International Journal of Mechanical Sciences 131–132 (2017) 971–981

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

An innovative approach for numerical simulation of stress relaxation of structural cables

Xiaoxiang Wang[b,c], Zhihua Chen[a,b], Yujie Yu[b,*], Hongbo Liu[a,b]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin, China
[b] Department of Civil Engineering, Tianjin University, Tianjin, China
[c] Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY, USA

ARTICLE INFO

Keywords:
Stress relaxation
Finite element modeling
Steel wire
Semi-parallel wire strands
Spiral strands
Cable supported structure

ABSTRACT

Relaxation test on cable with large diameter is usually difficult and money consuming due to its extremely large ultimate tensile strength. A simplified finite element modeling method for stress relaxation simulation of steel wire, semi-parallel wire strands and spiral strands was proposed. Simplified relationship between stress relaxation and creep of steel wires was derived and a simplified modeling method on spiral wire composition was proposed. The whole numerical approach incorporated the steel wire creep model and the simplified cable compositions to realize the simulation of stress relaxation behavior of structural cables. The effectiveness of proposed creep calibration and cable stress relaxation simulations were verified through relaxation test data of single-wires and 19-wire semi-parallel wire strands. The 19-wire, 37-wire, 61-wire, 91-wire and 127-wire semi-parallel wire strands and spiral strands at different initial stress levels were all simulated. Due to the spiral wire composition and corresponding gradient wire stress distribution under axial tension, relaxation rate of semi-parallel wire strands and spiral strands were all larger than that of single steel wire. Semi-parallel wire strands presented a decreasing relaxation rate with the increase of cable dimension. Spiral strands had larger relaxation rate than similar-sized semi-parallel wire strands, and present a slight relaxation increase trend with cable dimension. The proposed finite element modeling method can realize the stress relaxation analysis of large diameter structural cables, with only stress relaxation test data of single wires or small diameter cables.

1. Introduction

Cables are widely used in various engineering projects, especially in bridges and cable supported structures. As a key structural component, cables generally play a key role on structural stiffness and load bearing ability, and are usually subjected to long-term large tension loads during the in-service state with the internal stress sometimes being able to reach as high as 900 MPa. This long-term loading process can cause stress relaxation and creep phenomenon that would lead to gradual decrease on cable forces. Then this cable degradation phenomenon would further lead to additional structural deflection and stiffness decrease [1,2] or even cable slackening. Therefore, this degradation properties are quite important for tension structures or cable supported structures. Besides, with the increasing use of high-strength cables at high stress level, this time-dependent behavior gradually become an increasing concern and should be considered during the design process [3]. Stress relaxation and creep are two descriptions of the same time-dependent rheological properties of cable. Stress relaxation refers to the decrease in stress at a constant deformation. While creep is the change in cable length or geometry when the cable is held under constant stress [4]. Creep or relaxation causes changes in cable length or pretension level, which will influence member lengths and internal force in tension structures. This behavior, when interacting with other sources of time-dependent deformations, may affect the long-term structural performance, especially for pretension reinforced concrete structures [5], cable stayed bridges [6] and cable structures [7].

Due to the wide application of pre-stressed concrete structures, previous researches on creep and relaxation were mainly focused on high strength steel wires and spiral strands used for concrete reinforcement. Nakai and Tomioka [4] carried out creep and relaxation tests of single steel wires and spiral ropes, then proposed an analytical method for determining the creep strains and relaxation values of spiral ropes by considering rheological properties of single wires. Sinha and Levinson [8] performed stress relaxation tests on ASTM A228 steel wire with vibrating string technique, and found that the stress relaxation had a faster rate during early stage and a slower rate in later time duration. Zeren et al. [9] conducted experimental study on carbon steel wires with 8 mm diameter which were particularly used in pre-stressed concrete

* Corresponding author at: Department of Civil Engineering, Tianjin University, Tianjin, China.
E-mail address: yujietju@tju.edu.cn (Y. Yu).

http://dx.doi.org/10.1016/j.ijmecsci.2017.08.011
Received 8 May 2017; Received in revised form 10 July 2017; Accepted 5 August 2017
Available online 12 August 2017
0020-7403/© 2017 Elsevier Ltd. All rights reserved.

composites to study the effect of thermomechanical heat treatment on relaxation behavior. These previous researches on wires and simple strands were essentially important for understanding the rheological properties.

While due to the advent and rapid development of large diameter high strength strands and wire ropes, and their application on large span bridges or cable supported structures, this time dependent behavior and its effect to structures become more complicated [10]. Kaci [11] investigated relaxation properties of composite cables made out of Kevlar cords impregnated with a thermosetting resin for their possible use as pre-stressing tendons. Conway and Costello [12] presented a theoretical method that the axial viscoelastic response of a simple strand can be calculated with the stress relaxation material properties of constituent filament. However, early analyses and rheological models were based on linear creep theory with linear viscoelastic material properties of cable. Kmet and Holickova [13] once derived a non-linear relaxation (or creep) constitutive equations for strand cables under various tension structural elements, and then verified the effectiveness of proposed equations on a spiral strand rope example. Ivanco et al. [14] studied relaxation (or creep) of 1×7 and 1×19 steel spiral strands numerically and claim that rheological properties of spiral strands were closely related to clearance between wire layers. But previous tests and researches were still focused on small diameter strands.

The stress relaxation test for a specimen usually costs 120 h or longer [15–17]. However, it is not always feasible to perform such tests in such long time-periods. Besides, steel cables used in engineering projects generally have large diameters which require extremely high loading abilities on relaxation test machines. Whereas commonly used cable relaxation machines are only capable of testing small diameter cable specimens, then the relaxation properties of large diameter cables are hard to obtain. Therefore, stress relaxation tests on large diameter cables are rare and related researches and references are also limited. Many discrete numerical models and finite element approaches have been developed for strands and multi-layer steel wire ropes [18–21], but most models were used for static behaviors in longitudinal and lateral directions, neglecting the nonlinear relaxation effects. Since relaxation behaviors of strands and ropes play significant roles at design stage and degradation evaluation of cables, an appropriate computational model for cable rheological behavior is necessary.

The parallel/semi-parallel wire strands and spiral strands are the main cable types in tension structures, which are all composed of steel wires. For parallel wire strands, constituent wires lay in parallel with the central axis of cable, and therefore the relaxation property of parallel wire strands can be regarded as the same with that of single steel wire. However, for semi-parallel wire strands and spiral strands, constituent wires are helically wrapped toward the same or opposite direction around the core wire, which causes different relaxation rates between the whole cable and single wire. Stress relaxation test for a single wire is mature, therefore it is significant if the relaxation rate of large diameter cables can be derived from the test data of single wire. Then in this paper, a simplified novel finite element modeling method for the stress relaxation analysis and degradation behaviors of structural cables was proposed, which is especially suitable for semi-parallel wire strands and spiral strands. Effectiveness of developed models were validated with the stress relaxation test data of single wires and 19-wire semi-parallel wire strands. Then the model was further used to simulate stress relaxation and degradation behaviors of a wide range of semi-parallel wire strands and spiral strands that from 19-wire to 127-wires.

2. Basis of cable stress relaxation modeling method

2.1. Basic concept of large diameter structural cable stress relaxation simulation

Stress relaxation and creep are both resulted from the dislocation of crystal lattice, atomic diffusion and grain boundary sliding, and they are both associated with temperature changes. While for structural wires or cables, which generally possess high strength and elastic modulus, a slight length change can induce huge internal force variations. Stress variations and degradations are more important for structural cables like semi-parallel wire strands and spiral strands, and the stress relaxation rate is the criteria factor index for this time-dependent property. While in material science, this rheological characteristic is often described by creep, and is already incorporated into several analyzing software like ABAQUS and ANSYS. In this study, a simplified method was proposed, which synthesized creep rheological description from steel wire material input with the 3-dimentional modeling of spiral compositions, to establish the cable stress relaxation simulations and to investigate the corresponding degradation behaviors.

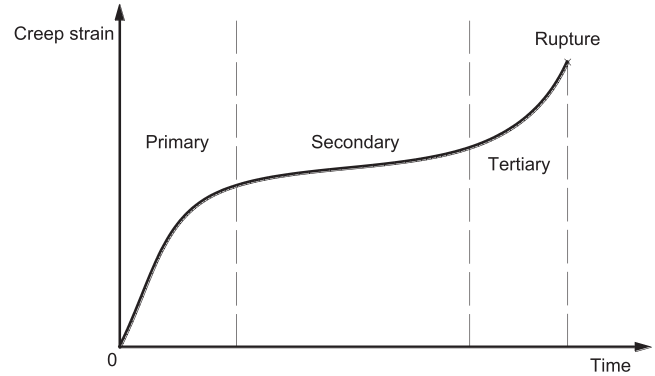

Fig. 1. Typical creep strain versus time curve.

2.2. Relation between stress relaxation and creep

Usually, relaxation rate R is used to indicate the relaxation extent of cables. Given initial stress σ_0 and reduced stress σ_1 caused by relaxation loss, relaxation rate can be calculated through Eq. (1). This factor is often obtained through relaxation test of 60 h, 120 h or longer, and the obtained data is then used to predict relaxation rate of 1000 h or life time rate.

$$R = \sigma_1 / \sigma_0 \tag{1}$$

The typical creep strain versus time curve of metal at constant load over sufficiently long time periods usually has three characteristic stages, which are primary or transient creep, secondary or steady-state creep, and tertiary creep stages [14], as shown in Fig. 1. In tertiary creep stage, the creep strain rate will grow rapidly and tested metals can no longer withstand the load and rupture in the end. Since in practical engineering projects, cables are almost impossible to bear loads that approaching their ultimate strength. Then only primary and secondary stage of creep were considered in this study and the corresponding stress relaxation rate curve is presented in Fig. 2.

The proposed cable relaxation simulation needs the rheological property of steel wires. The basic material input is based on standard stress relaxation test data, but in ANYSY this rheological property is defined in the form of creep. Therefore, a transformation process is needed to derive the creep strain-time relation based on the relaxation rate versus time curves from experimental test.

Given a measured relaxation rate-time relation $R(t)$, which is a time dependent value that represents stress relaxation rate $R(t)$ at t moment. Then according to Eq. (1), the reduced stress $\sigma_1(t)$ caused by relaxation loss at time t can be obtained as:

$$\sigma_1(t) = R(t) \cdot \sigma_0 \tag{2}$$

Then reduced axial tension force $F_1(t)$ caused by relaxation loss, and axial tension force $F(t)$ at time t can be expressed as follows.

$$F_1(t) = \sigma_1(t) \cdot A = R(t) \cdot \sigma_0 \cdot A \tag{3}$$