CREEP BEHAVIOUR OF HMPE FIBRES USED IN ULTRA DEEP SEA WATER MOORING ROPES

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Abstract. *With the development of oil fields in ultra deep waters, the replacement of steel ropes used to mooring floating structures by other with lesser linear weight, become a necessity. In shallow waters the drilling and production flotation units are anchored by conventional systems composed of steel chains and wire ropes in catenary geometric configurations. For deep and ultra deep waters the "taut-leg" system based on tightened synthetic ropes with lesser linear weight was developed. Nowadays these ropes are made of polyester (PET) and they provide the necessary compliance to the taut-leg system by means of the natural mechanical properties of the fibre. Due to the appearance of other synthetic fibres in the market, which intend to improve the performance of the proper mooring system, it became necessary to analyze and verify the mechanical properties of these fibres. Research has been doing with HMPE - High Modulus Polyethylene, material with excellent mechanical behaviour in tension and low density but with an inconvenient, to substitute polyester: significant creep at normal conditions of temperature was obtained. The present paper is concerned with a methodology to predict creep lifetime of HMPE yarns in this macroscopic approach, besides the classical variables (stress, total strain), an additional scalar variable related with the damage induced by creep is introduced. An evolution law is proposed for this damage variable. The model prediction is compared with curves obtained experimentally at room temperature showing a good agreement.*

Keywords: *synthetic mooring ropes; continuum damage mechanics; creep; viscoplasticity*

1. INTRODUCTION

With the development of oil fields in ultra deep waters, the replacement of steel ropes used to mooring floating structures by other with lesser linear weight, become a necessity. In shallow waters the drilling and production flotation units are anchored by conventional systems composed of steel chains and wire ropes in catenary geometric configurations. For deep and ultra deep waters the "taut-leg" system based on tightened synthetic ropes with lesser linear weight was developed (see API recommended practice for design, manufacture, installation, and maintenance of synthetic fibre ropes for offshore mooring, 2001, Bosman and Cloos, 1998, Del Vecchio, 1996, Del Vecchio and Costa, 1999, for instance). Nowadays these ropes provide the necessary compliance to the taut-leg system by means of the natural mechanical properties of the fibres.

Most fibre ropes comprise a core to withstand tensile loads and an outer jacket, which often has little tensile load bearing capability. Additional protective coatings or wrappings may be applied after rope manufacture. Typical rope construction types suitable for deepwater fibre moorings are wire rope constructions (WRC), and parallel strand types. The main structural levels in a fibre rope, although not all present in every construction, are: (i) Textile yarns, as made by the fibre producer and typically consisting of hundreds of individual filaments; (ii) Rope yarns, assembled from a number of textile yarns by the rope maker; (iii) Strands made up from many rope yarns; (iii) Sub-ropes of several strands; (v) The complete core rope assembly; (v) Rope, sub-rope and strand jackets.

Polymer based fibre ropes exhibit nonlinear behaviour and are subject to creep, potentially leading to creep rupture. Polyester ropes are not subject to significant creep at loads normally experienced in mooring applications. HMPE - High Modulus Polyethylene - is a material with excellent mechanical behaviour in tension and lower density than polyester, but with significant creep at normal conditions of temperature. HMPE yarns creep substantially, although the rate of creep is very dependent on the particular HMPE yarn in question.

The analysis of creep phenomenon in HMPE synthetic ropes accounting for different rope constructions can be extremely complex. The mechanisms proposed so far to explain the damage initiation and propagation processes are not able to elucidate all aspects of the phenomenon in different geometry/material systems (Schmidt et al, 2006, Pellegrin, 1999, Sloan, 1999, Hooker, 2000, Pearson, 2002, Petruska et al, 2005, Silva and Chimisso, 2005, for instance). Despite the lack of definition of a basic theory for creep failure for such complex systems, the evaluation of the susceptibility to creep is a basic requirement for safe and economic operation, since creep rupture remains as one of the main limitations for the use of HMPE synthetic ropes for deep water mooring of FSOP units and floating platforms. This objective is accomplished by the execution of a set of laboratory tests taking as specimen a sub-system (yarn). Creep tests in textile yarns, as made by the fibre producer and typically consisting of hundreds of individual filaments, are frequently used in order to obtain more detailed information about the macroscopic creep behaviour of the fibres. These tests are so far the most important techniques used to rank the susceptibility of different materials in a specific temperature. However, it is necessary a large number of tests in order to provide basic parameters to be directly used in engineering design, mainly to estimate the influence of the load and temperature on the creep process. Hence, the determination of the creep behaviour of HPE yarns is up to now strongly dependent on these CL tests, what makes attempts to model these tests advisable.

The present paper is concerned with the phenomenological modelling of creep tests of HMPE yarns at room temperature. The goal is to propose a one-dimensional phenomenological elasto-viscoplastic model that combines enough mathematical simplicity to allow its usage in engineering problems with the capability of describing a complex non-linear mechanical behaviour. The main idea is to use such model to obtain the maximum information in order to rank the susceptibility of different materials to creep from a minimum set of laboratory tests, saving time and reducing experimental costs.

In this phenomenological approach, besides the classical variables for an isotropic elasto-viscoplastic material (stress, total strain, plastic strain), the basic idea is to introduce an auxiliary macroscopic variable $D \in [0,1]$, related to the loss of stiffness of the specimen due to the damage (geometrical discontinuities induced by mechanical deformation and the simultaneous corrosion processes. If $D = 0$, the specimen is considered "virgin" and if $D = 1$, it is "broken" (it can no longer resist to mechanical loading). An evolution law is proposed for this damage variable. Examples are presented in order to illustrate the main features of the model.

2. MATERIAL AND EXPERIMENTAL PROCEDURES

The experimental tests on synthetic fibres used to made ropes in general or specific offshore mooring ropes, developed inside scientific or rope maker laboratories, follow specific normatives (API, ISO, ASTM, Cordage Institute). In the normatives are established rules and recommendations regarding sample, dimensions of the specimens, range of speed for the test machine, types of clamps, ideal condition of temperature and humidity and so on.

Usually, a mechanical tensile test is realized to determine mechanical characteristics like as yarn broke load (YBL), final elongation and tenacity for the mono or multi-filaments that compose a yarn. For most types of synthetic fibres, these mechanical characteristics were obtained using servo-hydraulic or electromechanical test machines with usual clamps (spool clamps or pneumatic clamps). Mechanical tests realized in samples of synthetic fibres used to make ropes, like as Nylon, Polyester, Polypropylene, Polyethylene, follow the above rules and devices. Nevertheless, it is very difficult to realize these mechanical tests in HMPE fibres because of the very low friction coefficient between filaments and the traditional grip devices (reels, mechanical and pneumatic clamps). The slipping between HMPE fibres and the clamps causes serious difficulties to realize tensile tests. Those difficulties were surpassed in the tests performed at POLICAB /FURG (Stress Analysis Laboratory of FURG), using special devices specially developed for HMPE fibres. The devices called "sandwich" were developed for tension tests, for long term and short term creep tests with excellent performance, without the occurrence of sliding between fibres and clamps. Multifilaments are glued with an epoxy resin inside wooden plates and mounted in aluminum supports pressed by screws, like a sandwich, as shown in the figures 1a and 1b.

Figure 2 show a sample of specimens for long term creep test with dead weight. Figure 3 shows a creep rupture and the end specimen clamped. In the creep rupture tests it was adopted a sandwich termination similar to that used in the long term creep test but without the steel sandwich. The specimen is put into the machine clamps like a sandwich formed by multifilament glued with an epoxy resin inside 2 polyvinyl sheets.

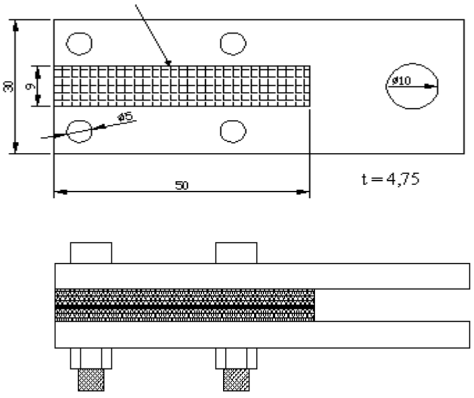

Fig. 1.a. Sketch

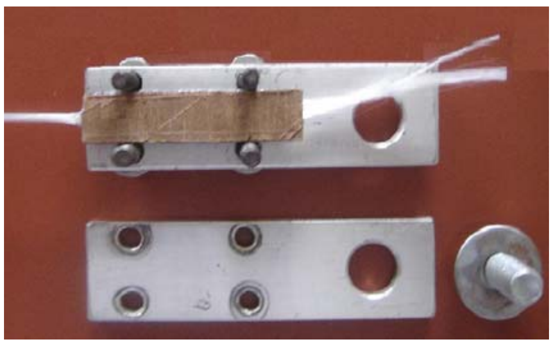

Fig. 1.b. The sandwich clamp.

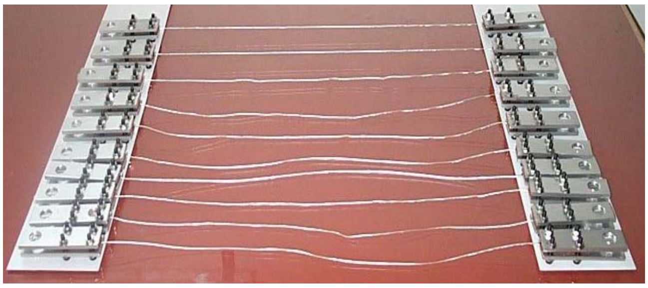

Fig. 2 A sample of HMPE creep specimens

Fig. 3 Creep rupture

The tensile tests were performed in an electromechanical test machine, EMIC model DL 2000, with special pneumatic clamps for yarn tests, with a 1 kN capability load cell, as shown in fig.a. The tests were performed in an atmosphere controlled room, with the following environmental conditions: 55 ± 2% of humidity and 20 ± 2º C temperature. Considering the final strain and the total machine displacement, for the tests of the HMPE multi-filaments (ISO 2062, 1993) it was used as an initial measuring length 500 ± 1mm and a test speed of 250 mm/min.

In the long term creep tests constant loads of 15 and 30% of YBL have been used. Such load values were used to represent the load conditions that a synthetic mooring line, a Taut-leg kind, can face in operation. For a storm condition, the maximum solicitation of a mooring line shouldn't exceed 30% of MBL (Minimum Break Load) of the rope. And for normal work conditions, the rope solicitation should be at least 15% of the MBL of the rope. During the creep test, the material under constant solicitation has successive reduction in its mechanical strength due an internal damage process resulting in length changes. In this way, it is interesting to analyze the creep phenomenon for the largest amount of time that would be possible. In the creep behavior evaluation of the researched HMPE fibers, it has been performed long-term tests in a "Dead weight device. For these tests the specimens were arranged with the length of 1000 mm, within its terminations, and the distance between measurement marks (Lo) was 900±1mm, 50mm adjacent to each termination. The elongation was taken as being the difference between the positions of the two measurement marks.

In the creep rupture test, testing loads corresponding to 60, 70, 75, 80, 85, and 90% of the mean rupture load of the material are adopted with an initial load rate of 500N/min. The effective length of a creep specimen was taken considering the distance between the faces of the clamps when was applied a pretension of 1 N (ASTM D885 (1998)). For all specimens was applied this pretension to obtain an initial length of 500±1mm.

The stress σ at a given instant t can be defined as the rate between the applied tensile force $F(t)$ and the average yarn fibre area A_o

$$\sigma(t) = \frac{F(t)}{A_o} \ ; \ A_o = \frac{\rho_l}{\rho} \Rightarrow \sigma(t) = F(t)\left(\frac{\rho}{\rho_l}\right) \tag{1}$$

where ρ_l is the mass of fibre per unit length and ρ the mass density of fibre material. Since the mass density ρ is the same for a given polymer material, to define the stress of a general yarn regardless the number of fibres it is only necessary to consider the tensile force F divided by the mass of fibre per unit length ρ_l:

$$\hat{\sigma}(t) = \frac{\sigma(t)}{\rho} = \frac{F}{\rho_l} \tag{2}$$

The HMPE multi-filaments tested in this work have linear weight ρ_l = 1760 dtex (where 1 dtex = 1 g /10000m). dtex is the most used unit for linear density of a yarn in textile industry and hence it will be adopted on the present study. Each specimen with initial length L_o = 500 ± 1mm was initially loaded at a rate α = 8, 3 N/sec until a limit constant load F_O. Fig, 4 shows the typical loading history the specimens are submitted to.

The strain ε at a given instant t can be defined as the rate between the elongation $\delta(t)$ and the initial length L_o

$$\varepsilon(t) = \frac{\delta(t)}{L_o} \tag{3}$$

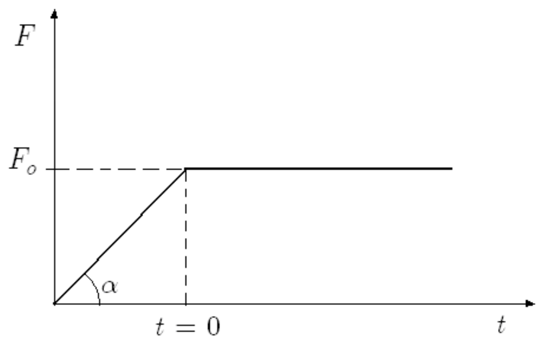

Figure 4: Typical loading history in a long term creep test

3. RESULTS AND DISCUSSION

3.1. Creep testing - Elongation curves at different load levels

Fig. 5 shows experimental creep curves at different load levels (level 1: F_o = 86, 3 N; level 2: F_o = 172, 6 N; level 3: F_o = 345, 3 N; level 4: F_o = 374 N; level 5: F_o = 402, 7 N; level 6: F_o = 431, 5 N). The rupture force in a tensile test with prescribed load history $F(t) = \alpha t$ is dependent of the rate α. For a rate α = 8, 3 N/sec, the average rupture force $\left(F_r / \rho_l\right)$ is 573, 3 N (hence the rupture stress $\hat{\sigma}_r$ for any multi-filament of this particular HMPE is given by $\left(F_r / \rho_l\right)$ = 575, 3/1760 $\approx$ 0, 33 N/dtex). The load levels correspond, respectively, to 15%, 30%, 60%, 65%, 70% and 75% of the rupture force.

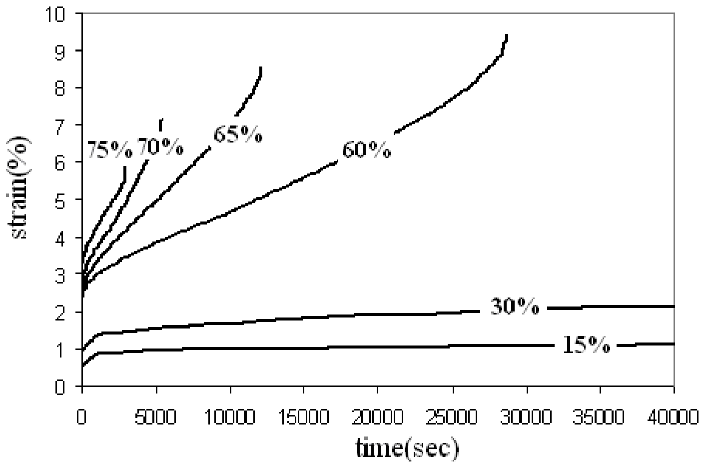

Figure 5: Experimental creep curves at different load levels.

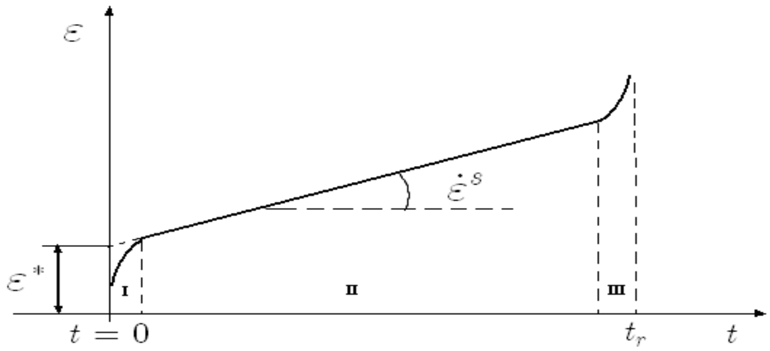

Figure 6**:** Typical experimental creep curve

From Fig. 5, it is possible to observe that a typical experimental curve shows three phases of behaviour: (i) a "primary creep phase during which hardening of the material leads to a decrease in the rate of flow which is initially very high; (ii) a "secondary" creep phase during which the rate of flow is almost constant; (iii) a "tertiary" creep phase during which the strain rate increases up to fracture (see Fig. 6).

It can be verified that the load level strongly affects the creep deformation rate and creep lifetime. Table 1 presents the experimental lifetimes obtained for different load levels. The secondary creep rates $(\dot{\varepsilon}^s)$ for different load levels are depicted in Table 2.

Table 1: Experimental creep lifetimes for different load levels. α = 8, 3 N/sec.

F_o **(N)**	t_r **(sec)**
345,3	28.710
374,0	12.162
402,7	5.425
431,5	2.935

Table 2: Experimental secondary creep rate for different load levels. α = 8, 3 N/sec

F_o **(N)**	$(\dot{\varepsilon}^s)$ **(% sec^{-1})**
86,3	0,0000014
172,6	0,000094
345,3	0,00017
374,0	0,00039
402,7	0,00058
431,5	0,00074

The strain $\varepsilon*$ (Table 3) is related to the secondary creep and depends on the loading rate α and of the maximum force level F_o.

Table 3: Experimental values of $\varepsilon*$ for different load levels. α = 8, 3 N/sec.

F_o **(N)**	$\varepsilon*$ **(%)**
86,3	0,50 1,02
172,6	0,68 1,73
345,3	0,70 2,79
374,0	0,78 3,05
402,7	0,74 3,18
431,5	0,75 3,37

3.2. Modelling

In this paper, in order to provide a better understanding of the results from creep tests, a simple one-dimensional model is proposed. The main goal is to present model equations that combine enough mathematical simplicity to allow their usage in engineering problems with the capability of describing a complex non-linear mechanical behaviour. All the proposed equations can be developed from thermodynamic arguments similar to Sampaio et al (2004) and Costa-Mattos (2008) that will not be discussed on this paper.

In order to build the model, it is considered as a system a tension specimen with gauge length L_o and a mass of fibre per unit length ρ_l submitted to a prescribed elongation $\delta(t)$. The following model is proposed to describe the creep damage behaviour of HMPE multi filaments:

$$F_o = (1 - D)\,\rho_l E\,(\varepsilon - \varepsilon_v) \tag{4}$$

$$\frac{d\varepsilon_v}{dt} = K\left[\exp\left(\frac{NF_o}{\rho_l}\right) - 1\right]; \quad \varepsilon_v(t=0) = \varepsilon* = \frac{F_o}{\rho_l E} + \left(\frac{aF_o}{\rho_l}\right)^b \tag{5}$$

$$\frac{dD}{dt} = \left(\frac{SF_o}{\rho_l(1 - D)}\right)^R ; \ D(t = 0) = 0 \tag{6}$$

where the variables ε, ε_v are defined as follows

$$\varepsilon = (\delta / L_o); \ \varepsilon_v = (\delta_v / L_o); \ \ \delta = \delta_e + \delta_v \tag{7}$$

with δ_e being the elastic or reversible part of δ and δ_v the irreversible parcel of δ. The basic idea is to introduce a macroscopic variable $D \in [0,1]$, related to the loss of stiffness of the specimen due to creep damage. If $D = 0$, the specimen is considered "virgin" and if $D = 1$, it can no longer resist to mechanical loading. E, K, N, S, R, a, b are material constants which depend on the material. Eq. (4) will be called the state law and Eqs. (5), (6) the evolution laws. Using boundary condition $D(t = 0) = 0$, it is possible to find the analytical solution of differential equation (6) that governs the damage evolution in a constant load (creep) test:

$$D(t) = 1 - \left[1 - \left(t\,(R+1)\left(\frac{SF_o}{\rho_l}\right)^R\right)\right]^{\frac{1}{R+1}} \tag{8}$$

Since rupture occurs when $D = 1$, it is possible to compute the time t_r until the rupture

$$D = 1 - \left(1 - \frac{t}{t_r}\right)^{\frac{1}{(R+1)}} \quad \text{with} \quad t_r = \frac{1}{R+1}\left(\frac{SF_o}{\rho_l}\right)^{-R} \tag{9}$$

From the equations here proposed it is possible to observe that during the creep test the damage variable increases slowly until almost the end of the test $(t = t_r)$ when it increases very fast until rupture $(D = 1)$, as it is shown in Fig.7.

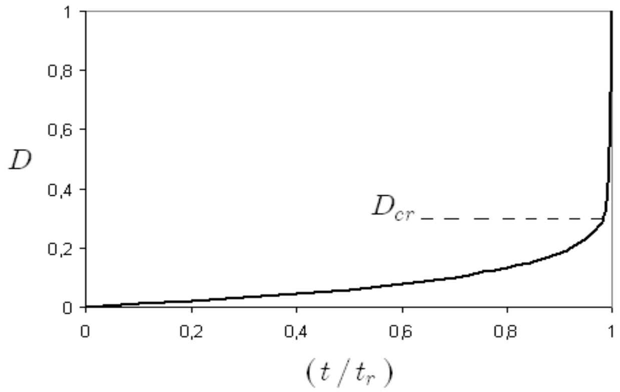

Figure 7: Damage evolution in a typical creep test.

If this kind of damage behaviour is observed, it is usual to consider a critical value D_{cr} of the damage variable, beyond which the evolution to the value toward $D = 1$ is so fast that it can be considered instantaneous. If, in a conservative approach, the failure is considered to occur when $D = D_{cr}$, the following expression is obtained

$$D = 1 - \left[1 - \left(\frac{t}{t_{cr} + \frac{(1 + D_{cr})^{R+1}}{R+1}\left(\frac{SF_o}{\rho_l}\right)^{-R}}\right)\right]^{\frac{1}{R+1}} \quad \text{with} \quad t_{cr} = \frac{1 - (1 - D_{cr})^{R+1}}{R+1}\left(\frac{SF_o}{\rho_l}\right)^{-R} \tag{10}$$

From Eq. (9) or (10), the curves of the damage evolution for creep tests under different conditions may be obtained. Examples of these curves are shown in the next section. As it is shown in the next section, the secondary and tertiary stages of the creep curve are fully described by this model. In this model, important parameters, such as steady state elongation rate, and time to failure are also taken into account. The variables R and S can be identified experimentally from the lifetimes obtained in two creep tests at different load levels, since the behaviour of the $\log(t_r) \times \log(\sigma_o)$ curve is linear, as shown in Eq. (11)

$$t_r = \frac{1}{R+1}\left(\frac{SF_o}{\rho_l}\right)^{-R} = \underbrace{\left(\left(\tfrac{S}{\rho_l}\right)^{-R}\frac{1}{R+1}\right)}_{\alpha}(F_o)^{-R} \Rightarrow \quad \log(t_r) = \log(\alpha) - R\ \log(F_o) \tag{11}$$

Parameters K and N can be obtained from the secondary creep rate $(\dot{\varepsilon}^s)$. Supposing that damage is negligible at secondary creep $(D \approx 0)$ and that $\frac{d\varepsilon_v}{dt} \approx \frac{d\varepsilon}{dt} = \dot{\varepsilon}^s$ it is possible to obtain

$$\dot{\varepsilon}^s \approx K\left[\exp(\tfrac{NF_o}{\rho_l}) - 1)\right] \text{ at secondary creep} \tag{12}$$

K and N can be identified using a minimum square technique. Nevertheless, for practical purposes, it is suggested to initially consider the law $\dot{\varepsilon}^s = \hat{K}\exp(\frac{\hat{N}F_o}{\rho_l})$. $\hat{K}$ and $\hat{N}$ can be identified experimentally from the secondary creep strain rates obtained in two tests at different load levels, since the behaviour of the $\log(\dot{\varepsilon}^s) \times F_o$ curve is linear, as shown in Eq. (13)

$$\ln(\dot{\varepsilon}^s) = \ln(\hat{K}) + \left(\frac{\hat{N}}{\rho_l}\right)F_o \tag{13}$$

K and N are very close to $\hat{K}$ and $\hat{N}$, and can be approximated (from $\hat{K}$ and $\hat{N}$) using the following iterative procedure:

(a) $i = 0$
(b) $N^i = \hat{N};\ K^i = \hat{K}$;
(c) Compute K^{i+1} from $\ln(\dot{\varepsilon}^s) = \ln(K^{i+1}) + \ln\left[\exp(\frac{N^iF_o}{\rho_l}) - 1)\right]$
(d) Once K^{i+1} is known, compute N^{i+1} using $\ln(\dot{\varepsilon}^s) = \ln(K^{i+1}) + \ln\left[\exp(\frac{N^{i+1}F_o}{\rho_l}) - 1)\right]$
(e) $i = i + 1$
(f) If $i < i_{\max}$ go to (c). Else $K = K^{i+1}$ and $N = N^{i+1}$

$i_{\max}$ is the maximum allowed number of interactions (suggestion: $i_{\max} = 5$). More sophisticated convergence criteria can be adopted, but they will not be discussed on this paper.

The strain ε^* at instant $t = 0$ is supposed to be given by the following relation (Eq. 5)

$$\varepsilon^* = \underbrace{\frac{F_o}{\rho_l E}}_{elasticity} + \underbrace{\left(\frac{a}{\rho_l}\right)^b (F_o)^b}_{primary\ creep} \tag{14}$$

The first parcel is the elastic deformation the second corresponds to the inelastic deformation after primary creep. Parameters a and b can be obtained from two creep tests at different load levels, since the behaviour of the $\log(\varepsilon^*) \times \log(F_o)$ curve is linear, as shown in Eq. (15)

$$\ln\left(\varepsilon^* - \frac{F_o}{\rho_l E}\right) = b\left[\ln\left(\frac{a}{\rho_l}\right) + \left(\frac{F_o}{\rho_l}\right)\right] \tag{15}$$

An explicit analytic expression for the creep deformation can be obtained using (5) and (9). Using these equations it is possible to obtain

$$\dot{\varepsilon}_v = \frac{K}{(1-D)}\left[\exp(\frac{NF_o}{\rho_l}) - 1)\right] \Rightarrow \dot{\varepsilon}_v = \underbrace{K\left[\exp(N\sigma_o) - 1)\right]}_{\dot{\varepsilon}^s}\left(1 - \frac{t}{t_r}\right)^{-\left(\frac{1}{R+1}\right)} = \dot{\varepsilon}^s\left(1 - \frac{t}{t_r}\right)^{-\underbrace{\left(\frac{1}{R+1}\right)}_{\beta}}$$

with $\varepsilon_v\ (t = 0) = \varepsilon^*$. Hence

$$\int_{\varepsilon^*}^{\varepsilon_v} d\varepsilon_v = \int_0^t \dot{\varepsilon}^s\left(1 - \frac{t}{t_r}\right)^{-\beta} dt \Rightarrow \varepsilon_v - \varepsilon^* = \left(\frac{\dot{\varepsilon}^s t_r}{1-\beta}\right)\left[1 - \left(1 - \frac{t}{t_r}\right)^{(1-\beta)}\right] \Rightarrow$$

$$\varepsilon_v = \left(\frac{K\left[\exp(N\sigma_o)-1)\right]t_r}{1-\beta}\right)\left[1-\left(1-\frac{t}{t_r}\right)^{(1-\beta)}\right]+\varepsilon *$$

Finally, using (4), the following expression is obtained:

$$\varepsilon = \frac{F_o}{(1-D)\rho_l E}+\varepsilon_v \Rightarrow \varepsilon = \frac{F_o}{\rho_l E}\left(1-\frac{t}{t_r}\right)^{-\beta}+\left(\frac{K\left[\exp(\frac{NF_o}{\rho_l})-1)\right]t_r}{1-\beta}\right)\left[1-\left(1-\frac{t}{t_r}\right)^{(1-\beta)}\right]+\frac{F_o}{\rho_l E}+\left(\frac{aF_o}{\rho_l}\right)^b \quad (16)$$

3.3. Comparison with experimental results

In order to investigate the adequacy of the model presented here, samples of HMPE multi filaments were tested and the experimental results were checked with the model. The model parameters identified experimentally at room temperature are presented in Table 4

Table 4: Model parameters (HMPE at room temperature).

$\rho_l E$ **[N]**	R [sec]	(S/ρ_l) [N^{-1}]	K [sec^{-1}]	(N/ρ_l) [N^{-1}]	(a/ρ_l) [N^{-1}]	b
165	10,314	$8{,}47\times10^{-4}$	$4{,}5\times10^{-7}$	$1{,}76\times10^{-2}$	$8{,}36\times10^{-4}$	0,26

The model prediction of secondary creep rate $\dot{\varepsilon}^s$ (Eq.12) for different load levels is presented in Fig. 8 and table 5. The predicted values $\varepsilon *$ of the deformation at the beginning of the creep test using Eq. 14 is presented in Fig. 9 and Table 6.

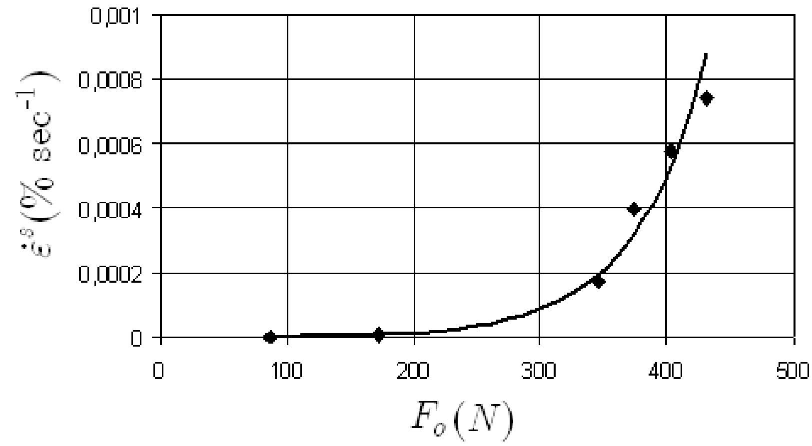

Figure 8: Secondary creep rate for different load levels. Comparison with experimental results. α = 8,3 N/sec

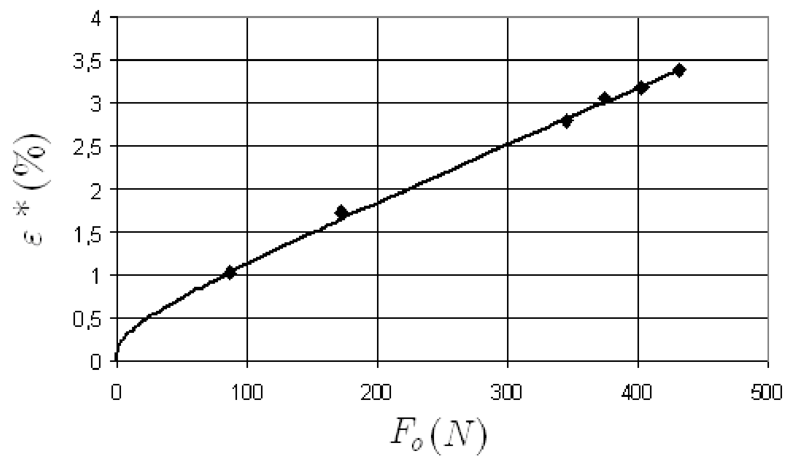

Figure 9: $\varepsilon *$ for different load levels. Comparison with experimental results.

Table 5: Secondary creep rate for different load levels. α = 8, 3 N/sec

F_o **(N)**	$\dot{\varepsilon}^s$ **(% sec^{-1}) experimental**	$\dot{\varepsilon}^s$ **(% sec^{-1}) model**
86,3	0,0000014	0,0000016
172,6	0,000094	0,0000089
345,3	0,00017	0,00019
374,0	0,00039	0,00032
402,7	0,00058	0,00053
431,5	0,00074	0,00088

Table 6: ε^* for different load levels.

F_o **(N)**	ε^* **(%) experimental**	ε^* **(%) Model**
86,3	1,02	1,02
172,6	1,73	1,64
345,3	2,79	2,80
374,0	3,05	3,00
402,7	3,18	3,18
431,5	3,37	3,38

The predicted creep lifetimes for different load levels using Eq. (9) are presented in Fig. 10 and Table 7.

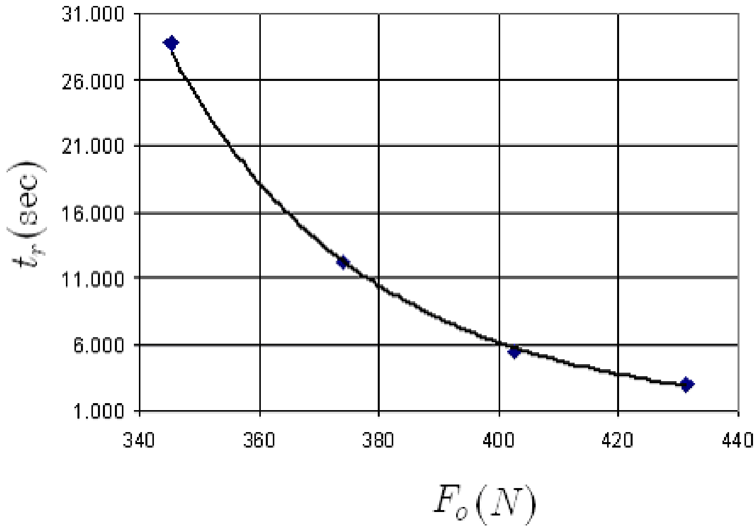

Figure 10: Creep lifetimes for different load levels. Comparison with experimental results.

Table 7: Creep lifetimes for different load levels

F_o **(N)**	t_r (sec) experimental	t_r (sec) model
345,3	28710	28346
374,0	12162	12441
402,7	5425	5803
431,5	2935	2846

Finally, Fig. 11 shows the theoretical and experimental creep curves at different load levels. The model prediction of the fracture time and elongation before rupture are in good agreement with the experimental results.

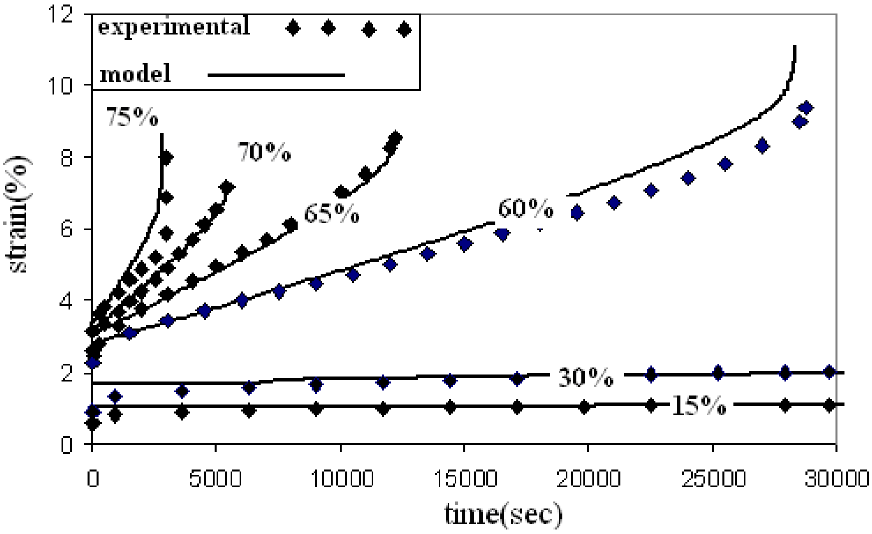

Figure 11: Creep curves at different load levels. Comparison with experimental results.

The initial stages of the creep curves are dependent on the loading history (stress and strain rates) adopted to reach the constant "initial" load F_o. Nevertheless, the final stages of the elongation-time curves (secondary and tertiary creep) seem to be little affected by this previous loading history.

4. CONCLUSIONS

The proposed model equations combine enough mathematical simplicity to allow their usage in engineering problems with the capability to perform a physically realistic description of inelastic deformation, strain hardening, strain softening, strain rate sensitivity and damage observed in creep tests performed in HMPE multi filaments at different load levels. The main idea is to use the model to obtain the maximum information about macroscopic properties of HMPE yarns from a minimum set of laboratory tests. Only two creep tests are required to identify all the other material constants (two different load levels). The agreement between theory and experiment is very good in tests performed at 15%, 30%, 60%, 65%, 70% and 75% of the rupture load.

The present paper is a step towards the modelling of creep tests in HMPE ropes using Continuum Damage Mechanics. The analysis of creep behaviour of mooring lines accounting for the different rope constructions can be extremely complex. The mechanisms proposed so far to explain the damage initiation and propagation processes are not able to elucidate all aspects of the phenomenon in different geometry/material systems. However, in normal operation conditions, the tensile load in synthetic mooring ropes should be less than 15% of the MBL (minimum break load). For a storm condition, the maximum solicitation of a mooring line should not exceed 30% of MBL. Since the loads levels are not high in operation, it may be possible to adapt the proposed theory for yarns to ropes with complex geometric arrangements. In this case, the parameters E, K, N, S, R, a, b that appear in the theory would be geometry dependent to account for different possible sub-ropes arrangements. Heating and internal abrasion certainly reduce the lifetime but can be accounted in a thermodynamic framework. However, it is important to remark that further experimental work with HMPE ropes is still required in order to fully characterize the dependency of the parameters on the geometry.

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