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Parametric modeling and comparative finite element analysis of spiral triangular strand and simple straight strand

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ABSTRACT

Spiral triangular strand (STS) and simple straight strand (SSS) are widely used in practical applications, but comparative analyses aimed for a better comprehension of the service behavior are seldom conducted due to the complex geometric configuration of STS. In the present study, a new parametric geometric model of STS, considering the effect of lay angle on the wire cross section, is proposed by means of parametric equations and Pro/Engineer software. Full 3D finite element (FE) models of the STS and SSS are developed with ANSYS software. Under axial tensile and torsional loads, the behaviors of the STS and SSS with the same lay angle and total wire sectional area are comparatively studied, and the comparison are conducted at different lay angles and outer wire diameters. The results of FE analyses show that nonlinear overall behaviors happen to the both kinds of strands. The STS results in smaller axial force and torque, but severer plastic deformation and von Mises stress than the SSS, and the discrepancies increase with increasing lay angle and outer wire diameter. The discontinuous contact lines of the STS lead to the nonuniform distribution of von Mises stress and significant contact pressure.

1. Introduction

Spiral wire strands and ropes are widely used in engineering applications such as suspended bridge, tower and harbor crane, elevator and mine hoist. They are strong, flexible and economical options for many lifting devices, owing to their abilities to support large axial tensile loads with relatively small torsion and bending stiffness. Therefore, it is desired to understand, predict and improve their comprehensive performances.

In the past years, different linear analytical models were presented to predict the mechanical behaviors of the spiral strands [1–6], but the precision of the models are very limited due to the simplifications used. In these models, some influencing factors are ignored, such as the complex helical configuration, Poisson's ratio effect, symmetric stiffness matrix, torsion, bending, contact, friction and local plastic yielding of wire ropes. Elata et al. [7] presented a new model for simulating the mechanical behavior of a wire rope subjected to axial loads. Compared with previous models that take the strand as an effective unit, their model considers the complete double-helix structure of the independent wire rope core (IWRC), and the performance solution of the rope is extended to the wire level. However, the torsion and bending stiffness of the rope are neglected in their work. Using general thin rod theory, Usabiaga and Pagalday [8] proposed a theoretical model that gives reasonable results of wire ropes subjected simultaneously to tensile and torsional loads. Based on the beam assumption, their work takes account of the double helical wires by using the general thin rod theory, but the inter-wire sliding is ignored. Further, effects of Poisson's ratio and local contact deformation of the rope on its performances are studied by Argatov [9]. In his research, the constitutive equations used are close-formed but the inter-wire contact is treated as being frictionless. From the comparisons between results obtained with the associated analytical models and 3D finite element (FE) method, Ghoreishi et al. [10] found that the analytical models used in the past can estimate accurately the rope's elastic stiffness for the lay angles only below 20°, beyond which a significant computation error occurs. The error is caused by the fact that the analytical models ignore some influencing factors such as the inter-wire contact. Hence, the above analytical models are not versatile in practical applications.

Since experimental works on wire strands and ropes are usually expensive, FE methods are being adopted gradually to analyze the mechanical behaviors of spiral strands and ropes. Considering the friction and contact effect, Jiang et al. [11–13] proposed a concise FE model based on the geometrical feature of a strand and corresponding boundary conditions. Their model is time-saving because only a sector of the strand needs to be meshed in FE analysis, while its

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application is limited due to the complicated constraints for the FE model. By using computer-aided design software, Imrak et al. [14–16] presented a modeling technique of the double helical wire rope. They also conducted FE analyses for axial tensile load condition in which the elasto-plastic property of the strand material, frictions and contacts between the wires are involved. Almost at the same period, Stanova et al. [17,18] made a mathematical representation of single and double helixes, using parametric equations with varied input parameters to determine the centerline of an arbitrary circular wire. And they studied the elastic behaviors of a multi-layered strand with a construction of $1+6+12+18$ wires under tensile loads by using Abaqus/Explicit software, but they did not take account of the elasto-plasticity of the wire. Judge et al. [19] made a comprehensive review on the study of wire strands and ropes, and established a full 3D FE model of multi-layer spiral strand cables including the elasto-plastic deformation, complicated contact evolution, and the local material failure. Their model is novel due to its accurate prediction of not only the axial load-axial strain curves, but also failure loads of the wire cable. In the cable's FEM analyses, the realizations of axial loading and contact condition are also important concerns. Kastratovic et al. [20] obtained the load distributions rules of wire strands and ropes by using two different types of axial loading (evenly distributed axial force and axial strain) and two different types of contacts (linear bonded and nonlinear frictional contact). Their work shows that the resulting numerical results are influenced by the way applying loading and the contact model chosen. Besides the above researches on the longitudinal behavior and stiffness of wire strands and ropes, the lateral behavior of a seven-wire strand, along with the interface stress state and friction effect, was studied by Yu et al. [21].

Most of the above studies are focused mainly on round strands and wire ropes. These strands and ropes are easy to manufacture and can be used under slight wear conditions (such as in control or aeronautic devices), in which case the friction interface is relatively smooth and the contact force at the interface is relatively small. While in cases with severe wear such as devices in dusty environment, the spiral triangular strands and ropes are good alternatives. Although the galvanization and sheath of wire rope with round strands both help to reduce the rope wear, they also lead to the complexity and high cost in manufacturing them. Featured by high structural stabilities and high fill factors, the spiral triangular strands and ropes have overall wear resistance when they are twisted about the sheave, which is due to their large bearing area. Moreover, their advantages are more significant in cases with heavy end loads or severe abrasive wear [22].

Owing to the complex configuration, however, the mechanical behaviors of the spiral triangular strands and ropes have been studied by only a few researchers. Rebel et al. [23] conducted tension–torsion tests of spiral triangular strand ropes for deep-level winding, and pointed out that the torque–tension properties of the ropes are important factors in the analyses. Based on the test results of two spiral triangular ropes in an accredited testing station, Molnar et al. [24] adopted a statistical method to evaluate and compare the quality of the ropes. Song et al. [25] depicted a 3D model of triangular strand rope and also analyzed the geometric characteristics of double helical wires. Their analysis shows that the curvature and torsion of the helical wires in the triangular rope will change greatly with its center line. However, the mechanical performance of the rope was not studied deeply and comprehensively. Through mathematical parametric equations and Pro/Engineer software, Fedorko et al. [22] proposed geometric models of spiral triangular strands that consist of two or three layers of steel wires. The computer modeling procedure can be applied to model strands of different configurations owing to the variable input parameters, providing a good approach for modeling and analyses of spiral triangular strands.

The above researches provide good references for the study and further application of spiral strands and ropes. Nevertheless, the elasto-plastic property and detailed mechanical behaviors of spiral triangular strands have seldom been studied, let alone the comparison of mechanical behaviors between spiral triangular and simple straight strands. In a comparison between bending performances of the spiral triangular strand and simple straight strand, Chen et al. [26] considered the wire's elasto-plasticity. Their conclusion shows that the bending stiffness, equivalent stress and plastic deformation of the former strand are smaller than the corresponding values of the latter strand. However, the extensile and torsional performances of the strands were not analyzed.

To well understand the service performances of the spiral triangular strands so as to prevent their failure and to select them reasonably, the present study proposes a new parametric geometric model of a spiral triangular strand by using parametric equations for the wire center lines and Pro/Engineer software [27]. Based on the proposed geometric model, 3D FE models of the spiral triangular strand are established in which some important influence factors, such as the elasto-plastic property of wire, inter-wire friction and contact, are considered. Besides this, FE models of a simple straight strand are formulated, which incorporate the same lay angle and total wire sectional area as those of the triangular strand. Further, a comparison of mechanical performances for the two kinds of strands is conducted under axial tensile and torsional loads and then associated conclusions about the spiral triangular strand are obtained.

2. Parametric modeling

2.1. Parametric equation of spiral triangular strand

The spiral triangular strand (STS in short) considered in the present study is composed of three parallel-lay straight wires in its core layer and m_1 wires in its outer layer. The outer wires are laid around the core with a lay angle α_t, which is assumed to be positive when the right hand lay direction is applied. The wire diameters in the core and outer layers are D_{t1} and D_{t2}, respectively. The minimum gap between wires in the core and outer layers is zero due to tight twist between them. The cross-section schematic of the strand in the x–y plane is shown in Fig. 1a, in which the section centers of the core wires are O_i ($i = 1$, 2 and 3) and that of one outer wire is H. And the bracketed symbols denote the projections of the foregoing spatial points onto the x–y plane.

With the origin at the central point O of the strand cross-section, we build a right hand Cartesian coordinate system so that the z axis is identical with the strand axis, and the x axis is perpendicular to the line going through points O_2 and O_3. Then the coordinates of O_i ($i = 1$, 2 and 3) are $(-\sqrt{3}D_{t1}/3,\ 0,\ 0)$, $(\sqrt{3}D_{t1}/6,\ -D_{t1}/2,\ 0)$ and $(\sqrt{3}D_{t1}/6,\ D_{t1}/2,\ 0)$, respectively. The STS modeled by the present study considers the influence of the lay angle on the sectional configuration of the outer wires, which is neglected by Fedorko et al. [22]. In the present research, the sectional shape of the outer wires in x–y plane is taken to be an ellipse, instead of a circle in the previous research [22]. Thus, the present dealing is more close to the engineering practice, which is agree with the point of view of Cartraud and Messager [28]. However, Cartraud and Messager did not make a performance study of STS. Here, the major and minor axes of the ellipse are $D_{t2}/\cos\alpha$ and D_{t2}, respectively. In light of the symmetric feature, the outer wire with a section profile centralized on point H in the x–y plane and satisfying $y_H = y_{O_2}$ is used for the following derivations.

As shown in Fig. 1a, the projection of the outer wire axis with a lay length is composed of 3 straight line segments (the blue parts in the figure) and other 3 arc ones (the green parts). The straight ones are distributed on the regular triangle ABC, and any arc one is tangent to the two adjacent straight ones on both sides. According to the geometric character of the projection, the whole expression of the outer wire axis can be obtained once the curve segments of HI and IJ are known.