rope applications made from Dyneema® a normal loading condition is in the range of 350 MPa and a storm condition of 575 MPa (calculated with a rope tenacity of 1.3 kN/(g/m)). In using a 10% elongation discard criterion, the mooring rope will be discarded long before the maximum elongation is reached. As a result a safety factor is then taken into account.

IV. DISCARDING HMPE ROPES BASED ON CREEP MODEL

The time to discard a rope can be estimated by using the creep rate properties of each characterized HMPE grade, combined with the 10% elongation discard criterion. As was shown in figure 17, for some very low load conditions the elongation of 10% was not reached. For these conditions, left of the dotted lines in figures 25 and 26, a maximum time-to-use discard criterion is proposed. The resulting graphs are shown in figures 25-28 for the four HMPE grades mentioned, which differ in raw material and production settings. On the horizontal axis the creep load is noted in Force (N) / rope mass (g/m). A typical rope with Dyneema®, loaded at 25% MBL, is comparable to a creep load of 325 N/(g/m). At this level the time to discard using Dyneema® SK78 is approximately three times longer than with Dyneema® SK75. At the same creep load, the time to discard using Spectra® fiber 900 is expected to be seven times shorter than with Dyneema® SK75. Spectra® fiber 1000 is expected to have a time to discard that is four times shorter than with Dyneema® SK75.

Note that in addressing rope discard criteria, other well known failure modes and the way these may have been addressed in any particular situation is not taken into consideration in the model under discussion nor in its output.

Dyneema® SK78

DSM Dyneema has investigated the effects of the raw material feedstock and production methods on creep lifetime, in a continuous effort to improve yarn performance. This results today in Dyneema® SK78 yarn with the best creep performance and in the near future will result in new developments for permanent mooring applications. Dyneema® SK78 is type approved for offshore mooring applications by Bureau Veritas [18] and the American Bureau of Shipping [19].

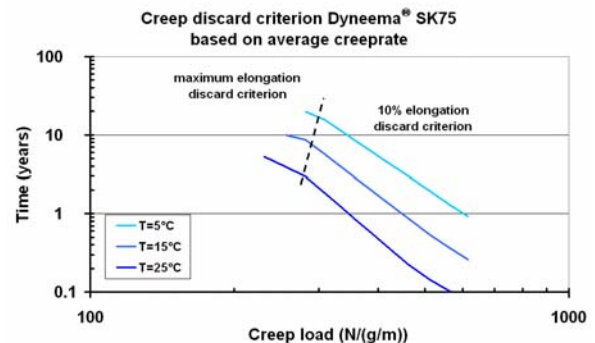


Figure 25. Based on the model, expected time to discard creep loaded rope applications using Dyneema® SK75

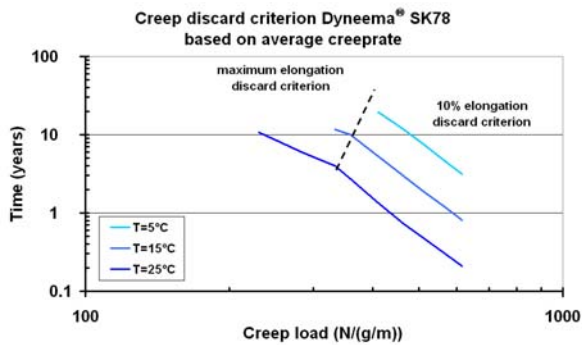


Figure 26. Based on the model, expected time to discard creep loaded rope applications using Dyneema® SK78

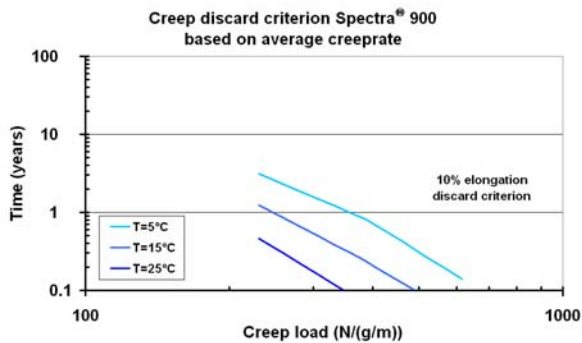


Figure 27. Based on the model, expected time to discard creep loaded rope applications using Spectra® fiber 900

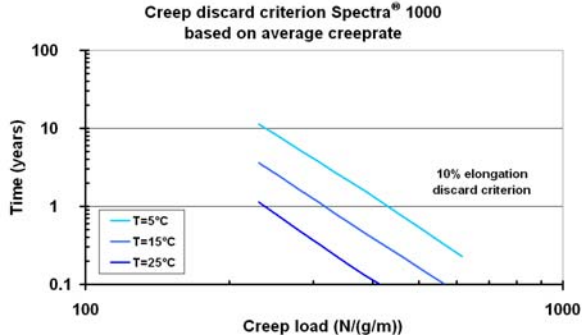


Figure 28. Based on the model, expected time to discard creep loaded rope applications using Spectra® Fiber 1000

V. CONCLUSIONS

High Modulus Polyethylene yarns subjected to creep loads show three creep regimes. Creep regime II “steady state creep” is characterized by a relatively constant creep rate. In this creep stage the retention strength is slightly reduced as a function of elongation.

The elongation at which creep regime III “failure regime” is entered is dependent upon the raw material, the applied load and the temperature.

Rope creep data is comparable to yarn creep data when the same stress level is applied.

As discard criterion a 10% permanent elongation is suggested in combination with a maximum time-to-use under a specific load condition.

Extensive research on the creep rupture property has now contributed to the description of the creep behavior of HMPE yarn. DSM Dyneema is able to predict creep elongations and estimate creep lifetime within a certain bandwidth on all of its commercial grades subjected to static loads. From these lifetime estimations it appears possible for an HMPE mooring rope to be designed such that it can withstand a long-term static load.

HMPE materials can differ when it comes to creep performance. Dyneema® SK78 shows the lowest creep rate leading to the highest creep lifetime.

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DISCLAIMER

The contents of this article are based on information and research believed to be reliable by the authors. Neither the authors nor DSM Dyneema accept any liability whatsoever for the use of or reliance on the contents hereof. Ultimate and sole responsibility for rope constructions and recommendations and/or decisions to discard the same lie with rope manufacturers and/or end-users.

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^a The authors are presently employed by DSM Dyneema BV of the Netherlands