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Validity and limitations of linear analytical models for steel wire strands under axial loading, using a 3D FE model

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Abstract

In the field of cable modeling, many models have been proposed to describe the mechanical behavior of simple straight strands under axial loading, and the predictions of these models have been compared to experimental data when available. However, the validity domain of these models has not been evaluated yet because the experimental results reported in the literature are very limited. This problem is addressed here, the results from nine linear elastic models of a 6+1 wire single layered strand (simple straight strand) subjected to static axial loads being compared with values from 3D finite element modeling. The analytical models are shown to give satisfactory estimations of the elastic stiffness constants for lay angles below 20°.

Keywords: Cable; Strand; Wire; Analytical model; Finite element

1. Introduction

Helically wound fibers or wires constitute a large class of important engineering components [1]. There are many kinds of such structure: one is the strand, defined as a structure made up of layers of helical wires wound around a central straight wire core. A wire rope is a structure made up of layers of strands wrapped helically around a central straight strand core. It is then possible to consider wire rope as a basic component to form a new wire rope with more complex cross section.

It is well known that a major advantage of such elements is their ability to support large axial loads with comparatively small bending or torsion stiffness. These structures play an essential role in various civil engineering applications, including the prestressing of concrete, stays for guyed masts, bridging applications such as hangers for suspension bridges as well as for mooring many offshore oil platforms.

Experimental work on large diameter cables requires specific, large and expensive testing devices. Design tools allowing rapid estimation of the overall axial elastic stiffness of stranded structures are, therefore, essential for designers. As will be detailed below, several analytical models based on different hypotheses (purely tension wires, curved beam theory, Poisson's ratio effects, friction effects and variations in core radius) have been developed and presented in the literature. However, comparisons between these models and corresponding discussion of their validity domain is not available in the literature. Nevertheless, it may be noted that the authors have usually compared their models with the experimental results reported in the earlier works. Jolicoeur and Cardou [2] compared the results obtained by several mathematical models available in the literature with the experimental 1+6 cables results reported by Utting and Jones [3,4], for six different lay angle (9.2°, 11°, 12.2°, 12.9°, 14° and 17°). Since the experimental results are very limited, obtaining a general conclusion is difficult.

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Nomenclature

R_c, R_w, R_k core, wires and wires centerline radius
k_r ratio of wire radius to core radius
α lay angle
P pitch length
A cross section area
I bending inertia modulus
J torsion inertia modulus
u_z, θ_z overall axial displacement and rotation angle
$u_{z,z}$, $\theta_{z,z}$ overall axial strain and twist angle per unit length
$u_{t,t}$ wire axial strain
$\Delta k'$, $\Delta\tau$ changes in curvature and twist per unit length in the wire
F_z, M_z overall axial force and torque
f_z, m_z non-dimensional axial force and torque
$F_b^i, F_t^i, M_b^i, M_t^i$ shear force, traction force, bending moment and torque in the ith wire
$k_{\varepsilon\varepsilon}, k_{\theta\theta}, k_{\varepsilon\theta}, k_{\theta\varepsilon}$ axial stiffness coefficients of traction, torsion and couplings
$\bar{k}_{\varepsilon\varepsilon}, \bar{k}_{\theta\theta}, \bar{k}_{\varepsilon\theta}, \bar{k}_{\theta\varepsilon}$ non-dimensional axial stiffness coefficients
E, G Young's and shear moduli
ν Poisson's ratio
$\zeta_i, \eta_i, \lambda_i, \mu_i$ Knapp's parameters [12]
Subscripts c and w refer to core and wire characteristics, respectively

The objective of the present study is to assess the validity domain of several analytical models for the elastic static axial (tension and torsion) behavior of a simple straight metallic strand (single-layered), consisting of six helical wires wrapped around a straight core. The influence of the assumptions of different analytical models will be discussed using comparisons with a complete three-dimensional (3D) formulation: a 3D finite element (FE) modeling has been used as a reference.

In Section 2, a description of the geometry of the structures studied and the corresponding axial elastic overall behavior matrix form are given. Next, the existing mechanical models assumptions and corresponding stiffness coefficient expressions are given in Section 3.

In Section 4, a 3D FE model is presented and FE results are compared with experimental data. In order to determine the validity domain, the stiffness matrix components are calculated using the selected analytical models. Then, the analytical results are compared with the FE model results, considered as a reference.

2. Strand overall behavior

Let us consider a single 6 + 1 straight strand cable made of six helical wires with a circular cross-section wrapped around a straight core as illustrated in Fig. 1. The geometry is characterized by the core radius R_c, the wires radius R_w, and the lay angle α measured with respect to the cable z-axis. The wires centerline is then a helical curve of radius R_h:

$$R_h = R_c + R_w. \tag{1}$$

It can be noted that the wire cross-sections, due to contact forces with the core, are bean-shaped but can be approximated by ellipses in the plane perpendicular to the structure z-axis (see Fig. 1). The pitch length denoted by P can be calculated using the following expression:

$$P = \frac{2\pi R_h}{\tan\alpha}. \tag{2}$$

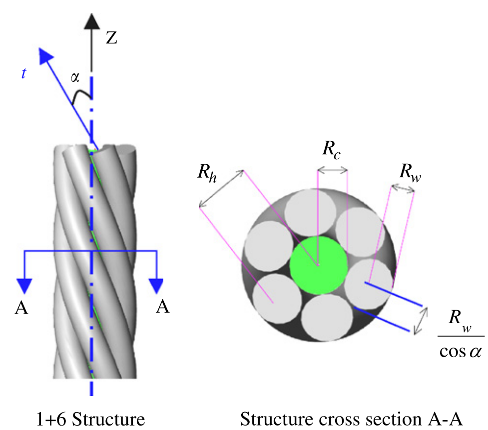

Fig. 1. Geometry of a simple straight strand or 1 + 6 structure.

The axial behavior of such a structure exhibits coupling between tension and torsion due to the helical design of the wires. Thus, the elastic overall behavior can be expressed in the form:

$$\begin{Bmatrix} F_z \\ M_z \end{Bmatrix} = \begin{bmatrix} k_{\varepsilon\varepsilon} & k_{\varepsilon\theta} \\ k_{\theta\varepsilon} & k_{\theta\theta} \end{bmatrix} \begin{Bmatrix} u_{z,z} \\ \theta_{z,z} \end{Bmatrix}, \tag{3}$$

where $u_{z,z}$ denotes the overall axial strain, $\theta_{z,z}$ the twist angle per unit length, F_z the axial force and M_z the torque. The four stiffness matrix components $k_{\varepsilon\varepsilon}$, $k_{\theta\theta}$, $k_{\theta\varepsilon}$ and $k_{\varepsilon\theta}$ are pure tensile, torsion and coupling terms, respectively. Moreover, the stiffness matrix should be symmetric, as can be shown from Betti's reciprocal theorem, cf. [5].

3. Analytical models

3.1. Overview

As previously indicated, several analytical models are available to predict the mechanical behavior of isotropic cables subjected to axial loads, based on knowledge of the component material behavior and geometry of the