Applied Ocean Research 39 (2012) 113–120

Contents lists available at SciVerse ScienceDirect

Applied Ocean Research

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

Modeling nonlinear creep and recovery behaviors of synthetic fiber ropes for deepwater moorings

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

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[b] School of Mechanical Engineering, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 6 June 2012
Received in revised form 19 September 2012
Accepted 22 October 2012

Keywords:
Synthetic fiber rope
Mooring
Aramid
Polyester
Time-dependent
Nonlinear
Creep
Recovery
Viscoelasticity
Viscoplasticity

ABSTRACT

The synthetic fiber ropes such as the aramid and polyester ones applied to deepwater mooring systems always exhibit obvious time-dependent like creep and recovery behaviors due to the viscoelasticity and viscoplasticity of the materials, which affect not only the modulus evolution of mooring ropes but also the dynamic response and fatigue performance of the taut-wire mooring system. In the present work, the Schapery's theory combined with Owen's one-dimensional rheological model is proposed to describe both viscoelastic and viscoplastic behaviors of the aramid and polyester fiber ropes. In the viscoelastic part, the Prony series is chosen to describe the transient compliance, which is more accurate than other functions especially under complex loadings; in the viscoplastic part, the adopted viscoplastic function is more suitable for the strain hardening behaviors and the stable state of the materials under variable stress levels. Detailed methods for identifying the model parameters are proposed, which can be applied to any component of the fiber rope such as the fiber, yarn, sub-rope and rope. The present model is capable of quantitatively capturing the change-in-length properties of fiber ropes reported by Flory et al., and can be easily incorporated in the commercial software for mooring analysis. In order to examine the feasibility and precision of the model, the viscoelastic and viscoplastic strains are calculated and compared with experimental and other numerical simulation results. It is observed that there is a good agreement between the predicted and experimental data, and the physically irrational results caused by the key parameter D_P previously noticed by Chailleux and Davies can be well eliminated. The present model provides a better tool to further understand the nonlinear behaviors of synthetic fiber ropes for deepwater moorings.

1. Introduction

Due to the increasing exploration of oil and gas in deep waters, synthetic fiber materials including polyester, polyamide, aramid and high modulus polyethylene (HMPE) have become attractive as the alternatives for the steel chain and wire ropes because of their advantages such as weight saving, smaller footprint and easier storage and installation. Since 1980s, serious consideration of synthetic mooring lines have begun with trial use of aramid fiber ropes [1]. After a period of research and development, nearly during 1990s, polyester ropes emerged as the leading method of minimizing the weight of the taut-wire mooring system while retaining acceptable station-keeping performance [2]. However, they are not perfect due to the complicated mechanical behaviors different to the linear elasticity of the steel materials. Their load-elongation characteristics are time-dependent and nonlinear, which are mainly caused by the polymeric nature of the fibers and the geometry construction mode of the ropes [3].

A number of investigators have studied the load-elongation characteristics and modulus behaviors of synthetic fiber ropes. It was demonstrated that they are strain hardening materials and the stiffness will become stable after a certain number of cycles of loading [4–15]. It should also be noted that an increasing elongation with time under loading, i.e., creep, may happen due to the viscoelastic and viscoplastic properties of the material. This may influence not only the modulus evolution and hysteresis behaviors but also the long term fatigue performance of synthetic fiber ropes. Strictly speaking, creep can not be ignored in the analysis and design of station-keeping systems. On the other hand, it was noticed by investigators that the creep behavior made the analysis of polyester ropes more difficult [16]. However, unlike the study of stable dynamic stiffness, the relative studies of modeling the creep behavior of fiber ropes are limited. Baltussen and Northolt studied the deformation mechanisms of polymer fibers and a continuous chain model developed for describing the tensile deformation of fibers was extended to include the creep behavior in a microcosmic way [17–19]. Chailleux and Davies proposed a nonlinear viscoelastic viscoplastic model to describe the creep–recovery response of the aramid and polyester fiber yarns [3,20], which was the first macroscopic quantitative model for

---

[*] Corresponding author. Tel.: +86 2227401510.
E-mail address: liuhx@tju.edu.cn (H. Liu).

0141-1187/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2012.10.004

Nomenclature

t	time
t_1	creep time
t_2	total time of the creep and recovery
t_e	effective time when the plastic deformation starts
$\varepsilon(t)$	total axial strain at time t
$\varepsilon_c\,(0)$	creep viscoelastic strain at time 0
$\varepsilon_c\,(t_1)$	creep strain just before the time t_1
$\varepsilon_r\,(t_1)$	recovery strain just after the time t_1
$\varepsilon_{ve}(t)$	recoverable viscoelastic strain at time t
$\varepsilon_{vp}\,(t)$	irrecoverable viscoplastic strain at time t
$\varepsilon_{vp}(t_1)$	irrecoverable viscoplastic strain at time t_1
$\Delta\varepsilon_{vp}$	viscoplastic strain increment
$\sigma(t)$	stress at time t
σ_c	constant stress
σ_Y	yield stress
σ_Y^0	initial yield stress
g_0	non-linear instantaneous elastic compliance
g_1	transient creep parameter which measures the non-linearity effect in the transient compliance
g_2	load rate effect on the creep response
a_σ	time scaling parameter
D_P	plasticity rate
p	instantaneous plasticity factor
a	expression of σ_c/E_p
E_p	elastic modulus of the linear spring
η_p	viscosity coefficient
H	hardening parameter
D_0	instantaneous creep compliance
D_1	creep rate
ΔD	transient creep compliances
ψ	reduced time
D_n	the nth coefficient of the Prony series
N	number of the terms in the Prony series
λ_n	the nth reciprocal of retardation time

describing both the creep and recovery strains of mooring ropes. A spring-dashpot-ratchet model was proposed by Flory et al. to represent the change-in-length properties of polyester fiber ropes and the creep was represented by a dashpot [21,22], but these models were still physical ones and only used for qualitative analysis. François and Davies [23] defined a "quasi-static stiffness" in order to empirically evaluate and model the viscoelastic response of the ropes, and figured out that a true "time domain" rheological model would require further effort.

Obviously, neither the model for microcosmically modeling the creep of fibers nor the qualitative model of the change-in-length properties of fiber ropes can be adopted in analyzing the creep behaviors of fiber mooring ropes. In fact, the viscoplastic strain of fiber ropes cannot be ignored and even needs to be precisely evaluated in the design and analysis of taut-wire mooring systems. For more nonlinear synthetic fiber ropes like polyester, the influence of the viscoplastic strain will be more significant. Although the model of Chailleux and Davies is quantitative to describe both the viscoelastic and viscoplastic strains of fiber ropes, there is still a necessity to be improved. It is observed that the logarithm representing the transient compliance in the viscoelastic function is too simple and might lead to inaccurate analysis under more complex loading conditions; the key parameter D_P in the viscoplastic function would lead to physically irrational results, as demonstrated later. Hence, a more rational and accurate model for capturing the creep and recovery behaviors of fiber ropes is meaningful to be developed.

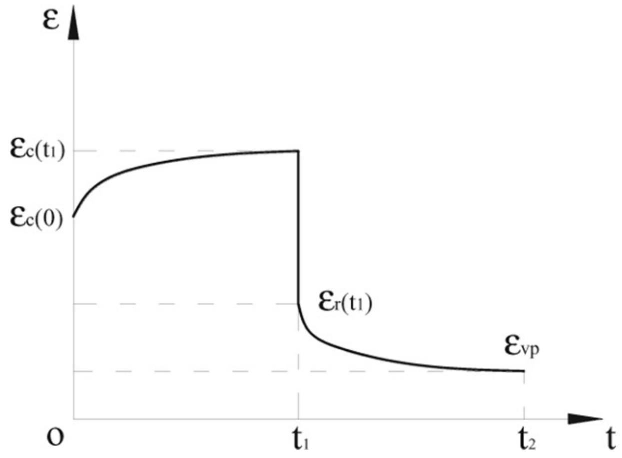

Fig. 1. A typical strain–time curve for a creep and recovery test.

In the present work, a nonlinear constitutive model combining the nonlinear viscoelastic Schapery's theory [24,25] and a viscoplastic spring-dashpot-slider model [26] is proposed. Note that the Schapery's model is just like a spring connecting a generalized Kelvin model which is constitutive of springs and dashpots. Therefore, this model is very similar to the physical unit model mentioned by Flory et al. [21,22], which can be used not only as the qualitative explanation of the mechanical behaviors of synthetic fiber ropes under complicated loading history but also as a quantitative analytical tool. Besides, this model can also be extended to the cases describing nonlinear cyclic behaviors under more complicated loading conditions. In the viscoelastic part, the Prony series is chosen to describe the transient compliance, which is more accurate than other functions especially under complex loadings; in the viscoplastic part, the adopted viscoplastic function is more suitable for the strain hardening behaviors and the nearly stable state of the materials under variable stress levels. Detailed methods for identifying the parameters of the model are suggested and demonstrated. Finally, the feasibility and precision of the present model are examined by comparing the viscoelastic and viscoplastic strains of aramid and polyester fiber yarns with experimental and other numerical simulation results.

2. The constitutive model

In this section, a combined constitutive model is proposed to take account of the nonlinear viscoelastic and viscoplastic behaviors of synthetic fiber ropes. The Schapery's single integral constitutive model is employed to describe the viscoelastic behavior and a one-dimensional dashpot-slider-spring model is employed to represent the viscoplastic behavior. It is assumed that the total strain $\varepsilon(t)$ of the fiber rope can be divided into two parts, i.e., $\varepsilon_{ve}(t)$, which represents the viscoelastic strain, and $\varepsilon_{vp}(t)$, which represents the viscoplastic strain. Therefore, the total strain can be written as

$$\varepsilon\,(t) = \varepsilon_{ve}\,(t) + \varepsilon_{vp}\,(t) \tag{1}$$

A typical creep and recovery strain–time curve is shown in Fig. 1, where $\varepsilon_c(0)$ denotes the initial creep strain when the load begins to act on the rope, $\varepsilon_c(t_1)$ denotes the creep strain just before the recovery process begins, $\varepsilon_r(t_1)$ denotes the recovery strain just after the recovery process, and ε_{vp} is the viscoplastic strain at t_2 which is the end of the recovery process.