The Analysis of 91-Wire Strand Tensile Behavior Using Beam Finite Element Model

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Abstract. Due to its complex geometry and high nonlinearity of inter-wire contact, the efficient prediction of the mechanical properties of a 91-wire strand is difficult by using the conventional three-dimensional solid finite element model (FEM). In this paper, a beam FEM for efficient analysis of the mechanical behavior of multilayered wire strands is applied to study the tensile behavior of the 91-wire strand. The beam FEM has a small model size and can be capable of taking into account the nonlinear factors such as the uneven wire bending, contact deformation and wire material plasticity etc. (International Journal of Perfromability Engineering (2017). By using the beam FEM, the axial tensile properties of the 91-wire strand have been predicted efficiently. The finite element analysis results have a good agreement with the experimental test results. Moreover, the contact behavior between contacted wires and the influences of above factors on the strand axial properties have also been analyzed effectively.

1. Introduction
Multilayered wire strands are developed based on the conventional simple spiral wire strands and has become a wide class of useful and important engineering components. Their major advantage is to support excellent axial tension capacity, corrosion resistance, and high temperature resistance and so on. 91-wire strands are a kind of frequently-used multilayered wire strand and play an indispensable role in various engineering applications such as suspension bridges, sports stadia and cable-membrane structures, etc.

In generally, the behavior of multilayered wire strands is predicated upon a combination of in-service and laboratory phenomenological observations and results for its complex geometry and loading conditions. This results in a large number of consumption of manpower and material resources. In order to effectively achieve the mechanical behavior of the multilayered wire strands, considerable progress has been made in the development of theories and models. Considering the wire local deformation, Xiang et al. [1] developed an elastic-plastic analytical model to study the mechanical behavior of wire strands. Chen and Meng et al. [2-4] studied the inter-wire contact by using their newly developed analytical models. Kalentev et al. [5] analyzed strand stress-strain state on the basis of considering the linear contact under different loading conditions. The first author has also developed a nonlinear analytical model for efficiently prediction of the mechanical behavior of the multilayered wire strand. The model is established upon Costello’s theory and Hertz contact theory and effectively studies the effects of wire contact deformations [6]. Finite element (FE) method is another important method for researchers and engineers to analyze the strand mechanical behavior.
Three-dimensional solid finite element models (FEMs) are widely developed in early stage. It can be capable of considering the actual strand geometry and nonlinear factors which are very difficult to address analytically. However, most published solid FEMs [7-10] are limited to the relatively simple wire strand constructions. Its usage for multilayered wire strands can be very expensive and the desired degree of refinement is frequently not within the practical limits of computer resources. Lalonde et al. [11] presented a beam FEM for the multilayered wire strands, which has a small model size compared with conventional solid FEM. Yu et al. [12] developed a beam-spring FEM to study the cable bending and wire sliding problems. The first author has also presented a beam FEM to study the mechanical behavior of the multilayered wire strands under axial loading [13]. In this paper the beam FEM presented by the author is applied to predict the axial tensile properties of the 91-wire strand. Comparisons between simulation and experimental results are conducted to validate the analysis correction. Furthermore, the inter-wire contact behavior and the influences of Poisson’s ratio, wire uneven bending and contact deformation on the strand tensile strength has also been studied by using the beam model.

2. Finite element model

In general, a 91-wire strand analyzed in this paper is shown in Figure 1. It consists of a straight center wire surrounded by five layers of wires. The adjacent layers of helical wires have the opposite helical sense and the outer layer of helical wires is six more than the inner layer. The diameters of helical wires are equal, but they are smaller than the diameter of the center wire. This ensures that contact occurs only between adjacent layers of wires but each of the helical wires in the same layer do not touch each other. For an arbitrary wire in the layer \(i\) (\(i=1, 2, ..., n\)), \(R_i\) represents the wire radius and \(\alpha_i\) denotes the helical angle, where \(n\) is the total number of wire layers in the strand structure. The strand is loaded axially with an axial force, \(F\), and an axial twist moment, \(M\), which represents the most basic loading case.

Figure 2 shows the 91-wire strand FEM by using the beam element method. The beam elements established along wire centerlines are used for wire discretization. The two-node contact elements distributed at the contact locations are used to simulate the line contacts between the first and second layer wires, and the point contacts between two successive layers of helical wires. The length of the strand beam model, \(\Delta z\), used for analysis is ten times the strand diameter. The size of the beam element is about 0.3 times the wire radius. The spacing between adjacent line contact elements is 0.2\(R_i\).
along the strand axial direction. The boundary conditions are also shown in Figure 2. The strand was subjected to non-rotation tension at the two ends of the model, which represents the most basic loading case in engineering applications. In this analysis, a mean strand axial strain, $\varepsilon$, of 0.01 was applied in increments of 0.001.

3. Finite element analysis results and discussion

The beam FEM of the 91-wire strand developed above has been implemented using ANSYS FE software. Table 1 details the geometric data of the strand. Using the FE discretization rule aforementioned, the beam FEM of the 91-wire strand is composed of 49811 beam elements and 7344 contact elements, and the total number of nodes is 62015. The Von Mises yield criterion was assumed. A bilinear isotropic hardening material model was used. The Young’s modulus is 188GPa, Poisson’s ratio is 0.3, and the yield stress is 1.54GPa and the plastic modulus is 24.6GPa in the plastic region.

![Table 1. The geometric data of the 91-wire strand.](image)

**Table 1. The geometric data of the 91-wire strand.**

| Layer number $i$ | Number of wires $m_i$ | Wire diameter $2R_i$ (mm) | Pitch length $p_i$ (mm) | Helical angle $\alpha_i$ (°) | Helical direction |
|------------------|-----------------------|---------------------------|-------------------------|-----------------------------|------------------|
| 1                | 1                     | 5.00                      | —                       | 90                          | —                |
| 2                | 6                     | 4.55                      | 106                     | 74.2                        | RH               |
| 3                | 12                    | 4.55                      | 207                     | 74.2                        | LH               |
| 4                | 18                    | 4.55                      | 307                     | 74.2                        | RH               |
| 5                | 24                    | 4.55                      | 408                     | 74.2                        | LH               |
| 6                | 30                    | 4.55                      | 509                     | 74.2                        | RH               |

![Figure 3. Contour plot of displacement at a strand axial strain of 0.004: (a) axial displacement and (b) radial displacement.](image)

Figure 3(a) shows the distribution of axial displacement, $u_z$, and Figure 3(b) depicts the distribution of radial displacement, $u_r$, at a strand axial strain of 0.004. It can be seen that the radial contraction occurs with the axial extension simultaneously as expected. The constant radial reduction occurs in the middle region, i.e. the length from $1.5d$ to $8.5d$, where $d=50.5\text{mm}$ is the nominal strand diameter. In other two end regions (i.e. 0-1.5d and 8.5d-10d), the radial reduction varies greatly due to the termination effects caused by boundary conditions.

Figure 4 shows the strand axial load as a function of the strand axial strain. An experimental test on the 91-wire strand was conducted by using the 5000kN tension test machine for the purpose of validation. Detailed information about the test is the same as that presented in the reference [13]. Analytical results predicted by Costello’s elastic model are also given in this figure for comparisons.
can be seen from this figure that the results predicted by the beam FEM are in good agreement with the test data.

Figure 5 shows the variation of the strand axial stress in a wire of each layer with the strand axial strain. For a given axial strain, the axial stress in center wire is bigger than those in helical wires, and the third-layer wire bears the smallest axial stress than other helical wires. Moreover, the stresses in all wires are relatively well-distributed and have no great variation with the increase of the strand axial strain. This indicates that the strand wires have a high material utilizing rate.

Figure 6. Variation of radial displacements of the centerlines of some selected helical wires along strand axial direction.

Figure 6 shows the variation of radial displacements of centerlines of some selected helical wires of each layer along the strand axial direction at the loading level of an applied mean axial strain of 0.004. It can be seen that in the regions free from termination effect, the radial displacements of each layer wires increase from the strand inner layer to the outer layer. The major value differences between adjacent layers are mainly caused by the contact deformation and the amplitudes of the distribution wave along the wires within the same layer shows the amount of deformation due to the uneven bending effect.

Figure 7 shows the variation of contact forces acting on sequential contact points along helical wires in each layer at the loading level of an applied mean axial strain of 0.004. It can be seen from this figure that the contact forces reduce greatly from the strand inner contacted layers to the outer ones. The amplitude of the decrement for two adjacent contacted locations is nearly 50%.

The effective Young’s modulus of a strand is defined as the ratio between the strand axial load and the product of the applied axial strain and the strand cross-sectional area. Figure 8 compares the effects of factors of Poisson’s ratio, wire uneven bending, and contact deformation on the effective Young’s moduli of the 91-wire strand. For comparison, the contact deformation has been incorporated into Costello’s theory by the authors and the effective Young’s modulus calculated using the analytical model is also listed in the figure. From this figure it can be concluded that the contact deformation plays a main role in determining the strand axial tensile rigidity and should be considered when developing accurate numerical models for multilayered strands.
Figure 7. Variation of contact forces acting on sequential points along helical wires in each layer.

Figure 8. Comparisons of Effective elastic moduli predicted from experiment and different numerical simulation models.

4. Conclusion
The tensile behavior of the 91-wire strand has been efficiently analyzed by using the beam FEM in this paper. For the global behavior of wire strand, i.e. load vs. strain, the finite element analysis results are in good agreement with the experimental test results. Compared with the Poisson’s ratio and wire uneven bending, the contact deformation caused by inter-wire contacts plays main roles in determining the strand tension strength. Furthermore, the contact behavior between contacted wires of adjacent layers has also been predicted. The maximum contact force and radial deformation occurs between the second and the third layers of wires.

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6. References
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