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An investigation on stressing and breakage response of a prestressing strand using an efficient finite element model

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ABSTRACT

The mechanical response of a wire strand is inherently complex because the helical wires undergo evolving stress and contact conditions as the strand is loaded. Further complications are added to the strand behavior if one or more of the wires break due to strand degradation over time. Although a detailed investigation on strand behavior is critically important for predicting the capacity of a broken strand as well as developing new monitoring approaches for wire break detection, there is little study available in the literature on wire breakage in a stressed strand. This paper provides an extensive investigation on stressing and post-breakage dynamic behavior of a prestressing strand. A finite element model is generally useful to study the global strand response, along with many localized phenomena that have strong influence on its performance, but are difficult to capture either experimentally or through closed-form analytical models. Investigations on certain behaviors, such as wire breaks, however, require a relatively large or even a full-scale model to adequately develop contact and frictional conditions. Moreover, such a sizeable model can account for any deviation points and may avoid edge effects. Consequently, several finite element parameters, such as the load ramp profile and duration, effects of damping and interwire friction, become critical for an accurate and efficient model. This paper first presents the use of a parametrized model to study strand behavior and evaluates the effects of these modeling parameters on strand response; load distribution and redistribution among the wires at the onset of interwire motion are also considered. The model is then used to simulate wire breakage in a prestressing strand, so that various aspects of post-breakage response can be examined. Numerical results show that a linear load ramp or stressing too quickly may lead to an inaccurate axial tension developed in the strand, whereas the inclusion of nominal mass-based damping has been found effective in achieving a quasi-static solution at a reasonable computational cost. In addition, the wire break simulation results indicate that breakage of an outer wire results in greater prestress loss than breakage of the center wire, which might have important implications for non-destructive wire breakage detection.

1. Introduction

Wire strands and ropes often find unique engineering applications because of their high tensile capacity coupled with workable bending flexibility. Accordingly, they are widely used in diverse engineering systems ranging from major transportation structures, such as bridges and aerial cableways, to various hoisting equipment like elevators and cranes. The mechanical behavior of steel cable, however, is complicated by its intricate geometric pattern. While being subjected to pretensioning or in-service loading, a complicated stress-state condition arises that combines the effects of tension, torsion, flexure, and shear along with multiple nonlinear phenomena such as interwire motion (the relative movement between wires), contact, friction, plasticity, and large deformation. Studies on cable mechanics, therefore, have received significant research attention for well over half a century. Presently, developing a better understanding of strand response to wire breaks is critical for the development of wire break detection techniques.

Several theoretical models have been proposed in the literature to explain the mechanical characteristics of wire strands and ropes, where strands consist of a layer of wires twisted around a center wire and ropes consist of strands twisted around a straight core. Costello and Phillips [1] examined the sensitivity of strand stiffness to the change in helix angle as loading progresses, as well as investigated its dependency on initial helix angle and end conditions. Their study, however, neglected the effect of friction and wire

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flattening to make the closed-form solution tractable. To obtain the static response of complex wire ropes with less computational effort, Velinsky et al. [2] linearized the nonlinear equations of equilibrium. The reduction of effective Young's modulus with addition of strands was demonstrated by analyzing a rope with an independent core. Later, Velinsky [3] compared these results with nonlinear theory and found them identical in practical load ranges.

Utting and Jones [4,5] conducted a series of experiments on seven-wire strands under tensile loads and proposed an analytical model that indicates insignificant effects of interwire friction and contact deformation on the overall strand response. Chaplin [6], however, reported that these phenomena, along with other factors, affect the failure mechanisms of wire ropes. Raoof and Kraincanic [7] considered the effects of interwire friction in their theoretical model and obtained the upper and lower bounds of rope's effective stiffness that correspond to the no-slip and full-slip condition, respectively. Unlike the classical discrete modeling approach [1–3] where each wire is treated as individual helical rod, Jolicoeur and Cardou [8] presented an alternative approach in which each layer of wires is represented by an orthotropic hollow circular cylinder. This semi-continuous model was applied to several types of cable, concluding that this approach tends to produce more satisfactory results for cables with larger number of wires. Elata et al. [9] considered the twisted wires in the outer layer of a rope and analyzed two extreme kinematic conditions: zero and infinite friction between adjacent wires. However, the flexural and torsional rigidity of wires were neglected.

In general, most of the aforementioned analytical models have made approximations and simplifying assumptions to obtain a closed-form solution. Although these models can be used to predict the global response of a cable, they are unable to provide a comprehensive description on many localized phenomena, such as yielding along contact lines, uneven bending of outer wires, and stress redistribution among wires. With the rapid advancement of computing technology, finite element (FE) methods have been developed over the past few decades to examine these characteristics in addition to other critical aspects of wire ropes, such as microstructural characterization during manufacturing process [10] and the mechanisms controlling their ductility [11].

Chiang [12] conducted a FE-based parametric study to show the individual and combined effects of different geometric, boundary, and contact conditions on stress response of a strand. By utilizing the helical symmetry of geometry and loading, Jiang et al. [13] developed a concise FE model of a seven-wire strand. The model was further extended [14] to analyze a three-layered 19-wire strand by updating the constraint equations and boundary conditions. Nawrocki and Labrosse [15] considered different interwire motions, namely, sliding, rolling and pivoting, and showed that pivoting and sliding governs the axial and bending behavior, respectively. Contrasting the conventional assumption of contact occurrence only between the center and outer wires, Jiang et al. [16] demonstrated that the contact also takes place between neighboring outer wires.

Erdönmez and Imrak analyzed the behavior of a curved strand [17] and later considered a rope to examine the load distribution among wires [18]. Stanova et al. derived parametric equations for geometric models of complex wire ropes [19] and implemented them in a FE program [20]. Zhou and Tian [21] proposed a FE model for single-layered strand based on geometric compatibility and material elasticity theory. Nodal constraint relations between core and helical wires were obtained for axial tension and bending. However, the model did not account for the effect of interwire friction or sliding. Kmet et al. [22] investigated a rope deviated over a saddle and observed non-uniform stress distribution among wires. Fontanari et al. [23] studied the elasto-plastic response of a rope with a polymeric fiber core. A FE model of length equal to 1/16 of helical pitch was used to examine the load distribution among wires in the elastic regime as well as the redistribution of load with the evolution of plastic deformation.

To reduce the computational demand, many of the previously proposed models either make simplifying assumptions or only consider a small segment of rope geometry (partial length and/or partial cross section) for analyzing stressed strands. However, a relatively large model with high mesh resolution is needed to study various phenomena, such as the strand response after a wire breakage, so that the contact and frictional conditions may adequately develop. In addition, the representative lengths used in existing models are often too short to observe interwire pivoting [24] or stick/slip friction [25,26] and the effects of such phenomena on load redistribution among wires while stressing. The requirement of a sufficiently large model, combined with high material and boundary nonlinearities, make the use of an explicit analysis scheme a favorable candidate.

In analyzing complicated contact problems like wire strands and similar structures, explicit time integration has proven successful for its computational efficiency, robustness, and solution stability (i.e., lack of convergence difficulty) [17,20,22,27]. However, simulating strand stressing in a quasi-static manner when using an explicit dynamic procedure requires special considerations such as proper selection of loading rate, time variation of applied load, and energy dissipation mechanisms other than frictional sliding, which become extremely critical in large models. The first part of this paper examines the role of these parameters in achieving an accurate model, and investigates the redistribution of load among wires at the stick/slip transition.

The second part of this paper deals with simulating a wire break in a prestressing strand and investigates post-breakage response. Although wire breaks in a rope or strand are quite common, occurring primarily due to corrosion, to date there have been few attempts to conduct a detailed study on this topic [27–35]; comprehensive investigation of the behavior of a broken strand is still an open problem. The use of monostrand tendons in building construction and the recent interest in flexible fillers for multi-strand post-tensioned tendons in U.S. bridges facilitates new monitoring methods for wire break detection [36–38]. Wire breaks in unbonded tendons allow changes in global strand and anchor response, which further highlights the necessity of a thorough investigation on strand behavior after the occurrence of any breakage. This paper considers various breakage scenarios, such as breakages of center or outer wires, varying confinement conditions, successive wire breaks, and the effect of friction on post-breakage response.

2. Model geometric and material properties

2.1. Geometric features

Although the construction of wire strands varies in different parameters, such as wire diameter, helix angle, number of wires, group pattern, and lays [39,40], the basic geometry of all these strands consists of a straight wire surrounded by a layer of helical wires [15]. The cable investigated in this paper is a seven-wire strand (Fig. 1), which is commonly used in prestressed concrete (PC) structures. The ASTM A416 Grade 270 strand [41] is made of six helical wires encasing the center wire. The helix angle and wire diameters have been chosen such that, in the undeformed configuration, each helical wire barely touches its two neighboring helical wires in addition to touching the straight center wire [16]. Details of the geometric and material data are listed in Table 1.