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Responds of a helical triple-wire strand with interwire contact deformation and friction under axial and torsional loads

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A R T I C L E   I N F O

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A B S T R A C T

This paper aims to provide an analytical solution for describing the behaviors of a helical multi-wire strand under axial and torsional loads with the impacts of the local interwire contact. Both the interwire contact deformation and sliding friction are considered by using a theoretical approach, which divides the internal forces and moments of the multi-wire strand into two respective parts defined in two deformed configurations: one is related to the frictionless deformation state, and another is the friction deformation state of the multi-wire strand. The theoretical analysis has also conducted to understand the global responds of the strand, the local contact deformation and the friction contributions for a helical triple-wire strand. The overall axial forces, the twisting moments, and the stiffness components of the triple-wire strand with different helix angles under tensional and torsional loads are obtained The analytical results are in close agreement with the Finite Element (FE) predictions, validating the proposed analytical solution. The extended theoretical model and the proposed analytical solution well predict the responds of the helical triple-wire strand with a large range of helix angles (from 55° to 90°). The impacts of interwire contact deformation using Hertz and rigid contact theory, as well as with/without friction forces on the helical multi-wire strand behaviors have been discussed in details. The results show that the local interwire contact deformation and friction play a significant role on the strand responds as the helix angle decreasing.

1. Introduction

Helical structures have been widely used in natural and artificial materials to achieve desired engineering purposes. For instants, wire ropes are extensively applied as vital structural members in the suspension bridges, building elevators and mine hoists because of their merits in transferring the tensile load without considerable bending or torsion stiffness (Feyrer, 2006). Some biological materials with helical structures like DNA chains, bill awns of storks and climbing tendrils of plants show outstanding mechanical properties and spontaneous formation considering the weak constituents from which they are assembled (Meyers et al., 2008; Pokroy et al., 2009). As one of the engineering design complicated electric conductor, the helical triple-wire strand element consisted of three independent wires which is the basic structure element of the CICCs developed by fusion scientists and engineers in superconducting coils and giant magnets (Hoenig and Montgomery, 1975).

During the past decades, extensive theoretical and experimental works have been conducted to explore the mechanical behavior of the helical structures of wire ropes. Under the simplification hypotheses, such as small displacements, ideal contacts and frictionless between wires, some theoretical models were proposed to provide analytical approaches for global mechanical responses of wire ropes. The simplest model ignoring the wire bending and torsion effects was firstly presented by Hruska (1951, 1952) to determine the rope stresses and radial forces. It was further modified by Knapp (1975) and Lanteigne (1985) to apply in multi deformation modes. The curved rod theory has been widely accepted as a more accurate and complex model for analyzing wire rope structures by Love (1944). Machida and Durelli (1973) studied the influences of bending and torsion stiffness of individual wires on the whole cable mechanical property. Costello and Philips (1976) developed a thin rod model with nonlinear equilibrium equations of curved rods, which included the effects of radius and helix angle variations, i.e., the Poisson's ratio effect. Kumar and Cochran (1987) further extended the thin rod model to derive a linearized and closed form of expression for axial stiffness coefficients. The linearized theories including the effects of curvature and twist variations for wire ropes under different modes of contact were developed and systemically

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reported in detail by Costello (1997).

It is known that the nature of interwire contacts in the strands is essential to determine their strength, performance and serviceability, and helps to predict the failures. Huang (1978) reported the contact effect for an elastic strand with a central core surrounded by a single layer of helical wires subjected to axial forces and twisting moments. While ignoring the local contact deformation, the Poisson's ratio effect and the contact forces between the central core and the helical wires were well considered. The contact forces between the core and wires, however, might play a significant role to split helical wires as the strand extending. Phillips and Costello (1985) analyzed the 6 × 25 filler wires IWRC rope with good considerations of the contact stress but impracticality ignoring the contact deformation. Based on the Hertz-theory, Kumar and Botsis (2001) studied the contact stresses of multi-layered wire-rope strands under tension and torsion loads, and then developed analytical expressions to determine the maximum contact stresses produced in the strands with metallic wire core. Some of their theoretical results have been verified by experimental observations, and the sensitivity analyses were performed for the pitch length in case of the Lang's lay rope and regular lay rope. Taken into account the interwire contact effects for capturing effective mechanical properties of multip-layer structural strands, a semi-continuous model was suggested by Raoof (1983), in which each layer of the twisted wire was modeled as an orthotropic complete cylinder. Comparing with thin rod models for the cable analysis, the results showed that the semi-continuous model would be a good candidate for predicting the performance of the cable primarily consisted of a large number of wires (Raoof and Kraincanic, 1995), while it could fail to evaluate the bending stiffness (Jolicoeur, 1997). The friction among wires in a strand also deserves to be considered carefully. Limited investigations have considered the effects of friction at the interfaces of wires. A frictionless analysis could result in unreliable conclusions obtained from the theoretically identical tests. For a straight single steel strand of seven-wire, Utting and Jones (1987a,b) firstly developed a mathematical model for describing the core-wire friction, and the theoretical model and predictions were compared with the experimental results. Lanteigne (1985) proposed a theoretical expression to predict the behavior of a frictional aluminum conductor steel-reinforced conductor under static loads. While the steel-aluminum wire friction has been well considered, the proposed expressions ignored the contributions of the deformation of the wires, the interlayer friction and slip. Some comprehensive investigations on the frictional core-wire in a strand under axial, bending, and torsional loads were conducted by Labrosse et al. (2000). Elata et al. (2005) reported the significant local stress variations in a double-helical wire whether the assumption of infinite friction or frictionless for the wires was considered. Based on the hypothesis that interlay friction is capable to prevent wires from sliding in the strands, a wire rope model with the material fiber tracking of cross section and the wire ropes simultaneously subjected to tensile and torsional loads was recently developed by Usabiaga and Pagalday (2008). Their model was established in the framework of Love's general thin rod theory and treated with doubly helical wires with the same rigorousness rather than straight and helical wires. Besides the theoretical models and analyses, many computational models have been proposed to achieve accurate predictions. Using a helical slice discretized with volume elements, Jiang et al. (1999, 2008) numerically investigated a simple straight wire rope strand under axial loads to predict its global behavior and the stress distribution in the wires. The results were compared with the linearized solutions and experimental results of Costello (1997), which shows a good agreement for the strand having the free end conditions, but sometime an obvious difference for the fixed conditions. Nawrocki and Labrosse (2000) presented a FE model using the Cartesian isoparametric formulation to simulate a straight wire rope strand with all the possible interwire motions. The role of the contact conditions in pure axial loading and in axial loading combined with bending was investigated to show that the interwire pivoting and sliding govern the cable response. Recently, FE simulations were widely applied to study more complex helical structures like two-layer spiral round, triangular and oval strands under mechanical loading, and steel wire ropes under fire conditions (Fontanari et al., 2015).

It should be noted that the analytical models mentioned above generally provided reasonably well predictions on the elastic stiffness constants of wire strands within a very small lay angle (i.e., most below 20°, or the helix angle higher than 70°). Increasing lay angle (or decrease of helix angle) generally results in quite discrepant observations presented against the theoretical results even with careful considerations of the interwire contact impacts (Argatov, 2011). To the best of author's knowledge, the effect of local contact deformations including interwire friction in the helix wires has not been well studied yet. This work aims to propose a comprehensive theoretical solution for a helical multi-wire strand subjected to uniaxial tension and torsion loads taking into account the local interwire contact deformation and friction. An analytical approach has also been developed to describe the behavior of a helical triple-wire strand by dividing the internal forces and moments into two parts: one is related to the frictionless deformation state and the other is the friction deformation state. The overall axial forces, twisting moments, and the stiffness components of the triple-wire strand with different helix angles were achieved. The FE predictions obtained from the commerical software ABAQUS have been used to validate the proposed solution. It shows a good agreement between the proposed solutions and the numerical predictions. Moreover, the influences of contact deformation and friction on the global behavior of the triple-wire strand and the local interwire contact characteristics have been discussed in details.

2. Geometrical description and fundamental equations

Consider a multi-wire strand, the centerline of any wire in a strand is a three-dimensional space curve (as shown in Fig. 1). In order to precisely analyze and model the equilibrium state and deformation of the multi-wire strand, the local coordinate systems are adopted. At an arbitrary point P of center line of any one of the wires, the well-known Frenet-Serret local coordinate frame, $\{P: \mathbf{N}, \mathbf{B}, \mathbf{T}\}$ where $\mathbf{N}, \mathbf{B}, \mathbf{T}$ respectively represent the unit basis vectors along the tangential, normal and binormal directions of the wire center line, is coincide with a new orthonormal local frame system of $\{P: \mathbf{E}_1, \mathbf{E}_2, \mathbf{E}_3\}$ in the initial undeformed configuration, as shown in Fig. 2a. In the final deformed state, the Frenet-Serret local coordinate frame and orthonormal local frame systems respectively are denoted by $\{P: \mathbf{n}, \mathbf{b}, \mathbf{t}\}$ and $\{P: \mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\}$, as shown in Fig. 2c. The angle between $\mathbf{e}_1$ and $\mathbf{n}$ is denoted as χ, and the curvature and the torsion of a space curve respectively are represented as κ, τ, then the curvature vector, $\boldsymbol{\omega} = \omega_i \mathbf{e}_i$, can be given as,

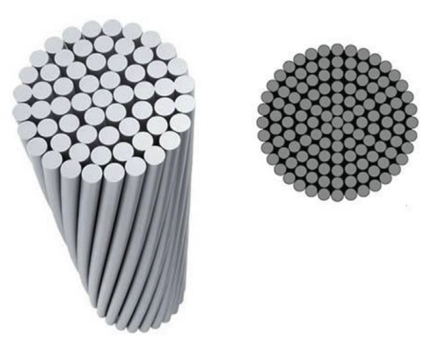

Fig. 1. Multi-wire strand structure and the cross-section profile.