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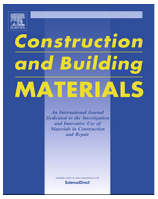

Finite element study of behavior and interface force conditions of seven-wire strand under axial and lateral loading

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HIGHLIGHTS

- Constrain in strand is partial restrained but close to fixed end.
- Strand shows elastic–plastic performance as the increasing level of stretching.
- Friction has little influence on longitudinal stiffness and limited influence on lateral behavior.
- Microslip and contact line migration mainly occurred between helical wires.
- Both strand bending phase and wire bending phase were observed near the termination when bending.

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ABSTRACT

Although numerous FE models have been proposed to analyze the mechanical behavior of simple strands, they seldom examine the contact condition and lateral loading behavior that may influence local stress distribution and lifetime performance. In this study, serial 3D FE models of a seven-wire strand were developed to discover the interface mechanism under longitudinal and lateral loading. A partially restrained model was proposed and carefully studied. Friction minimally influenced longitudinal stiffness and had a limited effect on lateral behavior. FEM analysis predicted uneven stress distribution under lateral loading simulation. Both strand bending phase and wire bending phase were observed near the termination. Microslip and contact line migration mainly occurred between helical wires.

1. Introduction

Lightweight cable-supported structures are widely used in large-span public structures, such as sports stadia and suspended bridges. Stiffness and ultimate capacity of the entire structure can be enhanced by combing the cable-strut system and pretension into traditional structures. Cable-supported structures offer economic and innovative structural solutions and create aesthetically pleasing forms.

Cable is usually modeled as a bar element or beam element with end freedom released, which often has a uniform cross-section, no compressive strength, and lateral stiffness for simplification. The reason is that the general function of cable or strand is to support large axial loads with comparatively small bending or torsion stiffness. Moreover, cables often have high safety degree in structural design. These simplifications are reasonable in most static conditions. However, numerous cable-supported structures that have been used for approximately 20–30 years may experience rusting and damage [1–3]. Cables often suffer from vibration [4] or dynamic loads in certain circumstances, such as cable-stayed bridges and suspended canopy. Thus, understanding the behavior of steel cables is necessary.

Wire ropes were constructed by wrapping wires spirally on a central wire, and the spirals can be wrapped onto a central strand to form various layers, which determines an extremely complex inner stress range [5]. Over the past decades [6], substantial efforts have been exerted to understand and model steel cables or wire ropes. Various mathematical models have been proposed to enable an analytical approach in evaluating the global mechanical response. However, the proposed models have limitations because

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of simplified hypotheses on real cases (absence of friction and sliding between wires, small displacements and strains, and uniform cross-section homogenized beam) [5]. Meanwhile, experimental work on cables often requires costly testing devices; for example, large-diameter cables require specific large and expensive devices, whereas small-diameter cables require a high degree of sophistication and accuracy. Several FE approaches over the past years have been employed to understand the mechanical behavior of cables. Nawrocki and Labrosse [7] developed a specific element model that considered the motion of inner wires, and studied relative motions between the core and the wires. They found that the inter-wire pivoting and sliding governs the global response of the cables under axial and bending loads, respectively. Other 3D FE studies focused on local stress distribution within wires [8,9] or in wire ropes [10,11]. Ghoreishi [12] developed 3D finite element modeling of "6 + 1" wire single-layer strand (simple straight strand), which are subjected to static axial loads, and compared the results with nine linear elastic theoretical models. The analytical models showed satisfactory estimations of the elastic stiffness constants for lay angles below 20°. However, these models assumed that no wire/wire contact would occur, and only core/wire contact would occur. Jiang et al. [13–16] developed concise FEM on seven-wire and three-layer straight wire rope considering friction and contact effect, and showed the elastic–plastic performance under stretching and stress distribution across the section. Most FE models study the static behaviors under axial loading, but do not consider friction, sliding effect, and elastic–plastic properties. Research on cables subjected to high transient loading conditions, such as impact and vibration, are extremely limited in cases where the loading condition is asymmetrical and cyclical, and local material failure as well as friction effect is significant or may dominate the cable behavior. Judge et al. [17] developed full 3D FE models that can accurately predict the complete mechanical behavior of multiple-layer spiral strand cables, including elastic–plastic deformation, complicated contact evolution, and local material failure. The model was used to simulate the quasi-static axial loading behavior but could also be used in studying the dynamic loading conditions.

Most of the concise FE analyses focused on longitudinal behavior and stiffness, but few covered the contact conditions and lateral loading behavior. In addition, previous simulations and experiment validations were limited in the elastic conditions without considering plastic development and sliding effect. This study mainly focuses on these problems and aims to understand the lateral loading behavior.

This study developed a full 3D FE model similar to the model presented by Judge et al. [17] and analyzed the mechanical behavior and friction effect under lateral loading. The objectives of this study are (1) to understand mechanical proprieties under different kinds of loading, including longitudinal and lateral loading; and (2) to study the interface stress state and friction effect in those circumstances. We started the research from a simple straight spiral strand, and considered a seven-wire strand comprising a central wire surrounded by six symmetrical helical wires.

2. Description of 3D FE model

2.1. Modeling method and geometrical parameters

A continuous element morphing process was applied along the length of the cable in the model proposed by Judge. However, another morphing method [12], which had similar geometrical parameters as the model proposed by Judge, was used to simplify the modeling process. The geometry of the core was obtained by the linear *z*-axis extrusion and the helical wires were generated by extrusion of circular areas along helical curves corresponding to the center axis of the wire. Material parameters were primarily settled according to the model of Judge, and the *MAT_PLASTIC_KINEMATIC model was used on cold-drawn steel wires. All simulation procedures were performed with LS-DYNA Explicit, and the general geometrical and material parameters used for all the models are listed in Table 1.

2.2. Constraints and end conditions

The meshed model is presented in Fig. 1. All of the strands had one end fixed in all displacement degrees to simulate the clamped end. We summarized three boundary conditions from previous research for the loading end. The fixed end disabled all degrees of freedom except displacement along the longitudinal direction, and the free end condition enabled rotation and displacement at each wire. Nodal coupled end enabled wires at the loading end to move and rotate together. However, in practical situations, certain sections of a wire would exhibit constraints as a result of the pulling effect from other sections of the same wire.

We developed a partially restrained boundary by inducing a short extra length cable (loading end in Fig. 1) to be closer to the real condition, and designed a cable model longer than the intended two-pitch length model (the entire length of the model was 180 mm but the effective part was approximately 157.33 mm). The force and constraint of each wire at the "boundary" section resulted from the pulling of the extra part of the helix wire. Yield strength was set to 6 GPa for the extra piece and other material parameters were the same as those reported in Table 1. The other end of the extra piece, which was referred to as loading end, was built as plane cross-section to facilitate the application of different loads, and the fixed-end constraint was applied to this end. The goal of setting that extra piece with higher strength was to obtain a restraint boundary similar to the real condition, as well as to reduce stress concentration.

2.3. Contact conditions

Two type of contacts occurred in the "6 + 1" cable, namely, wire/wire contact between helical wires and wire/core contact between helical wires and the core. Both types were in the shape of a helical line. A point-to-point contact may also occur between two spiral layers in a multiple-layer cable. The automatic contact algorithm, *AUTOMATIC_SURFACE_TO_SURFACE in LS-DYNA, was used in the simulations to prevent surface penetration and obtain interface force or friction conditions. In LS-DYNA, contact was calculated between the surfaces of different element parts. After the friction coefficients between different element parts were defined, contact elements automatically spread outside the surface of each part. Adjacent helical wires and the core were built into different parts to distinguish wire/wire contact from wire/core contact. (Fig. 1 shows different element parts in different colors).

Table 1
Geometrical and material parameters of the seven-wire strand cables.

Geometrical data	
Strand diameter (mm)	11.38
Central wire diameter (mm)	3.94
Helical wire diameter (mm)	3.72
Pitch length of strand (mm)	78.66
Model length (mm)	157.33
Lay angle (°)	17.03
Young's modulus (GPa)	188
Plastic modulus (GPa)	24.60
Yield stress (GPa)	1.54
Poisson's ratio	0.30