ANALYSIS WITH FINITE ELEMENT METHOD OF WIRE ROPE

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Abstract:
Wire rope strands are examined in computer environment. For this purpose generated models about finite element analysis of wire ropes, conducted researches and fatigue condition of wire ropes are examined. The condition required in order not to contact outer wires with each other is expressed with the purpose of modeling simple strand and the generated model is confirmed by using defined geometrical values. 3D solid model of simple strand used in finite element analysis is generated in CAD software SolidWorks™. Finite element analysis of simple strand is done by FEA software ANSYS™. Fatigue analyses are done by ANSYS/Workbench for experimental groups generated by using 3 different parameters which are strand length, helix angle and force range. Graphics which show fatigue life variance of axial loaded simple strand, are created by obtaining fatigue life distribution according to Goodman approach.

Keywords: WIRE ROPE, FINITE ELEMENT METHOD, ANALYSIS, FATIGUE

1. Introduction
Wire ropes, which are main components of systems like elevator, crane, etc., work at high stress conditions and are almost always subject to variable loads. The primary mechanisms responsible for stress fluctuations in wire ropes can be specified as tension-tension, bending-over-sheaves, free bending and torsion. Tension-tension fatigue determines the wire rope fatigue resulting from applying of variable axial tensile loading.

Most analytical solutions in the literature are based on the solution of equilibrium equations in connection with the boundary conditions and physical situation of the problem. In theoretical studies wire ropes are analyzed in different conditions, but most of them exclude frictional and contact effects. It is possible to consider frictional, contact and the other working conditions by using solid modeling and finite element analysis in computer environment.

Wire rope theory is based on equilibrium equations which are derived by Love. General equilibrium equations of a thin rod on arc length $s$ is derived and presented. Hruska’s study is the first one in literature investigating the mechanical behavior of wire ropes using the simplest constraints. Green and Lawes, in general theory of rods mention to restricted and linearized form to determine stress in helical wires in wire ropes. Costello [1] and then Utting and Jones [2,3] make different assumptions relative to the rope geometry or the interwire contact condition, considering each wire in a wire rope as a helical rod.

Analytical models of wire rope theory are compared by Cardou and Jolicoeur. According to this study mechanical models of helical strands are purely tensile or fiber model, semi-continuous strand model, theory of thin rods model and helical rod model [4]. Helical rod model is introduced by Philips and Costello based on the equilibrium equations derived by Love [1]. The method of separation the strand into thin wires and solution of the general nonlinear equations for the bending and twisting of a thin rod subjected to line loads is accepted and six nonlinear equations of equilibrium for each wire are examined [5].

Chaplin and Potts investigate the researches about wire rope endurance in offshore applications in a critical review. Fatigue mechanisms are determined depending on working conditions of wire rope used in these applications and experimental studies are presented comparatively [6]. Feyrer investigates the behavior and fatigue properties of wire ropes under tensile load and also behavior of wire ropes under bending and tensile stresses in his book in which his theoretical and experimental studies are collected [7].

The finite element method is used with a simplified model in a study conducted by Carlson and Kasper [8]. Chiang generates a small length of single strand wire rope for geometric optimization purposes [9]. Jiang et al. develop a concise finite element model using solid brick elements in which helical symmetry features of a strand is considered. Precise boundary conditions are developed by simplifying finite element model [10]. Jiang and Henshall investigate a finite element model of a 1+6 simple strand in order to determine the termination effects. The effects of a fixed-end termination on the contact forces (pressure) and the relative movements between the wires along the contact lines are determined [11]. Knapp et al. develop a software code for the geometric modeling and finite element analysis of wire ropes. Finite element mesh and nodes for all components of the model are generated automatically [12]. Elata et al. present a new model for simulating the mechanical behavior of a wire rope with an IWRC. The generated model considers the double-helix configuration of individual wires within the strand. The double-helix geometry is modeled with the parametric equations because of its complex structure [13]. Erdömez and Imam introduce an accurate 3D modeling approach and finite element analysis of wire ropes with IWRC [14]. Erdömez and Imam introduce a new methodology to define and to model nested helical structure (NHS) for wire ropes, and to present an accurate wire rope 3D solid modeling, which can be used for finite element analysis [15]. Erdömez and Imam develop a code considering both single and double helical geometry in modeling and analyzing wire ropes with IWRC and use it in modeling [16]. Stanova et al. derive mathematical models in order to generate geometric models of wire rope and strands and implement them in the CAD software CATIA™ [17]. Stanova et al. implement the generated mathematical geometric model in the FEA software ABAQUS/Explicit in order to predict the behavior of the multi-layered strand under tensile loads. Anil investigates the parameters effect on fatigue life of axial loaded simple wire rope strands in computer environment [17].

2. Fatigue in Wire Ropes
Essentially, the process of fatigue in metals involves crack initiation and propagation from some stress concentrating defect by mechanisms which involve local plasticity at the crack tip under the influence of a variable load. Wire ropes are constructed of a complex assembly of steel wires. The division of the load bearing capacity between many wires has two essential benefits; (i) it assures the essential combination of high axial strength and stiffness with bending flexibility, and (ii) allows the structural use of essentially brittle steel at very high stresses with subdivision of the structure to isolate local fractures.
Wire ropes work at high stress levels and are almost always subject to variable loads. In a transport system, tension fluctuations are the dominant source of fatigue stresses. In a given time and sufficiently high fluctuation in stress range, fatigue is inevitable. However complete failure of a wire rope requires that many wires are broken in close proximity. But the fatigue of a single wire in the wire rope is always more than stress fluctuation. There is usually some other process which exacerbates and accelerates the fatigue, and which focuses the process to specific locations. This process depends on fretting between wires or another degradation mechanism such as wear, corrosion, etc. The primary mechanisms responsible for stress fluctuations in wire ropes can be collect under four titles; tension-tension, bending-over-sheaves, free bending and torsion [6].

### 3.1 Generation of Simple Strand Model

The configuration and cross section of a loaded simple strand is shown in Fig. 2. For initial condition the strand include a center wire of radius R1, surrounded by m=6 helical wires of radius R2. It is assumed that the center wire is of sufficient size to prevent the outer wires from contact each other in order to minimize the effect of friction in the bending of the strand [1].

Fig. 2 Simple strand construction under load.

The initial radius of the helix for an outer wire is given by the expression

$$r_2 = R_1^2 + R_2^2$$  \(\text{(3.1)}\)

The initial helix angle \(\alpha_2\) of an outer wire is determined by the expression

$$\tan \alpha_2 = \frac{p_2}{2\pi r_2}$$  \(\text{(3.2)}\)

\(p_2\) is the initial pitch of an outer wire. An expression is derived to determine the minimum value of \(R_1\) in order to prevent the outer wires from contact each other. A wire cross section in a plane perpendicular to the strand is shown in Figure 2. Since the wires are thin, the equation of cross section can be assumed as elliptical and (p,q) is any point on the ellipse. Hence,

$$\left(\frac{p}{R\sin \alpha}\right)^2 + \left(\frac{q}{R}\right)^2 = 1$$  \(\text{(3.3)}\)

Also at the point \((p_1,q_1)\) the slope is equal to

$$\tan \left(\frac{\pi}{2} - \frac{\pi}{m}\right) = \tan \left(\frac{\pi}{2} - \frac{\pi}{m}\right)$$  \(\text{(3.4)}\)

Hence, the solution for \(p_1\) and \(q_1\),

$$p_1 = \frac{R}{\sin \alpha} \tan \left(\frac{\pi}{2} - \frac{\pi}{m}\right) \frac{1}{\sin^2 \alpha + \tan^2 \left(\frac{\pi}{2} - \frac{\pi}{m}\right)}$$  \(\text{(3.5)}\)

$$q_1 = \frac{R \sin \alpha}{\sqrt{\sin^2 \alpha + \tan^2 \left(\frac{\pi}{2} - \frac{\pi}{m}\right)}}$$  \(\text{(3.6)}\)

It is shown that \(r = b_1 + q_1\) in Figure 2. Hence,
\[ b_1 = p_1 \tan \left( \frac{\pi}{2} \frac{m}{m} \right) \]  

(3.8)

\[ r = R \left[ 1 + \frac{\tan^2 \left( \frac{\pi}{2} \frac{m}{m} \right)}{\sin^2 \alpha} \right] \]  

(3.9)

Equation (3.9) defines the radius of the wire helix in which the wires are just in touch with each other. Hence, the equation,

\[ R_2 \left[ 1 + \frac{\tan^2 \left( \frac{\pi}{2} \frac{m}{m} \right)}{\sin^2 \alpha} \right] < R_1 + R_2 \]  

(3.10)

must be valid in order not to be in contact outer wires with each other [1].

Geometrical parameters of the simple strand model which is wanted to be generated are given in Table 1.

**Table 1. Geometrical parameters of simple strand**

<table>
<thead>
<tr>
<th>Geometrical parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter (d)</td>
<td>11,400mm</td>
</tr>
<tr>
<td>Center wire diameter (2R₁)</td>
<td>3,940mm</td>
</tr>
<tr>
<td>Outer wire diameter(2R₂)</td>
<td>3,730mm</td>
</tr>
<tr>
<td>Helix angle (α)</td>
<td>78,2°</td>
</tr>
</tbody>
</table>

Hence, the initial radius of the helix for an outer wire is (see Eq.3.1)

\[ r_2 = R_1 + R_2 = 3,835mm \]

The initial pitch length \( p_2 \) of an outer wire is (see Eq.3.2)

\[ \tan 78,2° = \frac{p_2}{2\pi 3,835} \Rightarrow p_2 \approx 115,341mm \]

The condition required in order not to contact outer wires each other is (see Eq.3.10)

\[ R_2 \left[ 1 + \frac{\tan^2 \left( \frac{\pi}{2} \frac{m}{m} \right)}{\sin^2 \alpha} \right] < R_1 + R_2 \]

Simple strand model generated in Solidworks\textsuperscript{TM} for finite element analysis is shown in Figure 3.

![Generated simple strand model for finite element analysis](image)

**4. Analysis of with Finite Element Method**

In this chapter fatigue analysis of the simple strand is done with FEA software ANSYS\textsuperscript{TM}. The equations derived by Costello are regarded as a baseline, and finite element analysis results are compared with theoretical results in order to confirm generated finite element model. Fatigue life under axial loading and the effect of considered parameters on tension-tension fatigue life are investigated for generated strand models. Experimental groups have been generated by using 3 different parameters which are strand length, strand helix angle and force range.

### 4.1. Contact Condition

Contact condition is existed between wires of simple strand. Two cases are regarded; (i) determination of contact region and (ii) friction. Geometrical values provide the required condition expressed with Equation 3.10 in order not to contact outer wires each other. Hence, the contact is existed between center wire and outer wires.

Generated models remain over a critical length, considering the contact condition between center wire and outer wires. Simple strand lengths regard as 10 to 16 per cent of pitch length for defined geometric values. Jiang and Henshall [11] report that no contact is existed between the center wire and outer wires, from the fixed-end to 3 per cent of the pitch length. The contact loads (pressure) increase gradually and relative movements through the contact lines between center wire and outer wires for simple strand lengths which are from 3 to 9 per cent of the pitch length. The contact loads (pressure) reach the uniform value, and relative movements between center wire and outer wires reach zero value for simple strand lengths which are over 9 per cent of pitch length.

### 4.2. Boundary Condition

Boundary conditions are compatible with the model generated by Costello. One end is fixed in all directions while the other end is restrained not to displace in \( x \) and \( y \) directions. Considered loading condition is applied to the end, which is restrained not to displace in \( x \) and \( y \) directions, up to \( \varepsilon = 0,015 \) strain value in increments of \( \varepsilon = 0,001 \) linearly by using the displacement equivalent to the axial strain in order to confirm simple strand model.

### 4.3. Material Properties

Material model for finite element analyses is defined as bilinear isotropic (BISO) which is a non-linear material model. The curve in linear region is elasticity modulus of material.

In consequence of axial strain for fixed-end case, numerical force values obtained by finite element analysis are in accordance with theoretical force values of Costello. Numerical moment values obtained by finite element analysis are also in similar trend with theoretical moment values of Costello.

### 4.4 Finite Element Analysis

The method of finite element analysis of simple strand which is done in ANSYS Workbench environment of FEA software ANSYS\textsuperscript{TM} is presented. It is known that no contact is existed between outer wires of simple strand model, but it is between center wire and outer wires. Contact condition is defined as Frictional between center wire and outer wire and friction coefficient is inserted as 0,115.
longer fatigue life of the higher helix angle can be the less contact approximately linearly with the increase of strand length for variable helix angle. It is supposed that the reason for the tension-tension fatigue life increases with the increase of helix angle for 80° helix angle. Although strand length seems a little more effective than force range on number of fatigue cycles, they are both in similar trend approximately.

5. Conclusions

In present study, finite element analysis results and theoretical results of Costello are compared for fixed-end condition. Results in similar trend indicate that the generated model corresponds to the theoretical model. Experimental groups are generated by using 3 different parameters which are strand length, helix angle and force range. Strand lengths are 15mm, 17.5mm and 20mm with 78.2° helix angle and ε = 0.006 axial strain for each model. Force range is changed by using the axial pre-strains equivalent to the axial forces. The effect of variables used in experimental groups on number of load cycle is investigated.

References