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ANALYSIS OF WIRE ROPE "33X6X19S" ROPE BEHAVIOR BY MODELING IN 3D (CAD) AND NUMERICAL SIMULATION (CAE)

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Abstract. *This paper analyzes the behavior of the steel wire rope "33x6x19s" using numerical simulation through CAD (3D modeling) and CAE (Finite Element) tools. The study focuses on the deformation of the wire, specifically the elongation and normal stress and shear stress inside the wire rope where it is not possible to visually check.*
The paper will first discuss how the mathematical model of the complete wire rope is established. The wire rope has a complex geometric helix shape, as some wires may be straight, simple or double helix. Due to this complex shape, it was necessary to utilize the tool PTC Creo Parametric™ (Pro/ENGINER).
For the analysis of traction and friction effects in the cables core, the FEM Abaqus/CAE™ software was used.
By comparing the results from the analytical equation of wire rope elongation with the results from numerical simulation, excellent results were obtained. These results demonstrate that the modeling and simulation performed are reliable.

Keywords: *Wire rope, Stress Analysis, Finite Elements Analysis, CAD, CAE.*

1. INTRODUCTION

Breaks in wire ropes and lifting elements lead to risks regarding operations and machinery, resulting in the endangerment of people. Thus they must be designed with high safety coefficients. These elements are under constant tension and intermittent loads create wear. The wear occurs externally against the pulleys and internally by the relative displacement between the wires and strands. It is noteworthy to mention that the wire rope is helical; when pulled it produces internal tensions, torsion, friction, deformation by contact, variations of the local plastic limit, fatigue and crushing.

Based on this information, the study in question focuses on deformation, specifically on elongation, normal stress and shear stress inside the wire rope where one cannot visually check. In attempts to reduce the number of experiments that must be conducted to find out the wire ropes response to stress, various authors (Jiang, *et al.*, 2003) (Nawrocki and Labrosse, 2000) (Cardou, 2006) have published articles regarding their development of theoretical models. However, most of these articles are dedicated solely to strand and local effects that occur in the cables rather than the modeling of the complete wire rope. This case study will focus on "33x6x19 Seale" (33x6x19s) wire rope's behavior, using 3D modeling with finite element numerical simulation (CAE).

The study was based on using qualitative research; one of the theorists used was (Feyrer, 2007), who discusses tensions, kinematics and geometry of wire ropes. This research made it possible to collect the required data needed for this study.

CAD and CAE tools are used to create virtual models, thus eliminating the need to physically manufacture parts for analyses. However, in order to obtain reliable results, the mathematical model must be represented exactly like the physical object. As shown in this study, the wire rope has an incredibly complex geometry, making the use 3D graphic software a key tool to achieve proper results in the study.

The general purpose the study is to evaluate the stress and strain of the wire rope when it is subjected to traction, through utilizing engineering graphic software. The most important results of this work are as follows:

• The equations describing the wires (Usabiaga and Pagalday, 2008) (Wang, *et al.*, 1998) became solid 3D parametric curves using PTC Creo Parametric ™/Pro Engineer software (PTC Creo).

• Using Abaqus/CAE™ software both the normal and shear stresses and strains in center of the wire rope as a whole rope was obtained.

• By analyzing the elongation in detail, it was found that the elongation in the center of the wire rope is greater than the elongation of the wire as a whole. This is due to the friction and large number of wires in contact.

• By comparing the Abaqus/CAE results with the elastic elongation equation, the finite element method (FEM) was validated.

• The tensile stress in the center of the wire rope was compared with (Feyrer, 2007) equation.

2. METHODOLOGY

2.1 Wire Rope 33x6x19s

For this study the Wire Rope 33x6x19s was selected. The particular characteristics of this wire rope are described below:

Wire Rope 33x6x19s is considered to be a Lang lay rope. Lang lay rope cables consists of wires and strands that are twisted in the same direction. This configuration facilitates handling and makes the wire rope more flexible, as well as adds greater resistance to fatigue and abrasion. However, it has low resistance to kneading and is subject to internal wear, twists and strains. Wire ropes have been named according to their characteristics, analyzing the nomenclature gives significant information about the wire rope type. Below is a breakdown of “Wire Rope 33x6x19s” (Filho, 2009), (NBR ISSO 03108, 1998):

• "33" is the diameter of the cable.

• “6” is the number of strands; it consists of six strands with 15 to 26 wires in each strand. This gives the wire good resistance to bending and abrasion.

• “19s” represents the rope type and composition. The rope type is a Seale type, in Seale types the last layer of wires are disposed large diameter wires, this adds a strong resistance to abrasion. The composition is 9 + 9 + 1 = 19 wires.

The core is formed by Independent Wire Rope Core (IWRC), in another words, it has a wire rope as a core. This kind of structure is very common in the industry because it combines the flexibility and tensile strength characteristics

2.2 Geometry for CAD design

To create the 3D model of the wire rope a program called PTC Creo was used. It is a 3D CAD software that allows you work in a three dimensional environment and design solid models. The model has volume and surface area so you can calculate mass properties directly from the elaborate geometry (Foganholi, 2001). A great advantage of this software is the parameterization; it can build anything from simple shapes to shapes with complex geometry, such as wire ropes.

The wire rope consists of a straight line, simple helices and double helices (Wang, *et al.* 2013). The cable is basically formed by three layers; they will be referred to as S1, S2, and S3. The first (S1) is the core strand or only core, the second one (S2) is the intermediate strand and the third (S3) is the external strand (Usabiaga and Pagalday, 2008). Figure 1 shows the whole structure and each layer structure of 33x6x19s. For a better understanding, the straight wire is W10. The simple helices are W11, W20 and W30. The double helices are W21, W31 and W32.

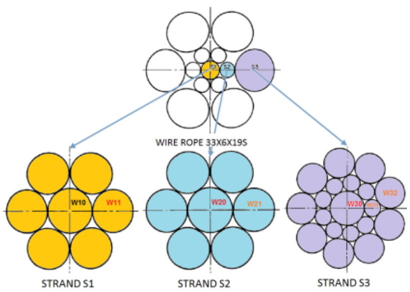

Figure 1. Structure wire rope 33X6X19s

2.2.1 Designing straight wire (W10)

The straight wire is the component of the cable with the simplest geometry. It is the first wire to be designed; it is in the center of the wire rope and is used as a reference to construct the other wires. It can be design with different tools on PTC Creo. However, this study only focuses on using the revolve command; this command is widely used in the construction of revolution parts (Waqas, 2010). The revolve command is common in CAD software, it is a basic command which creates curves that work as a profile for modeling, once a 2D profile is created it can be rotated on an axis to create a 3D surface (Brito, 2011).

2.2.2 Parametric equation

Mathematical equations allow the development of a model to represent the actual cable (Usabiaga and Pagalday, 2008).

2.2.3 Simple Helix (W11, W20, W30)

For this helix the wires and strands cover a spiral path. The equations (1, 2 and 3) below are used to generate the curve in three-dimensional planes according to (Usabiaga and Pagalday, 2008) and (Wang, *et al.*, 1998):

$$X_s = r_s \cos(\theta_s) \quad (1)$$
$$Y_s = r_s \sin(\theta_s) \quad (2)$$
$$Z_s = r_s\, \theta s \tan(\alpha_s) \quad (3)$$

where,

X_s, Y_s, Z_s - components along X, Y and Z in coordinate system.

r_s – helix radius.

θ_s - the angle of rotation of wires.

α_s - helix angle.

In the PTC Creo software there is a function called *curve from equation*. (Fialho, 2006) states that modeling "*Datum curve*" allows you create trajectories by equations. This equation can be expressed in terms of cylindrical and spherical Cartesian coordinates. In the model described in this paper cylindrical coordinates are used to express the equation in three-dimensional planes. This option contains three variables to be considered: r, t and theta, where r is r_s, theta is the amplitude e.g. length and the Z will be Z_s. This procedure is applied to all the simple helix components.

2.2.4 Double Helix (W21, W31, W32)

The double helix is formed by a helix that covered a simple helix. The parametric equations (4, 5, and 6) used for double helix (Andorfer, 1983):

$$X_w = X_s - r_w \cos(\alpha_w) \cos(\theta_s) + r_w \sin(\alpha_w) \sin(\theta_s) \sin(\alpha_s) \quad (4)$$
$$Y_w = Y_s - r_w \cos(\alpha_w) \sin(\theta_s) + r_w \cos(\alpha_w) \sin(\theta_s) \sin(\alpha_s) \quad (5)$$
$$Z_w = Z_s + r_w \sin(\alpha_w) \cos(\alpha_w) \quad (6)$$

where,

X_w, Yw, Z_w - components along X, Y and Z in coordinate system.

r_w – helix radius.

α_w - helix angle.

The application used is the same as the single helix application. However, it changes values and the equation of Z_w is added in the text window.

Another important step is the wire diameter extrusion through the built curve. The 3D model software has the sweep command which can be applied to a cross section of a curve (CENGAGE, 2013).

Following this concept, it is possible to apply this procedure to any wire rope type by changing the values of the equations.

Table 1 and 2 contain all of the dimensions of the related model (Wang, *et al.*, 1998), it is very important to make the model close to the real wire rope in order to increase the accuracy and create a realistic simulation.

After setting all the equations described above in PTC Creo, the wire rope 33x6x19s composition is reached as shown in Fig. 2.

Table 1. Structural parameters of strands 33x6×19s wire rope.

Strand	Form	N° of Strands	Strand radius (mm)	Helix Parameters		
				r_s(mm)	α_s(rad)	L_s(mm)
IWRC: S1	Straight	1	2.271	-	-	-

S2	Simple Helix	6	2.016	4.287	1.236	77.48
Seale:						
S3	Double Hélix	6	5.110	3	1.225	199.61

Table 2. Structural parameters of wires in 33x6×19s wire rope.

Wire	N° of wires per strand	Wire radius, (mm)	Helix parameters						
			r_s	α_s	L_s	r_w	α_w	L_w	n
Straight:									
W10	1	0.801	-	-	-	-	-	-	-
Simple Helix:									
W11	6	0.735	1.536	1.286	33.02	-	-	-	-
W20	1	0.704	4.287	1.236	77.48	-	-	-	-
W30	1	1.456	11.41	1.225	199.6	-	-	-	-
Doble Helix:									
W21	6	0.656	4.287	1.236	77.48	1.360	1.414	54.3	1.508
W31	9	0.712	11.41	1.225	199.6	2.168	1.784	62.6	-3.385
W32	9	1.243	11.413	1.225	199.61	3.867	1.940	62.6	-3.385

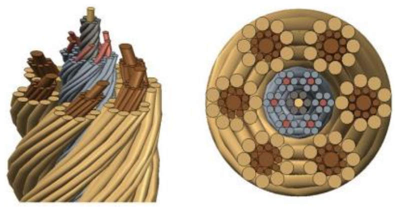

Figure 2. Wire rope 33X6X19s 3D model by PTC Creo

2.3 Using CAE, Finite elements mesh

The mathematical model was produced using the PTC Creo software (Tavares, 2014) and exported with Parasolid® format to Abaqus/CAE software. It is a finite element software that has an extensive tool library to solve problems of variability, making it one of the most reliable CAE programs (ABAQUS, 2000).

To study the internal behavior of the wire, an 8 millimeter long segment was analyzed. The mesh elements are small and generate a big matrix to solve, this requires a high consumption of RAM which can sometimes cause errors. For this reason, it is recommended that only a small segment be analyzed. Figure 3 shows the model developed for the analysis (blue color). The meshes are composed of rectangular hexahedral and solid elements. These are the most suitable elements for solid forms similar to helical springs (Arcanjo, 2008). The dimensions of each element are approximately 0.25x0.25mm.These dimensions are essential to obtain adequate finite element analysis results, because they allow for greater precision and a good quality mesh (Kim and Sankar, 2011). The mesh of each independent wire was generated using Abaqus/CAE. The parameters generated with the meshes: number of elements is 1’319’988 according to the type of C3D8R Abaqus/CAE library, in general, is to reduce integration with a point located in the middle of the element. Figure 4 shows the elements and the mesh generated for the wire rope.

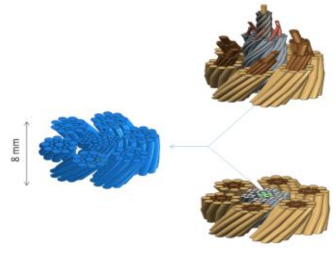

Figure 3. Model developed for the analysis

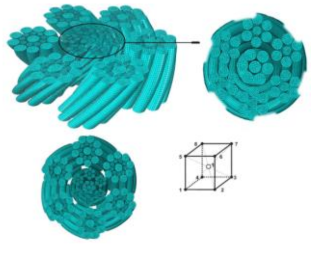

Figure 4. Verification of mesh accuracy

2.4 Material property

The material used is similar to AISI 1020 steel with a modulus of elasticity, E=200 GPa and Poisson's ratio is 0.3, because the wires are in contact the friction coefficient is 0.15 (Wang, *et al.* 2013). It assumed that the wires are a homogeneous material and isotropic in the entire volume. For the calculations, EIPS quality is considered with a tensile strength of 1770-2160 MPa (CIMAF, 2009).

2.5 Boundary condition, Interaction and Loads

The wire ropes are used most often pulled at their extremes. In the study one side is clamped (Coutinho, 2008) for all wires as is shown in Fig. 5. Another important point is the kinematics, using coupling, an Abaqus' restriction tool, a reference point was placed at a certain distance from the cross section. Relating this point with the face as shown in Fig. 5. This reference point is added a rotation restriction on wire rope axial and an strain of 0.018 accord to the length and applied force. This value is different than Wang´s simulation (Wang, *et al.* 2013). He uses a smaller value and gets important results. Its cable has a different configuration in terms of construction with only two layers, demonstrating the significant influence of the constructive form of the wires rope in the simulation results. Thus, kinematics is reached when the wire rope is being pulled. For the contact between the wires the interaction pairs and discretization technique Surface-Surface (S-S) was used, making relations surfaces "master and slave" between the wires (Shibu. *et al.*, 2011), (DASSAULT, 2013). As contact property was used penalty method that is widely used to solving contact friction problems (Sant´Ana, 2005) (Stanova, 2011) (Affonso, 2012). Another important factor is the size of the relative displacements (sliding). In this case finite-sliding was used where the contact area and pressure distribution are calculated from the deformed models (CENGAGE, 2013). The axial load's purpose is to pull the wire rope, therefore, it was added in a reference point (Stanova, 2011). The study was conducted with loading 177'990 N acquired by the Design Factors is 4 for static loads and Minimum Breaking Load (MBL) is 72.6 Tf for this specific wire rope (CIMAF, 2009). Figure 6 shows the axial loading in RP point.

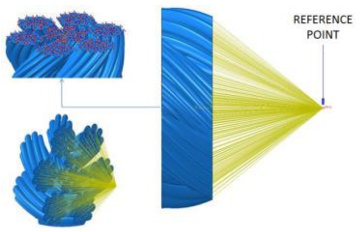

Figure 5. Model boundary condition

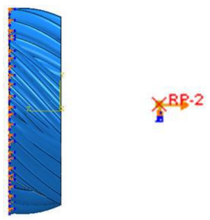

Figure 6. Axial loads

3. RESULTS AND DISCUSSION

The construction of the model was created using the software PTC Creo. This one of the softwares to create simple geometries, such as the wire rope core, as well as complex geometries, such as simple and double helices. When exporting 3D model to Abaqus/CAE there was an incompatibility extension formats, to solve this problem the Parasolid extension was used. Figures 7 and 8 shows the important results that may be obtained using the whole wire rope model: U Magnitude: resultant displacement (Elastic Elongation) (Δ_L); Max Principal: Maximum principal stress (σ_1); S33: normal stress in Z axis i.e. the direction of the wire rope axis (σ_Z); Mises: equivalent Von Mises stress (σ_{EQ}); S12: shear stress in the 1-2 plane i.e. X, Y plane (τ_{XY}); S23: shear stress in the 2-3 plane i.e. Y, Z plane (τ_{YZ}).

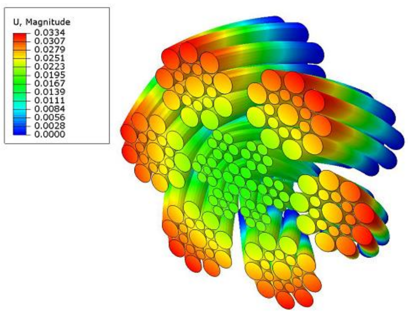

Figure 7. Elongation results about whole wire rope

The high incidence of internal stresses on wire rope has been found in analysis by the finite element Abaqus/CAE that includes shear stress or torsion. This can be observed in the cross section as shown in Fig. 8. The symmetric stress distribution predicting the response compatible with the interactions between the wires due to large contact with each other. According to the color diagram it was possible to prove that there are tensions tangencies promoting torsion at moment static loading but these shear stresses are smaller than normal or tensile stresses.

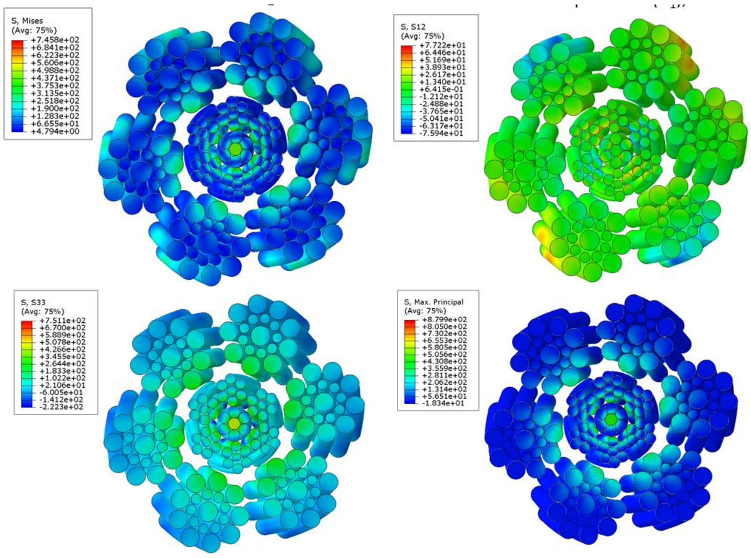

Figure 8. Stress distribution in the whole wire rope

Therefore, a separate analysis was done for core S1 with the same conditions of the whole model; the results are shown in Fig. 9 and 10. The values of the normal and tangential stresses in both analyses are smaller than the fracture point of materials. Figure 7 shows the elongation results. In the center of the wire rope the elongation is smaller due the number of wires in contact. This is caused by friction between the wires. The elongation of the whole wire rope was 0,0334mm and the core analysis was 0.828mm.

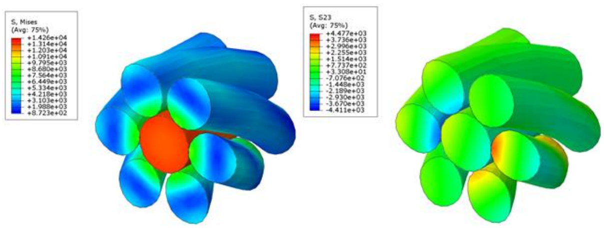

Figure 9. Stress distribution in core analysis

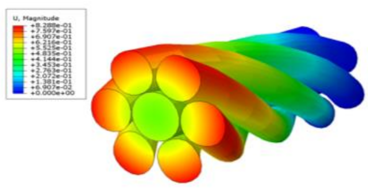

Figure 10. Core elongation

These results are similar to Wang and Shibu (Wang, *et al.* 2013), (Waqas, 2010) results, who state that the highest stresses are in the central wire core and the wires friction with each other as shown in Fig. 7.

The computational time was very high for the whole wire rope because the quantity of interaction between the wires and the number of elements are more than one million. It took 3.8 hours to calculate using a PC configuration Intel Core 2.5GHz processor i7-2920XM 16.0 GB of RAM and a 64-bit system, while core analysis was 5 minutes with the same configuration.

3.1 FEM and Analytical Calculations Results

The simulation results were great, however to have reliable results a validation is necessary. These results were compared with elastic elongation equation and the tensile stress in the center wire by (Feyrer, 2007) equation.

The first one is elastic wire rope elongation that is found by (CIMAF, 2009):

$$\Delta L = \frac{P.L}{E.A_m} \tag{7}$$

where,

Δl: elastic elongation; P: applied load, (177’990 N); L: length of rope, (8 mm); E: modulus of elasticity which was selected the value of 98.066 GPa to whole wire rope and 142.196 GPa to core considering both new elements; Am: metal area, this area is found by

$$Am = F.Dc^2 \tag{8}$$

F: multiplication factor, (0.395); Dc: nominal diameter of the wire rope or strand in millimeters, (33mm).

The simulation result of the elongation was 0.0334 as show in Fig. 7. This was compared (Tab. 3) with the elastic elongation, that was 0.0337. This validates the method and reliability of the 3D mathematical model that was generated by PTC Creo, with only 0.89% of error. These simulations are more precise for the S1 core, where the error was only 0.48%, which ensures the survey credibility.

Table 3. Comparison of analytical results calculated with finite element method (%).

Model	Load(N)	Analytical	Simulation	%
Whole Wire rope	177’990	0.0337	0.334	0.89
Core S1		0.824	0.828	0.48

As seen in previous studies and in the results of this work, a high incidence of normal stress is the central core wire called W10. Thus this can calculate these stresses in the wire and compare these results with the (9) equation described by the author (Feyrer, 2007):

$$\sigma_{tk} = \frac{F_k}{A_k} = \frac{\dfrac{\cos^2 \alpha_k}{1 + \nu_k \cdot \sin^2 \alpha_k} \cdot E_k}{\displaystyle\sum_{i=0}^{n} \left(\frac{z_i \cdot \cos^3 \alpha_i}{1 + \nu_i \cdot \sin^2 \alpha_i} \cdot E_i \cdot A_i \right)} \cdot S. \tag{9}$$

where,

σ_{tk} - real tensile stress in wires of the layer *k*.

Fk - tensile force in a wire of a specific wire layer k.

A_i, A_k - the cross-section of a wire in the wire layer *i* and *k*.

α_i, α_k - lay angle of a wire in the wire layer *i* and *k*.

ν_i, ν_k - Poisson´s ratio of a wire in the wire layer *i* and *k*.

E_i, E_k - the elasticity module of a wire in the wire layer *i* and *k*.

Z_i – number of wire in the wire layer *i*.

S - the strand tensile force.

Where the tensile stress in the central wire (core) is $\sigma_{t,0}$. It can be observed in the colors analysis of the normal stress bar (σ_z) in Fig. 8 that the stress on W_{10} is between 345.5 and 426.6 MPa then it can deduce the following condition:

$$345.5 \text{ MPa} < \sigma_{t,0} < 426.6 \text{ MPa}$$

The analytical result of the calculation using the Feyrer equation (9) was 388.67 MPa. The results obtained by the FEM simulation Abaqus/CAE meet this condition, thus making them reliable. This study was validated by Analytical basis mainly of great importance for the study equations in terms of wire rope.

4. CONCLUSION

By analyzing the studies of the wire rope it can be concluded that the principal stresses are internal, especially in the central core wire by contact between wires which may cause possible rupture failures. The accuracy of the results can be emphasized in the quality of the 3D geometric model generated by the PTC Creo software, where it can get the parametric equations of simple and double helix.

The elongation that produced by the simulation once the analysis takes effect in the entire wire is less than when the core is analyzed. This occurs for the reason that there is a great amount of wires in contact; by consequence, the effect of the friction is greater. The elongation of the entire cable was 0.0334mm, while in the core it was 0.828mm.

In order to validate the applied methodology, the simulation results were compared with the results of the elastic elongation analytical equation. The same for the complete cable (0.0337mm) and for the core (0.824). The percentage of error was 0.89 and 0.48% respectively, which constitutes a conclusive validation of these results and the reliability of the mathematical model.

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