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A simplified finite element model for structural cable bending mechanism

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ABSTRACT

A simplified finite element modeling method for structural cables on bending and wire sliding problems are proposed and formulated. The model is characterized by a beam-spring composition that uses helically arranged short-beam elements to simulate spiral wires, radially-placed rigid beams to replace wire sections and spring elements to capture contact extrusion and friction between adjacent wires. Winding and contacting patterns for semi-parallel wire cables and spiral strands are discussed and then used to formulate the model establishments. In semi-parallel wire cable, any selected wire section can be simplified as a seven-node set to represent the center wire and the surrounded six contact spots. While in spiral strand, wire section can be replaced by four rigid beams that connect the four contact points to wire center. Helical wire compression, sheath pinch effect and contact friction are all considered and calculated, and then bending simulations are conducted on large dimension cables with different end conditions, wire constructions and pretension levels. Simulation results are compared to the test data, and prove that the proposed model can well predict the bending behavior and the varying trend of flexural stiffness. Both cables all express a bilinear elastic–plastic like flexural strength–deflection response. Semi-parallel wire cable has sinusoidal deflection out of the bending plane, and the range of bending gradient is influenced by the cable end conditions. Galfan strand shows little unwinding and torsion effect due to the canceling out effect from alternative twisting between adjacent layers. The model can efficiently simulate long and large dimension cables in a short time, implying its promising applicability in cable studies.

1. Introduction

Cables are composed of assemblages of wires that are helically wrapped around a core, which provide high longitudinal strength and minimal lateral stiffness. Cables often function as structural elements in different structure fields, as semi-parallel wire cables in bridges, strands in cable-supported structures, wire ropes in conveyance, and conductor cables in electrical substations and transmission lines. Due to the helical wires wrapped construction, the mechanical behavior of cables under tensioning and bending is complex, especially given the potential frictional sliding between wires in cables. The effective bending stiffness of cable may vary between two extreme states that correspond to fully stuck and fully slipped wires, and these states can differ by as much as two orders of magnitude [1]. Furthermore, the construction of cable would exhibit an extremely complex inner stress state within the assemblage of wires [2]. Although strands and cables are primarily used for axial loading capacity, practical applications often impose some transverse loads or curvature like wind, water flow or hangers. Such perturbations may cause stress concentrations in cable wires, especially near the ends or terminations, with a consequent danger of fatigue failure [3].

Due to the complex construction, deforming mechanisms of cable, especially the bending behavior, are difficult to understand. Different approaches have been explored to identify and predict the characteristics of bent cable. Several previously developed bending simulations [4-7] and dynamic tests [8,9] reveal that actual strands showed an intermediate performance between parallel-arranged wire bundle and solid beam mode as a result of wire slips in the cable. However, test data are scattered due to the inherently complex mechanism, high testing and measurement requirements, and different choices of testing methods. Given the difficulties and uncertainties in cable testing and measurements, theoretical deductions were also proposed to describe this bending behavior. Nevertheless, consistent conclusions are still difficult to reach. Contracted results may even be generated as a result of dissimilar basic assumptions and simplifications. In Lanteigne's models [10], slipping begins from the outermost wires, whereas wire slip starts

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near the neutral axis in Papailiou's model [6] and in Raoof's test observations [4]. Nonetheless, these studies mainly focus on electrical conductors, with not much discussion on structural cables.

Finite element (FE) modeling has offered a means of predicting the friction condition and behavior of bent cables in recent years [11,12]. However, numerical simulations are often employed with full-scale modeling and fine mesh with 8-node brick elements and contact elements; thus, numerous elements are generated and the calculating magnitude is considerable [13]. To diminish the calculation amount and to ensure convergence, such FE models are often limited within a short piece [14] or are simply built with no wire slippage assumptions [15,16]. As a result, overall behavior is difficult to determine, and then the accuracy and detailed bending mechanisms of long cables are hard to get. Other theoretical studies involve complex equations and deductions that are challenging to understand and hard to be applied for in-depth studies [1,17,18]. Chen [19,20] recently proposed a simplified finite beam element method to analyze the thermal expansion mechanism of cables. This method simulates the twisting of wires using helically arranged short beams, which effectively solves the thermal expansion problem experienced with steel cables.

In the current study, an advanced FE modeling method is proposed for the bending and wire sliding problems of structural cables. The twisted wires, contact conditions, and stick–slip state in the cable are considered in this model. Wire contact compression and the corresponding friction resistance are also calculated and incorporated into the simulation. Moreover, wire contacting pattern of semi-parallel wire cables and spiral strands are discussed and are used to formulate the model establishment processes. Cables with different dimensions, wire constructions, end conditions, presence, and pretension magnitudes are all simulated, and then the results are compared and validated with experimental data. Finally, the flexural stiffness, deflection patterns and wire force distributions are carefully studied and compared for both semi-parallel wire cables and spiral strands.

2. Formulation of the advanced nonlinear finite element model

2.1. Basic concept of the advanced finite modeling method

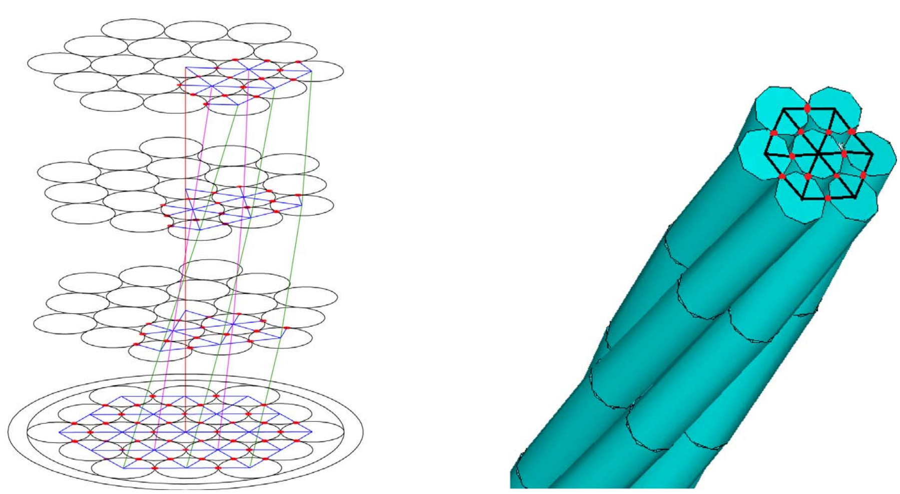
The proposed FE model simulates twisted wires and inter-wire interactions through specially arranged beams and spring elements. In this study, several basic assumptions are adopted:

1. Wire sections are supposed to follow the plane section principle; thus, the shear deformation in each wire is ignored.
2. Sliding is supposed to occur only along the longitudinal direction. Coulomb friction is adopted for the contact friction calculation with the friction coefficient μ.
3. Plasticity development for steel wires is not considered in this study. All wires are made of the same material and remain elastic during bending.

Under these assumptions, the cable can be characterized by a beam spring composition. Wires are simplified into series of helically arranged, short-beam elements that are positioned along helical wire axes to achieve a slight twisting angle (represented by the red, pink, and green lines in Fig. 1(a). These elements are hereafter referred to as "wire beams"). Six short beams with a length as the wire radius, and a large modulus are placed divergently along the wire section (denoted by the blue lines in Fig. 1(a). These beams are hereafter called "rigid beams") to ensure the plane section assumption for helical wires. Nonlinear spring elements are positioned at the outer end of the divergently distributed rigid beams. These spring elements represent contact spots (the red spots in Fig. 1(a)) and are used to integrate contact extrusion and friction resistance. This method converts line contact into point interactions at the ends of the rigid beams. Three spring elements are placed at the contact spots: two springs (the X,Y springs) along the wire section plane to simulate the extrusion effect, and another spring (the Z spring) along the longitudinal direction of cable to govern the contact friction. Therefore, friction resistance can be calculated based on the sum force of X,Y springs, whereas real-time friction and slip can be obtained according to the force and elongation of the Z spring. An FE model of a seven-wire strand is presented in Fig. 1(b), in which element dimensions are displayed as helically arranged wire beams. The black lines and red points represent the rigid beams and spring elements, respectively.

2.2. Selection of elements in the cable model

The advanced nonlinear FE models are established and computed using the commercial finite element software ANSYS.



(a) Arrangement of elements in the FE modelling method; (b) 3D display of a seven-wire strand model

Fig. 1. Formulation of elements and example of a FE model. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).