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Modeling of helically stranded cables using multiple beam finite elements and its application to torque balance design

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HIGHLIGHTS

- A new FE modeling method of helically stranded cables is proposed.
- Multiple beam finite elements are adopted for the new FE modeling.
- The beam FE model is very effective in terms of accuracy and computational efficiency.
- Using the beam FE model, a practical procedure for torque balance design is presented.

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ABSTRACT

In this paper, a method for the effective modeling of helically stranded cables for which multiple beam finite elements (FE) are used is presented, and a design procedure for the torque balance of the cables using the beam FE model is proposed. Regarding the beam modeling, the wire-to-wire contacts and the elastoplastic material behavior are considered. The proposed beam model is advantageous because the accuracy of the corresponding numerical results is as good as that of the full solid FE model, while the computational cost is significantly reduced. Using the beam FE model, the mechanical behavior of helically stranded cables is analyzed under axial and transverse loadings. The numerical results are compared with those of full solid FE models and available experimental results, where accuracy and computational cost are investigated. This paper also proposes a practical procedure for torque balance design of helically stranded cables using the proposed beam FE model.

1. Introduction

Cables and ropes that consist of helically stranded wires have been used in a wide range of engineering applications, and the understanding of their mechanical behavior is a very important issue for cable designers and manufacturers; however, it is not easy to formulate accurate predictions regarding the behavior of these wires because of the corresponding complex geometry and the internal contacts that exist between the individual wires. While experimental tests are necessary for the attainment of accurate predictions (see the previous works by Utting and Jones [1–3]), laboratory experiments are typically very expensive and difficult to conduct. The analytical or numerical modeling of cables, if sufficiently accurate, can replace such costly tests, which are carried out routinely by cable manufactures, and can lead to a considerable cost reduction.

Several analytical models [4–10] that enable the prediction of the mechanical behavior of cables and ropes under various loading conditions are available. Although these analytical models are simple and easy to use, the validity of these models is limited for simple stranded cables under axial loading because of the difficulty regarding the consideration of the complicated geometry, the material, and the complex contact behavior among the individual wires; in particular, wire-to-wire contact behavior is very complicated.

The finite element analysis has been successfully used to predict the behavior of cables; in particular, full solid finite element (FE) models have been developed for which the wire-to-wire contact, the wire yielding, and various loading conditions are considered (see Refs. [11–17]). The predictive ability of the full solid FE models regarding the complicated behavior of wires are far more accurate than those of the analytical models; however, in terms

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of helically stranded cables, this kind of modeling is not trivial. All of the individual wires must be precisely placed in the FE model and must be in contact with each other without penetration to avoid the emergence of numerical instabilities during a nonlinear solution procedure; furthermore, to accurately capture the geometry of the wires and to model the complicated wire-to-wire contact conditions, very fine meshes that can incur a considerable computational cost are required.

In the cable design phase, full solid FE models are quite often the cause of a time delay that may result in losses of opportunity and profit for a new cable product. To overcome this problem, analysts have come up with strategies such as the use of coarse mesh, or even an adjustment of the element size; however, these strategies can be very labor intensive and do not always work, and this could be why the full solid FE model for analysis of helically stranded cables is a very good solution but has a limitation in applying it to cable design. Overcoming this limitation is a major interest of cable designers and manufacturers. The cable designers require a tool that is reasonably accurate and simple to use; this is especially important during the preliminary design stage of a new cable system. This outstanding need is the motivation of this work.

In this study, we propose a beam FE model for a computationally efficient prediction of the mechanical behavior of helically stranded cables whereby complicated contacts and the elastoplastic behavior of wires are included; here, the wires are modeled using beam finite elements, and the wire-to-wire contacts are modeled using beam-to-beam contacts. Compared to the solid FE models, the degrees of freedom (DOFs) are significantly reduced, but the resulting predictive capability is as good as those of the solid FE models; furthermore, a large modeling effort is saved because the beam FE model is very effective in terms of both accuracy and computational cost.

The torque balance design of cables is very important for the prevention or minimization of an undesirable twist, which is due to the coupling between the stretching and the twisting when cables are axially loaded with tension. The torque balance design generally requires a large number of torque analyses, and these must be performed accurately during the preliminary design stage. The solid FE models are proper in terms of accuracy, but the computational costs are too high; indeed, the solid models have not been used for the torque balance design of cables in engineering practice, where the use of the beam FE models can be a practical solution. In this paper, a design procedure for the achievement of the torque balance of helically stranded cables is suggested, whereby the proposed beam FE model is used.

This paper is organized as follows: The basic background theory of helically stranded cables under axial loading is introduced in Section 2; the FE models for the prediction of the mechanical behavior of the cables are presented in Section 3; in Section 4, the computational cost are investigated, and the accuracies of the FE models are verified through a comparison of the numerical results to the analytical and experimental results; a procedure for the torque balance design of the cables is proposed in Section 5; and the conclusions are given in Section 6.

2. Basic background theory

In this section, the equations regarding an understanding of basic cable mechanics under axial loading are provided, and these are also used for the comparison with numerical results.

In helically stranded cables, the kinematics of axial stretching and twisting are coupled together, and twisting can therefore occur under a pure axial loading; in such a case, it can be assumed that all of the wires in a given layer carry exactly the same loads. Global cable kinematics are designated by the cable axial strain ε and the cable twist rate $\delta\theta/h$ (twist per unit length). The linear elastic response is governed by the following equation:

$$\begin{bmatrix} F_T \\ M_T \end{bmatrix} = \begin{bmatrix} K_{\varepsilon\varepsilon} & K_{\varepsilon\theta} \\ K_{\theta\varepsilon} & K_{\theta\theta} \end{bmatrix} \begin{bmatrix} \varepsilon \\ \delta\theta/h \end{bmatrix}, \tag{1}$$

where F_T and M_T are cable axial force and cable torsion, respectively, and in the stiffness matrix components, the subscripts ε and θ denote axial stretch and twisting, respectively.

Fig. 1(a)–(c) shows the geometry of a single-layer helically-stranded cable and the developed geometry of a helical wire.

The axial strain and shear strain of the cable are given by the following equation:

$$\varepsilon = \frac{\delta h}{h}, \;\; \gamma = r\left(\frac{\delta\theta}{h}\right)\tan\alpha, \tag{2}$$

where h is cable length, r_c is core radius, r_w is wire radius, r is wire centerline radius $(r_c + r_w)$, γ is shear strain, θ is twist angle (rad), and α is helix angle. It is assumed that the axial strain is constant in both the core and the wires, and that the shear strain is constant in the wires. The shear strain is not induced in the core due to the axial loading.

In Fig. 1(c), the following relations can be established:

$$h = l\sin\alpha, \;\; r\theta = l\cos\alpha, \tag{3}$$

where l is the length of the helical wire in the developed geometry.

It is assumed that the core is rigid radially, the deformation is small, the material is linear elastic and isotropic, and the slips between the wires are ignored. The axial strain of the helical wire ε_w is then obtained by the following equation:

$$\varepsilon_w = \frac{\delta l}{l} = \varepsilon\sin^2\alpha + \gamma\cos^2\alpha. \tag{4}$$

The equilibrium equations for the resultant forces and moments can be derived for a general twisted and bent rod [5]. As shown in Fig. 1(d), s is the arc length along the wire, and F_x, F_y, and F_z are the forces acting on the wire in the x, y, and z directions, respectively. M_x and M_y are the bending moments about the x axis and y axis, respectively, and M_z is the twisting moment acting on the wire. κ_x and κ_y are the curvatures in the x and y directions, respectively, and τ is the twist per unit length.

Assuming that there is no curvature in the x direction, the changes of the curvature $\Delta\kappa_y$ and the twist $\Delta\tau$ can be calculated by the following equations, respectively:

$$\Delta\kappa_y = -\sin 2\alpha\left(\frac{\delta\alpha}{r}\right) = -\sin 2\alpha\sin\alpha\cos\alpha(\varepsilon - \gamma), \tag{5}$$

$$\Delta\tau = \delta\left(\frac{\sin\alpha\cos\alpha}{r}\right) = \cos 2\alpha\sin\alpha\cos\alpha(\varepsilon - \gamma), \tag{6}$$

and the final curvature κ_y and twist τ with their initial values κ_{y0} and τ_0 are given by

$$\kappa_y = \kappa_{y0} + \Delta\kappa = \frac{\cos^2\alpha}{r} - \sin 2\alpha\sin\alpha\cos\alpha(\varepsilon - \gamma), \tag{7}$$

$$\tau = \tau_0 + \Delta\tau = \frac{\sin\alpha\cos\alpha}{r} + \cos 2\alpha\sin\alpha\cos\alpha(\varepsilon - \gamma). \tag{8}$$

From the equilibrium equations, M_y, M_z, F_y and F_z can be simply expressed as the following formulas:

$$M_y = EI\Delta\kappa_y, \quad M_z = GJ\Delta\tau, \quad F_y = M_z\kappa_y - M_y\tau, \quad F_z = EA\varepsilon_w, \tag{9}$$

where E is the Young's modulus of the wire, I is the moment of inertia of the helical wire cross section, J is the polar moment of inertia of the helical wire cross section, and A is the cross sectional area of the helical wire.