Applied Ocean Research 52 (2015) 234–244

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

A creep–rupture model of synthetic fiber ropes for deepwater moorings based on thermodynamics

Yushun Lian[a], Haixiao Liu[a,b,*], Wei Huang[a], Linan Li[c]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, Shanghai 200240, China
[c] School of Mechanical Engineering, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 20 September 2014
Received in revised form 18 June 2015
Accepted 19 June 2015
Available online 14 July 2015

Keywords:
Synthetic fiber rope
HMPE
Aramid
Mooring
Time-dependent
Viscoelastic property
Creep rupture
Damage model
Thermodynamics

ABSTRACT

The synthetic fiber ropes such as polyester, aramid and high modulus polyethylene (HMPE) are increasing applied to deepwater mooring systems for oil and gas exploitation. Due to that mooring ropes generally bear tensions for a long period, synthetic fiber ropes that are composed of the viscoelastic material would present creep behaviors and even the creep rupture, which is the failure mode of greatest concern especially for HMPE ropes and on which still less study can be found. A creep damage analysis of synthetic fiber ropes is of necessity to ensure the safe and economic operation of mooring systems. Therefore further investigation on the creep–rupture behavior is beneficial to fully establishing confidence in the viability of synthetic fiber ropes for deepwater moorings. In the present study, a creep–rupture model is proposed within the framework of thermodynamics to investigate the creep and damage behaviors of synthetic fiber ropes. Methods for identifying the model parameters are also proposed in detail, which apply to any component of fiber ropes such as the fiber, yarn, strand and rope. Experimental data of aramid yarns available from the literature are utilized to validate the constitutive model. Creep and creep–rupture tests of HMPE strands at different loading levels are specially performed to further examine the present model. The present work demonstrates that the proposed model can effectively describe the viscoelastic property and damage evolution of synthetic fiber ropes at different loading levels.

1. Introduction

As the offshore oil and gas explorations are moving to deeper waters, synthetic fiber ropes including polyester, aramid and high modulus polyethylene (HMPE) have become attractive as the alternatives for the steel chain and wire ropes due to their excellent properties. Synthetic fiber ropes were first proposed as mooring lines in the 1960s [1], and since then lots of studies have been conducted. In 1983, the first attempt that aramid fiber ropes are utilized as the main part of mooring lines was made, although it failed attributed to not considering the fiber axial compression fatigue [2]. Therefore, aramid fiber ropes appeared to be a good choice for deepwater moorings provided that compression loading can be avoided [3–5]. In 1992, experimental researches about the mechanical behavior of polyester ropes were first systematically performed by Del Vecchio [6]. The experimental results including dynamic stiffness, creep and fatigue of polyester ropes made great contribution to the application of polyester ropes for deep water moorings. In 1997, Petrobras installed the first polyester mooring system in the Campos Basin, offshore Brazil [7]. After that polyester ropes have become the preferred option for depths down to 1500 m. However, with numerous discoveries of natural resources in deeper waters, the question of whether polyester ropes can be utilized and provide enough stiffness to maintain acceptable platform offsets at all depths has been raised. Based on the fact that aramid and HMPE fiber ropes have shown higher stiffness than polyester ropes on the condition of equivalent minimum breaking load, they are considered as alternatives to polyester ropes [5,8–10]. However, compared to polyester, HMPE has a lower break extension, easier creep failure and a higher modulus which will cause a larger cyclic load range in storm. Considering the above factors, a preferred hybrid rope configuration has been proposed. This configuration is to use the stiffer HMPE rope in cooler water closer to the seabed and the polyester rope in warmer water closer to the vessel or platform. Hybrid mooring lines can provide the stiffness needed to handle maximum loads during station-keeping in storm, while ensuring sufficient elasticity to damp peak loads induced by waves [11,12].

To ensure effective and safe operation of these mooring systems, investigating the creep mechanism of synthetic fiber rope is of great necessity. For polyester and aramid mooring systems

* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China. Tel.: +86 2227401510; fax: +86 2227401510.
E-mail address: liuhx@tju.edu.cn (H. Liu).

0141-1187/$ – see front matter © 2015 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2015.06.009

Nomenclature

t	time
t_1	creep time
t_r	total time of the creep rupture
$\varepsilon(t)$	total axial strain at time t
$\varepsilon_{ve}(t)$	recoverable viscoelastic strain at time t
$\sigma(t), \sigma_{ij}$	actual or nominal stress
$\overline{\sigma}(t), \overline{\sigma_{ij}}$	effective (undamage) stress
ρ	mass density
η	specific entropy
φ	Helmholtz free energy
q	heat flux vector
T	temperature
$\bar{\xi}^{(m)}(m = 1, \cdots, M_{\text{int}}^{ve};\ M_{\text{int}}^{ve} \geq 1)$	viscoelastic internal state variables
$\bar{Q}^{(m)}$	thermodynamic conjugate forces associated with the viscoelastic internal state variables
Y	damage force
σ_c	constant stress
g_0, g_1, g_2	viscoelastic nonlinear parameters
a_σ	time scaling parameter
D_0	instantaneous creep compliances
ΔD	transient creep compliances
ψ	reduced time
D_n, λ_n	Prony series' coefficients
ϕ	damage scalar
ϕ_{cr}	critical value of damage scalar
t_{cr}	critical time of damage scalar
ψ_d	damage 'continuity' scalar
A, R	creep damage coefficients
E_0	Young's modulus of elasticity
R_v	the triaxiality function
σ_{eq}	the Von Mises equivalent stress
σ_{ij}^D	deviatoric stress
σ_H	hydrostatic stress

designed to API 2SK safety factors, creep failure is not a typical design issue in the intact mooring condition [7]. However, for conditions which result in high fiber loads (greater than 70% of the fiber break strength) for a long duration, creep failure can be a concern [13]. Especially for HMPE ropes, the creep rupture is the failure mode of greatest concern [14]. Developing a creep damage analytical model that can accurately predict the creep and rupture behaviors of synthetic fiber ropes is desirable for engineering.

Synthetic fiber ropes are typically composed of many levels of components such as the fiber, textile yarn, rope yarn, strand and rope. When a constant load is applied to a tensile specimen which can be any components of fiber ropes, the creep–rupture curve including primary, secondary and tertiary regions can be obtained, as shown in Fig. 1, which was observed by lots of researchers [10,14–20]. Even though creep rupture experiments is worthy of being systematically conducted and short-term creep behavior is not the area of main interest for mooring engineering, most researchers paid more attention to the short-term creep behavior of synthetic fiber ropes due to the cost of creep rupture tests at the normal temperature and operational load. Two methods are generally used to predict the creep behavior of synthetic fiber ropes. One is by predicting the creep rate. For example, Jacobs [21] developed a two-process creep rate model to describe the primary and secondary creep of HMPE yarns. Based on Jacobs's work, Vlasblom and Bosman [17] presented an updated model seeking to accurately predict the creep rate, but the tertiary creep of HMPE fiber ropes was still not modeled. The other is by directly

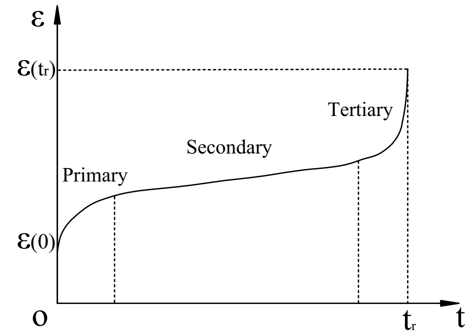

Fig. 1. A typical strain–time curve in creep–rupture tests.

computing the creep strain. Chailleux and Davies [4,22,23] primarily proposed a quantitative macroscopic model which combines the Schapery's viscoelastic with Perzyna's viscoplastic models to predict the creep–recovery and long-term creep behaviors of synthetic mooring lines, and the predictions accorded well with the creep and recovery loading test results. Derombise et al. [24] proposed a nonlinear model to describe the time-dependent and aging effect properties of aramid fibers based on the formulation by Chailleux and Davies. Huang et al. [25] presented a nonlinear constitutive model combining the Schapery's viscoelastic theory with the Owen's viscoplastic model to capture the creep and recovery behaviors of synthetic fiber ropes.

To sum up, these constitutive models could accurately describe the phenomena of initial and secondary creep, while they are not well enough to describe the tertiary creep of fiber ropes. In terms of creep failure time, Huntley and Whitehill [26] found that the failure time of polyester ropes correlates well with that of polyester yarns under constant load. Bosman [27] proposed a test method to measure the assured residual life span of a mooring rope by utilizing a creep test. Bradon and Chaplin [28] evaluated the residual creep life of polyester mooring ropes by utilizing the ARELIS (Assured Residual Life Span) method and developed a statistical model to quantify the uncertainties of this method. An empirical model to describe the time-dependent creep failure of synthetic fiber ropes was proposed by Giannopoulos and Burgoyne [18]. This model has a simple expression that can predict the time to failure under a given load, but it cannot describe the whole creep process. It should be noted that, the main limitation of above models is lack of introducing the damage variable and damage evolution law. This damage variable was originally proposed by Kachanov [29,30] in 1958 to account for the damage evolution of metals under a constant load, which laid the foundation of continuum damage mechanics. Karayaka et al. [31] initially presented an idea of adopting continuum damage mechanics to account for the long-term performance of synthetic mooring ropes due to the interaction between creep and fatigue. However, they did not propose a model that can quantitatively compute the damage value of ropes. To address the issue of degradation of rope properties, a reliable computational damage model was proposed by Beltran et al. [32] and Beltran and Williamson [33–36], yet it was not utilized to capture the creep–rupture behavior of synthetic fiber ropes. Although the literature in developing thermodynamic based constitutive models for materials including metals, polymers and asphalt mixes is rather mature and rich [37], few attempts are available for developing such constitutive models for synthetic fiber ropes. da Costa Mattos and Chimisso [20] first proposed a mathematical model to quantitatively describe the creep tests of HMPE fiber yarns based on the thermodynamic framework. However the primary creep is neglected in the model, which means that the model still needs to be improved. To enhance the knowledge of the whole creep process of synthetic