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Formulation and validation of an efficient numerical model for energy conductor cables based on finite beam elements

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Abstract.

Brazil is a country with continental dimensions and the availability of energy throughout the national territory becomes a challenge, since hydroelectric power plants are responsible for 75% of the generation of energy in the country, which requires large extensions of transmission lines according to the Ministry of Mines and Energy (1). These transmission lines are formed by cables that need clamps for their fixation. Most cases of conductor cable failures occur in the contact region within the clamp where visual inspection or the application of sensors for measuring voltages and controlling the failure process becomes an activity of high level of difficulty according to CARDOU (2).

This work develops a methodology through computer simulation using finite element analysis to analyze the contact stresses in 7 layers and 120 wire helical cables. According BAUMANN (3) beam elements were used, this strategy aims to obtain a lower computational cost compared to modeling with solid elements. The validation of the results is made by comparing the results for the tensile test present in the literature in the models developed by LALONDE (4) and JUDGE (13) and also with analytical results. The models showed convergence of results, showing a difference of about 1%. The commercial software Ansys APDL version 2020 R1 is used to develop this work.

Keywords: Multilayered wire strands, Finite element modeling, Inter-wire contact, Beam-to-beam contact, Frictional contact

Introduction

The availability of energy is a fundamental factor for the socioeconomic development of any nation. In the particular case of Brazil, hydroelectricity corresponds to about 75% of the energy matrix, which is directly related to the country's natural conditions. This type of energy will remain predominant according to projections until 2030 (1).

As the country's dimensions are continental, it makes necessary the implementation of large transmission lines to ensure that energy can reach the most diverse areas. One of the regions of the country that has great prominence is the Is the North, which is not yet connected to the National Interconnected System (SIN) and has great generation potential given by its large water resources. In order to be explored, it demands socio-environmental feasibility analysis, which can bring benefits to the States and communities where these hydroelectric plants are located.

As they are geographically distant from the other centers, for the generation of energy in the North of the country, it is necessary to have transmission systems that are adequately dimensioned for the supply of large blocks of energy, over long distances according Ministry of Mines and Energy (1). These transmission lines employ conductive cables that connect the plants to the consumer centers, which are fixed along their trajectory by suspension clamps, dampers or spacers in the fixation tower. Usually, it is at these fixation points that the cable failure occurs, leading to great damage according AZEVEDO (5).

Wind-induced vibrations are known to cause fatigue failure in these transmission cables, producing alternating flexural stresses in the region of contact between the conductor and the fastener. In this region, conductors are also subjected to significant static loads, bending forces and a force exerted by the clamp. This combination of loads promotes conductor wear and also wear at inter-wire contact points that can lead to premature cable failure. According to LALONDE (6) Given the critical importance of maintaining the structural integrity requirements of the transmission networks, it is necessary to understand these load conditions on the cables as a tool to prevent failures.

Most of these failures in conductor cables occur in the contact region inside the clamp where visual inspection or the application of sensors for measuring voltages and controlling the failure process becomes an activity of high level of difficulty according CARDOU (2). In attemptto to overcome this difficulty, a thermograph is used in an attempt to identify the areas of failure of the wires, yet, as the wind exchanges heat with the cable, the fatigued zone is cooled, making this method ineffective according to AZEVEDO (5).

That is why it is necessary to use other tools to analyze the stresses that are associated with the cable failure process. One of the strategies that can be used is the Finite Element (EF) modeling using an approach with 3D beam elements, this methodology has the advantage due to its computational cost, when compared to the employment of 3D solid elements. For LALONDE (4) this strategy can be used not only for energy conducting cables, but also for other multilayer cable configurations used in Engineering.

This work has computational nature and aims to contribute to the development of a methodology for simulating contact tension between transmission line cables using simplifications in order to compare with experimental results. The main objectives of this computational model are the comparison of its tensile values to results found in literature and to data obtained experimentally.

2 Mathematical formulation

Multilayer cables are made up of a straight wire core and helical concentric layers of round wires wound clockwise and counterclockwise alternatively. They can be applied for various applications, with energy transmission being one of the main ones. In most cases they are composed of two materials, being the steel core responsible for absorbing the mechanical loads, in addition to the several layers of aluminum wires responsible for carrying the electric current. Figure 1 shows the formation of a multilayer cable with a straight core and successive layers.

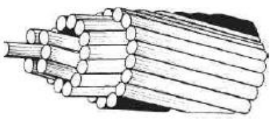


Figure 1: Basic structure of helical cable
Source: PAPAILIOU, 1995

Historically, there is an variety of ways of solving the problem analytically, but they showed not being so promising, because although this type of conductor seems to have a simple construction, they are quite complex to describe mathematically, especially with regard to their mechanical behavior. One of the difficulties is the calculation of the flexural stiffness which for some models is assumed to be the sum of the flexural stiffness of the individual wires.

This assumption assumes that the individual wires are each flexed around their own longitudinal axis, so the stress can be calculated for the outermost layer of the conductor. This model has the advantage of being a simple application, but its validity can be doubtful, since the calculated stresses represent only a trend and do not always reflect the real stresses. There is a discrepancy between the stresses calculated as described above and the actual stresses in the wires, especially in the innermost layers, where failure occurs frequently.

One of the most important steps towards the solution of this problem is the study of conductor flexion, including the effect of variable stiffness caused by the construction of the conductor, also considering the effect of internal friction and curvature according PAPAILIOU. (7).

Some researchers introduced the slip between wires by means of Coulomb's Friction Law, considering pressure between layers and difference in axial tension in the contact of the wires in certain curvatures. This procedure results in a gradual variation of the flexural stiffness between two extremes: EI_{max} (without sliding according to equation 1) and EI_{min} (complete sliding, equation 2). In the equations E_j, A_j, γ_j and R_j represent the elastic modulus of the wire j, cross-sectional area, angular position and radius of the corresponding layer, respectively, while I_{0j} is the moment of inertia of the wire (in relation to its own axis).

$$EI_{max} = \sum E_j(I_{oj} + A_j R^2{}_j sin^2(\gamma_j)) \quad (1)$$

$$EI_{min} = \sum E_j I_{oj} \quad (2)$$

In the study presented by Papailiou in the late 1990s, a model was described in which friction was also defined by the axial tension of the wire. The model leads to a variation in flexural stiffness between EI_{max} and EI_{min} based on the distance from the neutral axis of the wire. Incorporating EI variations along the wire under free bending conditions, the approach was implemented in a finite element analysis. Comparisons with experimental results showed good correlations second PAPAILIOU (8).

Several authors have proposed complete 3D modeling using finite elements. In these numerical studies, each wire of the multilayer cable is discretized with solid 3D elements, where the contact elements simulate all types of contact between wires. In some cases, the model is responsible for plastic deformations.

However, the full 3D solid modeling approach inevitably generates models that lead to high computational costs. This partly explains why EF-based 3D yarn models are almost exclusively limited to short and axi-symmetrical wire loads (axial tension and torsion). In practice, to minimize the contour effects, multilayer yarn analysis in conditions of free bending would require a model capable of supporting long spans with short pitch length. Unfortunately, current finite elements models seem inadequate when it comes to efficiency by analyzing the flexion free of multilayer wires according LALONDE (4).

Some more recent works have developed an intermediate approach using finite element modeling, in which it eliminates some theoretical hypotheses, making them computationally accessible. This approach uses one-dimensional 3D elements known as beam elements combined with a contact algorithm to describe the wire geometry and contact interactions.

Second ZHOU (9) this strategy was evaluated in the modeling of a single layer cable, in which contact interactions were managed through coupling equations between corresponding nodes, the slip between wires not being considered, being limited to single layer cables under small deflections. Other studies have extended the approach of modeling multilayer cables, but subjected to large deformations and displacements, the model being validated through comparison with experimental results in which the study showed that frictional forces control hysteresis and flexural stiffness LALONDE (4).

3 Methodology

3.1 Generation of multilayer cable geometry:

Multilayer cables are made up of a straight wire core and helical concentric layers of round wires wound clockwise and counterclockwise alternativaly. For the elaboration of a mathematical model that represents this type of cable, there are some geometric parameters that are used: Diameter in the core (d0); Wire diameter of each layer (d_i), shown in yellow in figure 2; Average layer radius (r_i), represented in red in figure 2, where i represents the layer number.

To calculate these rays, equations 3 and 4 are used, in which the latter is the representation for any layer. And the helix parameter of the cable's central line is controlled by equations 5 to 7, where ∅ represents the rotation angle being positive counterclockwise and negative clockwise, hw is the length to go through a step represented by equation 8 and α is the angle between the axis of the spiral element and a line parallel to the longitudinal axis (lay angle) second WU (10).

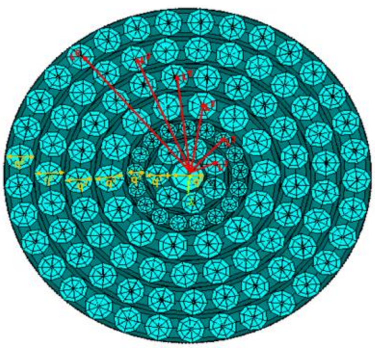


Figure 2: Geometric parameters multilayer cable

$$r_1 = \frac{d_0 + d_1}{2} \tag{3}$$

$$r_i = r_{i-1} + \frac{d_{i-1} + d_i}{2} \quad (4)$$

$$x = r * cos\, \emptyset \quad (5)$$

$$y = r * sen\, \emptyset \quad (6)$$

$$z = \frac{r}{tang\ \alpha}\ \emptyset \quad (7)$$

$$h_{wi} = \frac{2\pi r_i}{tang\ \alpha_i} \quad (8)$$

Parametric equations are used to generate the spatial curves of the center line of the wire for each layer, in this model all wires can be represented by the equations by changing only the parameters according WU (10). Ansys APDL - Ansys Parametric Design Language software was used to develop this work.

Using the equations presented above, two cable models with length L = 200 mm were generated. The first has 7 wires and a layer, its geometric and material parameters are shown in table 1, using 1209 beam elements for its representation; the second with 120 wires and 6 layers has the parameters shown in table 2, which was discretized with beam elements approximately 8 mm long and for its representation 61464 elements were used.

Table 1: Geometric parameters of the 7-wire cable

Layer	Number of wires	d_i(mm)	E (GPa)	ν	E_t(GPa)	σ_y(MPa)	α_i(º)
Core	1	3.94	188	0.3	24.6	1540	-
1	6	3.73	188	0.3	24.6	1540	11.8

Table 2: Geometric parameters of the 120-wire cable

Layer	Number of wires	d_i(mm)	E (GPa)	ν	E_t(GPa)	σ_y(MPa)	α_i(º)
Core	1	5.8	188	0.3	5.5	1540	-
1	7	4.3	188	0.3	5.5	1540	11.94
2	17	3.2	188	0.3	5.5	1540	14.75
3	14	5.3	188	0.3	5.5	1540	14.37
4	21	5.0	188	0.3	5.5	1540	15.23
5	27	5.0	188	0.3	5.5	1540	15.66
6	33	5.0	188	0.3	5.5	1540	15.95

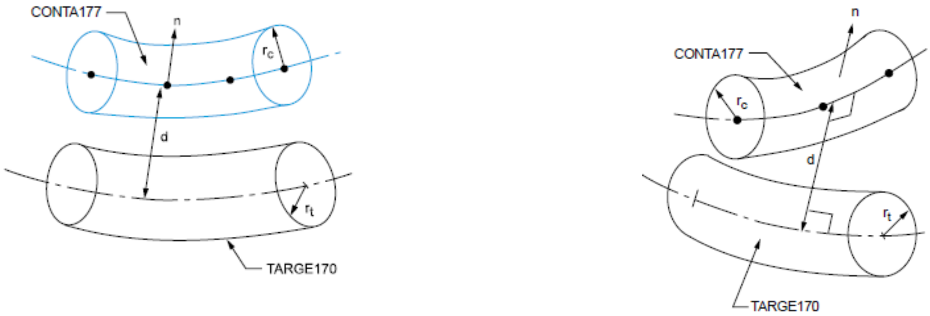
The procedure is repeated for the other wires of the other layers that the cable may have, it is important to note that the more points are used for discretization, the greater the fidelity of the representation of the central axis of the cable. After the generation of the middle axes of each of the wires, the elements are generated, which have a cylindrical shape and have the same diameter as the wire of each layer. Figure 3.a shows the elements created to represent the 7-wire model and 3b for the 120-wire model.

3a: 7-wire model 3b: 120-wire model

Figure 5: Representation of the multi-layer cable with elements

3.2 Contact problem

Within a multilayer cable, there is radial contact between two layers and lateral contact between wires of the same layer, so the methodology of forming contact pairs between cylindrical elements was used, because between these elements there is line contact. For that, beam elements were used, which can be TARGET 170 and CONTA 177. Ansys APDL allows to use these elements for parallel contact and cross contact, figure 4a shows the use in parallel contact and 4b in cross contact.



4 a: External Contact (Two Beams Roughly Parallel)   4 b: External Contact (Two Beams Cross Each Other)
Figure 6: Contact type using CONTA 177 and TARGET 170
Source: ANSYS Mechanical APDL Contact Technology Guide

For the radial contact (contact between different layers) it was considered that there were a parallel type contact in which a wire of the second layer, for example, is a master element (TARGET 170) and the wire of the first is the slave element (CONTA 177). For each yarn in the first, the combination was made with all the wires yarns in the second and so on until the sixth layer.

In the lateral contact between the wires of the same layer, it was considered a cross-type contact in which the pairs between wires of the same layer were considered, taking the first as an example, there is the contact between the first wire and the second wire, then the contact of the second wire with the third and so on until all pairs between wires of the first layer are completed. The same procedure was performed on the other layers.

In addition to the numerical analysis, it is possible to calculate the contact force between the helical cable elements. According to CARDOU (2) the contact force for cable with 1 layer is represented by a load distributed along the element and can be calculated by equation 9, where F1 is the traction force, R1 represents the average radius between the core and the first layer and α is the lay angle.

$$q = \frac{F_1}{R_1}\, sen^2\alpha_1 \tag{9}$$

4 Results

For the validation of the present model, a tensile test was performed in order to compare with the results presented in the literature for cables of the same geometry and material. In this test the cable was embedded in one of its ends and in the other a load T was applied, as shown in the schematic representation of figure 5. The graph in figure 6a shows the comparison of the results between the model developed in this work and some other works for the 7-wire cable for the relationship between force versus deformation and figure 6b shows the comparison for the 120-wire cable.

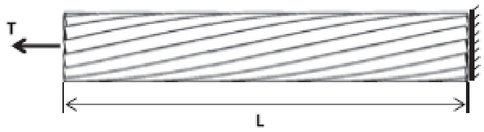


Figure 5: Schematic representation of the test
Source: Lalonde, 2017

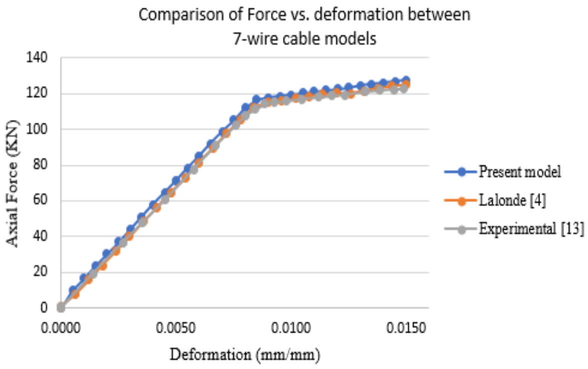


Figure 6a: Comparative graph strength versus strain for 7-wire tensile test

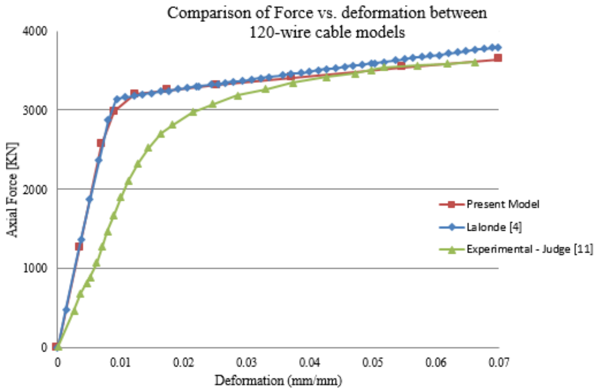


Figure 6b: Comparative graph strength versus strain for traction test model 120 wires

It is possible to observe from the graphs for tensile tests that both models developed in this work showed convergence with the results obtained in the literature, both for the plastic elastic regime. In the 7-wire model, the results also converged with the experimental results. The 120-wire model showed a difference within the plastic regime of the order of 1% for the model developed by Lalonde, which is mechanically acceptable. Comparing the results of the 120-wire model with the experimental results, there was a deviation of the curve within the elastic regime.

The execution time of the simulated traction test was 15 seconds for the model with 7 wires and 3 hours for the model with 120 wires, in the analyzes a core i7 computer with 32 GB of RAM was used. Figure 7a shows the displacement result for the 7-wire model and figure 7b shows for the 120-wire cable, where the blue region is the crimped region and the red region where the load was applied. Table 3 shows the comparison of contact forces for the 7-wire cable model, through which it is possible to observe that the difference between the present model and the analytical results were below 1%.

Other validations will be made later for this model in order to compare with results obtained experimentally in order to evaluate how much the model developed in this work represents the physical reality of the contact problem between wires of a cable formed by 6 layers and 120 wires.

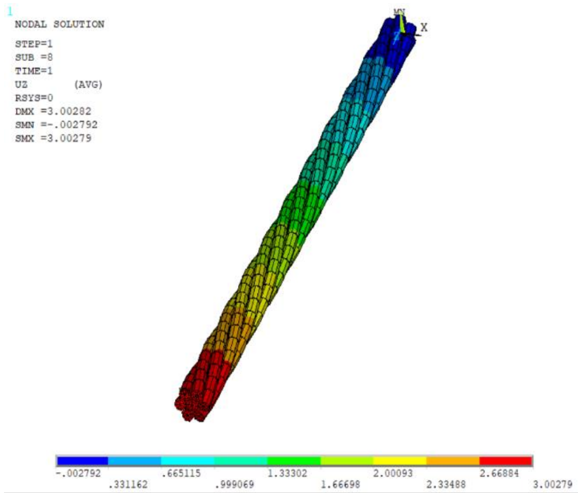


Figure 7a: Results displacement for cable with **7** wires

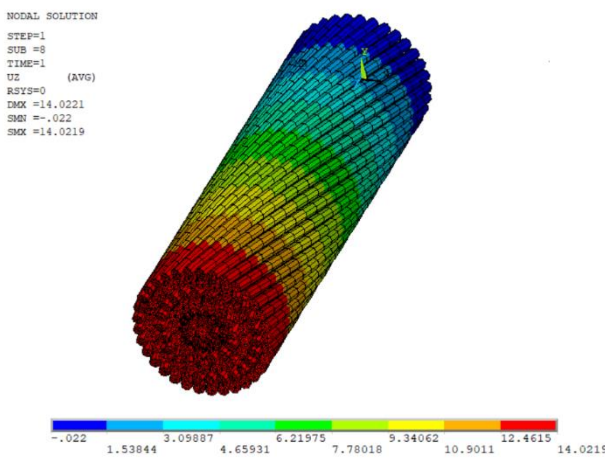


Figure 7b: Results displacement for cable with 120 wires

Table 3: comparison of contact forces for the 7-wire cable model

Strain (ε)	p (N/mm) theoretical	p (N/mm) Lalonde [4]	p(N/mm) Present Model	Diference(%) Presente model- theoretical	Diference(%) Presente model- Lalonde [4]
0.0020	48	43	47.9	0.21%	11.40%
0.0040	90	85.9	90.2	0.22%	5.01%
0.0060	132	127.9	132	0.00%	3.21%
0.0080	174	169.9	173	0.57%	1.82%
0.0012	191	189.9	190.1	0.47%	0.11%

4 Conclusions

This work is computational in nature and aimed to contribute to the development of a methodology for simulating contact tension between transmission line cables using simplifications in order to compare with experimental results, with the specific objectives of validating the computational model through comparison of tensile test results with results presented in the literature and validation of the model by comparing tensile test results obtained experimentally.

Through the results it was possible to observe that the model converged to results close to those of the other models within the elastic regime and presented a small divergence of the order of 1% within the plastic regime. A second, however, experimental validation will be developed for this same cable in order to compare the results.

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6 References

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