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The establishment of a numerical model for structural cables including friction

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ABSTRACT

A friction element is presented in this paper. The element was incorporated into a simplified numerical model of cables, which were established by a beam element. A detailed numerical model was implemented based on general-purpose finite element software. Moreover, a flowchart of a numerical analysis was proposed. The accuracy of the proposed numerical model was validated by comparing the results derived in this work to the analytical results derived from Costello's theory and experimental results. The bending performance of 1×37 semi-parallel wire cables was investigated. Then, the dynamic response of cable caused by wire break was analyzed. Sensitivity analysis was conducted to investigate the influence of several factors on dynamic response. Results indicated that the friction element proposed in this paper can capture the sliding among different wires and thus can be efficiently adopted in dynamic analysis.

1. Introduction

Stranded cables are used in a wide variety of applications for structural engineering and power and signal transmissions [1]. Spiral wire rope strands are groups of wires laid helically in successive layers over a straight center wire in a regular geometric pattern to form an integral unit to provide axial strength and stiffness [2].

The cables are constantly the key components that determine the safety of the entire structures. The mechanical property of strand cables is equally complex as the existing complex interactions among cable wires. Many investigations have been conducted on the mechanical behavior of strand cables on the basis of elaborate numerical models [3,4]. Utting and Jones [5,6] developed a mathematical model of a strand to explore the change in helix angle under load, effects of Poisson ratio on wires, wire flattening under interwire pressure, and effect of friction between the core and helical wires. Nie et al. [7] proposed a cable anchorage system modeling method for self-anchored suspension bridges through multi-scale modeling technology. The cable equivalent proportional damping parameters and periodic excitation functions resulting from the crossover cable motion on the winder drum were identified in this work. Jiang proposed a concise finite element model for three-layered straight wire rope strand. However, the numerical model was still established by solid elements [2,8]. Montoya et al. [9] proposed a simplified semi-analytical contact–friction approach. Elasto-perfectly plastic springs were placed at the contact points between the wires to model the load transfer due to friction between tightened parallel steel wires. Hong et al. [10] developed a mesoscale mechanical model of the bending behavior of helically wrapped cables under tension. The model represents the nonlinear dissipative behavior of the cable arising from the slippage of wires under friction forces. Sun et al. [11,12] analyzed the effects of friction coefficient and self-rotating ratio on the contact stress based on FE simulation.

Cables are the key components of structures. Thus, many researchers have conducted investigations on this problem [13,14]. Torkar and Arzensi [15] conducted the failure analysis of a broken multi-strand wire rope from a crane. Elata et al. [16] handled the mechanical behavior of a wire rope with an independent wire rope core. In their recent work, Shen et al. [17] performed fretting wear tests on the self-made fretting wear rig to investigate the fretting wear behaviors of steel wires under friction-increasing grease conditions.

For investigations on the dynamic response of strand cables, Chen et al. [18] adopted Euler–Bernoulli beam model to develop the governing equations of the cable and considered bending stiffness to manage the low-tension problem in the local area of a towing cable. An accurate solution considered the axial elongation. Kaczmarczyk and Ostachowicz [19] proposed a simulation model that investigated the dynamic response of a deep mine hoisting cable system during a winding cycle.

Many researchers have conducted numerous works to improve the numerical model of strand cables. The present work aims to develop a

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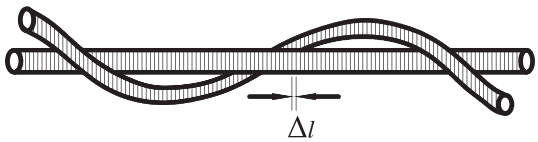

Fig. 1. Segmentation along the cable length.

numerical model based on general-purpose finite element software. The friction element that can be adopted in the dynamic analysis was proposed. The dynamic response of the cable after wire break was analyzed. In addition, the influence of friction on the bending performance of cables was investigated.

2. Establishment of a numerical model

2.1. Theoretical model of friction element

Friction occurs along the contact line of different wires. It can be influenced by normal force and friction coefficient among different wires. Contact behavior among different wires can be captured by establishing a detailed numerical model containing contact elements. However, this method requires robust computing power, and only a small numerical model can be analyzed to date. Finite element concept can be adopted to overcome this problem.

The cables can be divided into numerous segments along the cable length, and the length of each segment is Δl, as illustrated in Fig. 1. Then, the small wire segment is considered the research object. The stress diagram of one wire segment is depicted in Fig. 2.

The internal forces of a wire segment include force and moment in three orthogonality directions. In addition, the wire segment is also subjected to force from neighboring wires, including normal stress, σ_n, and friction. The friction can be decomposed into f_1 and f_2. The direction f_2 is along the cable axial direction, and f_1 is perpendicular to cable axial direction. The value of σ_n within Δl can be considered a constant. Then, normal force and friction can be derived according to Eqs. (1) and (2).

The wire segment was assumed to contact with one neighboring wire through two points. Then, the contact stress can be transformed into a contact force, as displayed in Fig. 2. Normal forces at points 1 and 2 are ${F_N}^1$ and ${F_N}^2$, respectively. The sum of the two normal forces should be equal to the original value to maintain the equilibrium condition of forces. Therefore, the right part of Eq. (1) can be derived. Then, friction forces f^1 and f^2 at points 1 and 2 can be derived, correspondingly. The friction at two contact points can be decomposed into two directions similarly. Then, Eqs. (3) and (4) can be derived.

$$\Delta F_n = \sigma_n \times \Delta l = {F_N}^1 + {F_N}^2 \tag{1}$$

$$f_1 = \mu(\sigma_n \times \Delta l) \times \cos\beta, f_2 = \mu(\sigma_n \times \Delta l) \times \cos\gamma \tag{2}$$

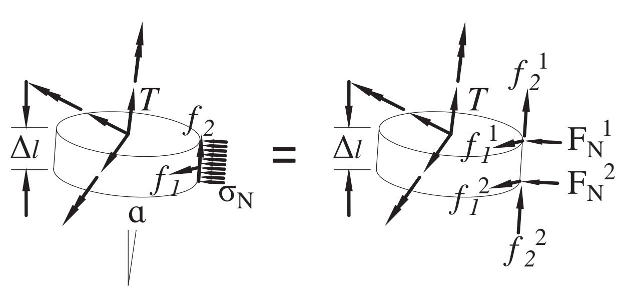

Fig. 2. Equivalent normal stress.

$${f_1}^1 = \mu {F_N}^1 \times \cos\beta, {f_2}^1 = \mu {F_N}^1 \times \cos\gamma \tag{3}$$

$${f_1}^2 = \mu {F_N}^2 \times \cos\beta, {f_2}^2 = \mu {F_N}^2 \times \cos\gamma, \tag{4}$$

where α, β, and γ are cable geometrical parameters.

Eq. (5) can be derived through Eqs. (2), (3), and (4). The equivalence of friction can be ensured. All of the contact forces can be equivalent automatically if the other forces are maintained.

$$f_1 = {f_1}^1 + {f_1}^2, f_2 = {f_2}^1 + {f_2}^2 \tag{5}$$

Two contacting surfaces can carry shear stresses in the basic Coulomb friction model. No motion occurs between the two surfaces when the equivalent shear stress is less than the limit frictional stress (f_{lim}). This state is known as sticking. The model defines an equivalent shear stress at which sliding on the face begins as a fraction of the contact pressure. The two faces will slide relatively with each other once the shear stress is exceeded. The coefficient of friction can be any non-negative value [20,21].

The Coulomb friction model is defined as.

$$f_{\text{lim}} = \mu F_n + b, \|f\| \le f_{\text{lim}}, \tag{6}$$

where f_{lim} is the limit frictional force, μ is the coefficient of friction, F_n is the contact normal force, and b is the contact cohesion. The equivalent frictional force can be defined as

$$\|f\| = \begin{cases} |f| & \text{equivalent friction for 2D contact} \\ \sqrt{{f_1}^2 + {f_2}^2} & \text{equivalent friction for 3D contact} \end{cases}, \tag{7}$$

where f_1 and f_2 are considered in the tangential contact plane between the wires. The contact and target surfaces will slide relatively with each other once the equivalent frictional stress exceeds f_{lim}. This state is known as sliding.

The normal distributed force F_n and the tangential distributed forces f_1 and f_2 exist along any line of contact among the helical wires, as presented in Fig. 3.

The adopted nonlinear friction element should capture the mechanical characteristic of friction, i.e., the friction value was relevant to frictional coefficient and normal force, and the direction of friction depends on relative motion tendency. The value of a static friction force can be determined by the equilibrium condition of forces.

The nodal displacement vector of two-node friction elements can be written as [22].

$$\{\delta\}^T = \{u_i, v_i, w_i, u_j, v_j, w_j\}. \tag{8}$$

If θ_1, θ_2, and θ_3 are the angles of friction element with global coordinate system after deformation, then

$$\cos\theta_k = (x_{ik} + u_{ik} - x_{jk} - u_{jk})/L, k = 1, 2, 3, \tag{9}$$

where L is the length of friction element after deformation.

The internal force F of a spring element can be derived according to the predefined load–deflection curve.

The friction can be decomposed along a coordinate axis.

$$F_{ik} = -\cos\theta_k, F_{jk} = -\cos\theta_k, k = 1, 2, 3 \tag{10}$$

The displacement of a 3D two-node friction element can be represented through nodal displacement and shape functions.

$$u = \frac{1}{2}(u_i(1-s) + uj(1-s)) \tag{11}$$