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MODELING AND NUMERICAL ANALYSIS OF THE WIRE STRAND

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ABSTRACT

The kinematics nonlinear equilibrium equations given in the well know classical treatise on elasticity by Love in 1944. Most of the studies based on the well known beam theory and frictional effects are neglected in most of the analytical models. The aim of this article is to create a realistic 3-D structural model of a wire strand and to build an analysis model taking into account the frictional and sliding effects. Axial loading and bending over a sheave problems are solved numerically over the new generated 3-D model and numerical results are presented. Furthermore wire rope construction using double helices is described.

Keywords: Wire strand, wire rope, double helices, axial loading, bending problem.

TEL DEMETİN MODELLENMESİ VE NÜMERİK ANALİZİ

Özetçe

Lineer olmayan kinematik denge denklemleri Love'nin 1944'de elastisite üzerine yazdığı ünlü klasik inceleme tezinde verilmiştir. Çalışmaların çoğu iyi bilinen kiriş teorisi üzerine kurulmuş olup sürtünme etkisi birçok analitik modelde ihmal edilmiştir. Bu makalenin amacı tel demetine ait gerçekçi bir üç boyutlu yapısal modelin ve sürtünme ve kayma etkilerinin yer aldığı bir analiz modelinin oluşturulmasıdır. Eksenel yükleme ve makara üzerine eğilme problemleri nümerik olarak oluşturulan yeni üç boyutlu model ile çözülmüş ve nümerik sonuçlar sunulmuştur. Daha sonra ise çift helis kullanarak tel halat modellemesi izah edilmiştir.

Anahtar kelimeler: Tel demet, tel halat, çift helis, eksenel yükleme, eğilme problemi.

INTRODUCTION

Ropes are found a wide usage area ranging from hoisting systems, cranes, elevators and bridges. Large tensile force strength of the wire ropes is very important in these application areas where as the small bending and torsional stiffness. Twisting and bending moments, and torsional strength become important parameters to different application areas and have to be taken into account. Due to high demand to use ropes in a wide ranged area brought together theoretical investigation about the different aspects such as tension, torsion, twisting, contact, slip, frictional effects and etc.

Wire rope theory is based on a well known classical treatise on elasticity by Love in 1944. General nonlinear equilibrium equations are derived and presented in [1]. The mechanical behaviors of the wire ropes are investigated in [2] based on torsion and shed light to the bending analysis of the open-coiled helical springs in axial plane by bending moment and lateral load. Green and Laws, in general theory of rods [3], mentioned to a general and linearized form to determine stresses in helical constituent wires in cables. Governing equilibrium equations are taken as a starting point in most of the analytical analysis. Costello has presented the general behavior of the wire ropes in different aspects and gathered these in [4]. Wire rope analyses with cross-sections are investigated in [5]. There are a number of test results presented in [6, 7]. A concise finite element model which takes full advantage of the helical symmetry features of a strand has been developed for a simple straight strand by Jiang et al [8]. Fatigue life of a large diameter wire rope prediction is made from test data from small diameter rope using interpolation and extrapolation in [9]. A finite element model of a simple straight strand based on a Cartesian isoparametric formulation has been given by Nawrocki [10]. For simulating the mechanical response of a wire rope with an IWRC (independent wire rope core) a new model which fully considers the double-helix configuration of individual wires is given in [11].

In this study, a simple strand model and the governing equilibrium equations were given and axially loaded simple straight strand was analyzed by both numerical and analytical models. In addition the bending problem was modeled for the wire strand and the equilibrium equations were solved.

An illustrative numerical example was also given to illustrate the behavior of a wire strand bent over a sheave. The obtained results were compared with analytical and numerical results. At the end of the paper 3-D wire rope model construction is explained for further studies.

Geometry of a simple straight strand

A loaded simple straight strand is illustrated in Figure 1. Configuration and cross section of this strand consists initially of a straight center wire of radius R_1, surrounded by $m=6$ helical wires of wire radius R_2. Center wire radius is chosen sufficiently such that to prevent outer wires touching each other. This is the general aim to decrease frictional effects due to bending of the strand.

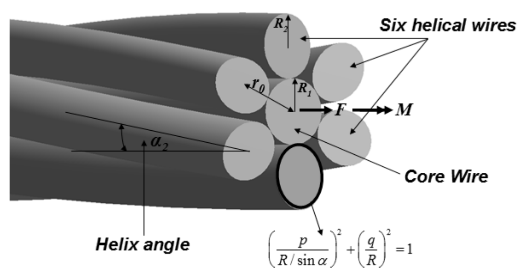


Figure 1: Loaded simple straight strand wire (1+6)

Modeling the wire strand

A simple straight strand model is constructed with a center wire of radius R_1, surrounded by six helices wound around with the helix angle α_2. The helix angle α_2 is determined by $\tan\alpha_2 = p_2/2\pi r_2$, where p_2 is the pitch length of an helical wire, $r_2 = R_1 + R_2$. The (1+6) wire rope strand model is constructed by using both SolidWorks® and Abaqus/CAE®. Core wire is created in the Abaqus/CAE while the helical wire is created in SolidWorks and imported in Abaqus/CAE. While constructing the helical part in certain lengths, number of control points to build a helical wire causes the main problem. Control points are used while sweeping procedure and number of increase in these points fails the operation. To create a good helical part, a helical path created in SolidWorks. It is easy to model a helix using the standard tools. A helical wire is constructed by sweeping a helical path with a circular surface. After modeling a long wire using this procedure and passing to the Abaqus with ParaSolid format or IGES format creates non-proper surfaces which even could not meshed. Approximately 400 mm length can be taken as an upper bound which can be built with proper modeling techniques. There are two possibilities to construct long and good wire strand models. One of them is to create a pitch length wire and then using linear and radial patterns to construct the whole wire strand model. The other is to create the whole model using SolidWorks and then using a mesh program such as HyperMesh® to create the mesh of the model and then transfer it to the Abaqus/CAE. The second scheme is much more coherent to the most of the problems. Because there should be a constraint to connect each wire to the preceding one and this connection creates gaps during the analysis stage at the first scheme. But the whole model is created in SolidWorks and meshed with HyperMesh to create the whole model at a unique part at the second scheme.

Another important issue is the element selection and the mesh size. If the created mesh is coarse then problem may not converge due to increased time steps and there will be no solution. Eight-node linear brick, reduced integration hourglass control type element is used for the analysis in Abaqus. Triangular and tetrahedral elements are geometrically versatile and are used in many automatic meshing algorithms. It is very convenient to mesh a complex shape with triangles or tetrahedra, and the second-order and modified triangular and tetrahedral elements in Abaqus/CAE are suitable for general usage. However, a good mesh of hexahedral (brick) elements usually provides a solution of equivalent accuracy at less cost. Quadrilaterals and hexahedra have a better convergence rate than triangles and tetrahedra. For this reason, brick elements are preferred to use. The material density, elasticity, plasticity and Poisson’s ratio are defined as problem dependent. Coefficient of friction is defined as 0.2 and general contact controls is defined because of the interaction capability of each wire in the strand. Explicit analysis is carried on the constructed model. For the axial loading models, one edge of the wire strand is constraint with encastre boundary condition while force is applied to the other edge. While modeling the bending of a wire strand over a sheave, a straight wire strand is put over a sheave which is defined as a rigid body. Two edge of the wire strand is wrapped around the sheave to construct the analysis model. Analysis stage begins after force or displacement boundary conditions are applied to the edges of the strand.

Numerical Example and Model Verification

In the literature, one of the most important test results were presented by Utting and Jones in 1987 [7]. Jiang *et.al.* has created a finite element model and solved the axial loading problem over a cross-sectional part and given the results in [8]. An illustrative example is given here which includes theory, test and the numerical results. The axial loading problem geometry definitions and numerical model parameters are given in Table 1.

Table 1: The design values of the strand

Strand diameter	11.4 mm	Elasticity modulus	188000 N/mm^2
Center wire diameter R_1	3.94 mm	Plasticity	24600 N/mm^2
Outer wire diameter R_2	3.73 mm	Poisson's ratio	0.3
Pitch length p	115 mm	Friction coefficient	0.115
Helix angle α	78.2^o	Minimum break load	1765 N
Strand length h	116.92 mm		

The numerical results are compared with the analytical and test results given in Figure 2. It can be concluded that the numerical analysis are harmonious with the theory and the test results.

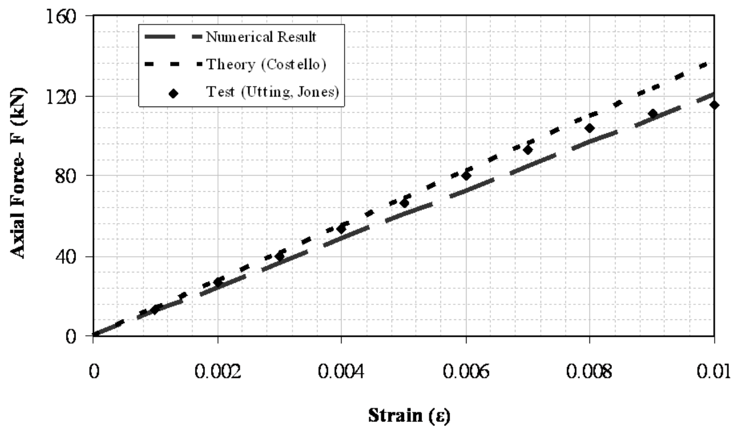


Figure 2: Test, Theory and Numerical result comparison

Bending of a strand over sheave illustrative example

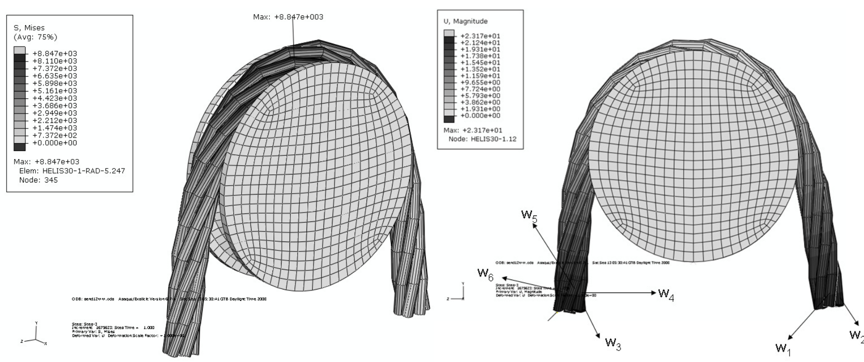
One of the most important applications of wire rope is the bending around a sheave problem where a straight wire strand is considered. The geometrical and the numerical analysis model parameters are given in Table 2. A straight wire strand with the given parameters and a sheave whose diameter is 12mm is created. The sheave is placed tangent to the straight wire strand at the mid point at first step of the analysis. Then 20mm displacement boundary condition is applied to the each edge of the strand to bend the wire strand around the sheave which completes the first step.

Table 2: The design values of the bent strand over a sheave

Strand diameter	2.35 mm	Elasticity modulus	190000 N/mm^2
Center wire diameter R_1	0.83 mm	Poisson's ratio	0.29
Outer wire diameter R_2	0.76 mm	Friction coefficient	0.2
Pitch length p	18.8 mm	Minimum break load	6011 N
Helix angle α	75.12^o	Applied force	1000 N
Strand length h	45 mm		
Sheave diameter	12 mm		

At the second step of the analysis one of the edges of the strand is fixed by defining encastre boundary conditions while 1000*N* concentrated force is applied to the other edge of the strand. Thus, pulling one of the edges of the strand is analyzed in this example. Figure 3(a) shows the von-Misses distribution over the bent wire strand and Figure 3(b) shows the displacement distribution over the wire strand. It can be clearly seen that maximum stress and maximum displacement positions of the strand is positioned as expected over the upper midpoint of the sheave and at the fixed edge of the strand respectively as shown in Figure 3(b) where wire numbers are given.

Analysis results for the maximum stresses are 8605, 8358, 8760, 8668, 8847, 8686 N/mm^2 for wires W_1 through W_6 and 8039 N/mm^2 for the center wire. According to the analysis W_5 has the maximum von-Misses stress value.



(a) Von-Misses stress (b) Deformation

Figure 3: Stress and deformation distribution of the wire strand bent over a sheave

Wire Rope Model

Due to its complex geometry it is still more difficult to model and analyze wire strands using numerical methods. Most of the analysis are based on the modeling arc length of a simple straight strand to see the mechanical behavior of the strands using finite element method and compare the numerical solution with the experiment or analytical solutions. The aim of the present study considers a realistic complete model instead of an arc length of a strand. The construction of a real model starts with the core strand. A straight wire is surrounded by 6 helical wires with right lay produce the core strand. Then the outer wires of the 6 outer strands are constructed with the use of double helix geometry. Double helix is modeled with the parametric equations because of its complex nature [11]. A code is generated to construct the both single and double helical wires in a pitch length and run in SolidWorks®. The outer double helical wires are organized to construct a left lang lay wire rope. The complete final model of the wire rope is constructed in Abaqus/CAE® consisting of 7x7 wire rope as shown in Figure 4. Simple straight strand geometry was discussed and then the double helical wires were modeled using parametric formulations given in [11].

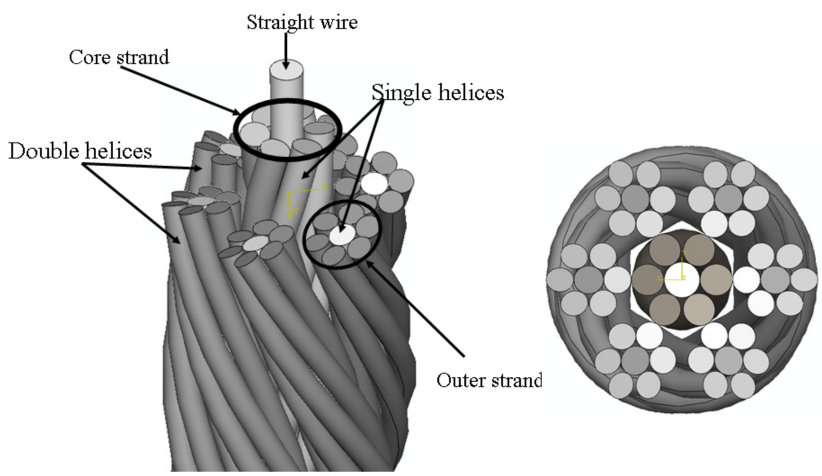


Figure 4: A left lang lay 7x7 wire rope structure with cross section

CONCLUSION

In this paper, three-dimensional wire strand model and analysis a realistic numerical analysis procedure is explained briefly. An illustrative example showing the validity of the presented numerical model is given for straight wire strand and compared with Costello's theory and the test results gathering from the literature. Bending model of a strand over a sheave is constructed in three-dimensional environment and analyzed numerically. Using the proposed 3-D wire rope model further analysis could be followed analyzing the behavior of the wire ropes under certain loading conditions.

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