NUMERICAL SIMULATION OF HIGH-VOLTAGE COMPOSITE CABLE FOR OFFSHORE WIND

Fouad ECH Cheikh[1,2], Raj Jyoti Das[1], Monssef Drissi-Habti[1*#], Nicolas Ravot[2], Fabrice Auzanneau[2]

[1]PRES LUNAM IFSTTAR COSYS Dept, CS4 Route de Bouaye, 44344 Bouguenais Cedex France
[2]CEA, LIST, F-91191 Gif-sur-Yvette, France
fouad.echcheikh@cea.fr
raj.jyoti-das@ifsttar.fr
monssef.drissi-habti@ifsttar.fr
nicolas.ravot@cea.fr
fabrice.auzanneau@cea.fr
*Director of The Consortium Durability of Intelligent Structures (http://macsisit.blogspot.fr)
#To whom correspondences should be addressed (monssef.drissi-habti@ifsttar.fr)

Keywords: Submarine Power Cable, Offshore Wind, Renewable Energy, Mechanical Loading, Finite Element Analysis, Contact, Friction

Abstract

In submarine power cables, conductors are subjected to variety of mechanical loads, that affect the material properties and eventually lead to failure. In this study, a simple straight ”1+6” strand is modelled as a copper conductor and the relationship between mechanical loads to which conductors are subjected to and its mechanical responses is addressed. Finite Element Analysis (FEA) of the model is carried out to study localized non-linear effects such as contact stress, friction and plastic deformation.

1. Introduction

We recently completed a simulation of the mechanical behavior of High-Voltage Cables that takes into account the overall damage mechanisms acting when the cable is loaded under tension and torsion [1]. The conductor of a high-voltage power cable is made of pure Electrolytic Tough Pitch(ETP) copper [2]. Its main features are its ampacity and resistivity. ETP Copper has excellent electrical conductivity but poor mechanical properties. ETP copper exhibits non-linearity below the defined yield limit of 0.2% plastic strain making it difficult to calculate the mechanical load-carrying capacity of copper conductors. Conductor cross-section can vary between circular, stranded with several wires or segmented into different shapes depending on the type of applications. Stranded conductors made up of several layers show better electrical and mechanical performance compared to the others. A stranded conductor due to its geometry and its effect on the mechanical behaviour requires a detailed study. The vast majority of work to date has been devoted to metal steel cable, in which the center and helical wires are homogeneous. There has been considerable research already carried out using analytical models on independent wire rope core (IWRC), where the core and each of the helical wires are described by curved beams, like Hruska (1953), McConnell and Zemek (1982) [7-8], Costello (1997) and Labrosse (1998) [3-4]. Similarly, numerous numerical modelling of 2D and 3D models of steel cable have already been performed but mostly using ANSYS or Nastran (see eg Jiang 1999 [6]).

Excerpt from ISBN 978-3-00-053387-7

Power cable conductors preferably use electrolytic tough pitch (ETP) copper due to high electrical conductivity and low electrical resistivity around 17 Ω/ km. One of the major drawbacks associated with using ETP copper is its poor mechanical properties. For copper conductors the stress-elongation relation for each wire exhibits non-linearity well below the defined limit of 0.2% plastic strain and poor creep properties below maximum cable operation temperature makes it interesting to study numerically. The current work is focusing on these kind of cables. This study is based on a numerical 3D model of the constitutive part of a cable which is a strand made of a central wire surrounded by 6 helicoidal wires cable that is designed and modelled entirely in ABAQUS (Fig. 1).
In the current work, stranded conductors will be studied in detail so as to understand the various mechanical phenomena associated with the conductors when loaded under quasi-static mode.

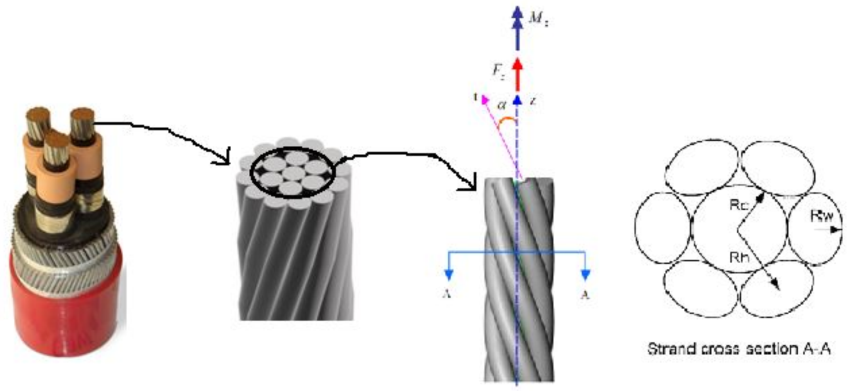

Figure 1. Breakdown of a copper conductor to a "1+6" strand model.

2. Numerical Modelling

This work focusses on creating a 3-Dimensional finite element model that will allow us to analyse and predict the electromechanical behaviour of the conductive cores of EHV cables, specifically their electrical parameters RLCG (R and L are respectively the resistance and inductance per unit length longitudinal, G and C are the conductance and capacity per unit length transversal). The analysis will be conducted based on several parameters related to geometry and mechanical condition of the cable. In case of copper conductors, both elastic and plastic behaviour need to be investigated as copper is a very deforming material and eventually it can influence its electric transport capability. A cable experiences different types and magnitudes of mechanical loads for various periods of time over its whole lifetime. There can be numerous causes leading to plastic deformation of cables under the experience of mechanical loads, amongst them two causes are stated here:

- The cables can be subjected to an overstress following exceptional events. This can lead to generation of plastic deformations if overstress is well beyond the limit of proportionality (Fig. 2). Predicting and analyzing such events are important to study their effects on electric transport capacity of the cables.
- The second case includes the effects of inter-wire friction causing localized plasticity at point of contact between wires (Figure 3). Studying the dependency of extent of plasticity on coefficient of friction and maximum level of stress under fatigue is also important.

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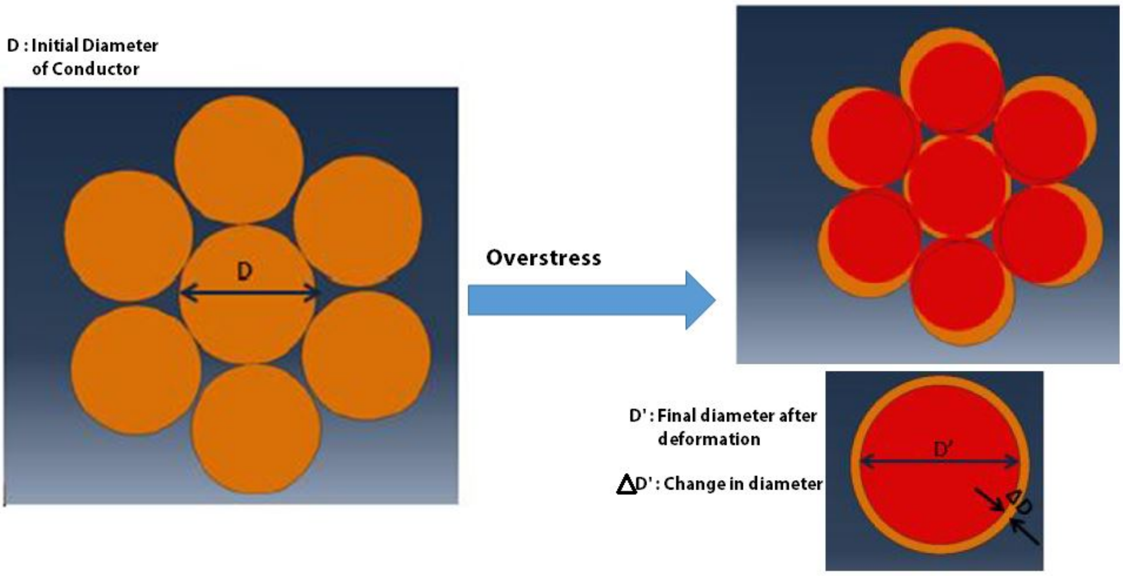

Figure 2. Change in cross-section area of conductor due to Overstress.

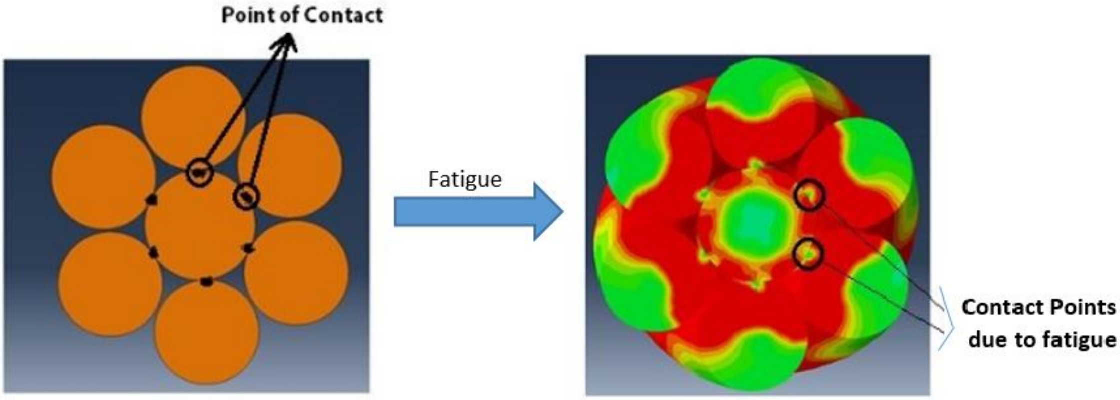

Figure 3. Case of cyclic loading (Fatigue).

Generally, conductors used in cables are set as ”1+6+12” type, where there is a core, six wires helically wrapped around the core and 12 wires are helically wrapped around the six inner helical wires.In our study, we simplified the structure of copper conductor to a ”1+6” model as can be seen in Figure 1. It is done to speed-up the process of FEA because once numerical analysis is performed on a ”1+6” model, it can be easily extended to ”1+6+12” model. The conductor is made from a layer of m constituents called wires, which have a circular section of radius R_w, wounded helically around a core of radius R_c. In general, m is 6 and hence the classic appellation of (1 + 6) is used for a conductor such as that illustrated in Figure 1. The initial radius of the helix for an outer wire is given by the expression:

$$R_\mathrm{h} = R_\mathrm{c} + R_\mathrm{w} \tag{1}$$

The initial lay angle α is measured between a tangent to the helix and cable axis. It is determined by the following relationship:

$$\tan\alpha = \frac{2\pi R_\mathrm{h}}{p} \tag{2}$$

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where p is the initial pitch of an outer wire. The radius of the cable R_g equals to radius of the core wire R_c plus twice the radius of the helical wire R_w:

$$R_\mathrm{g} = R_\mathrm{c} + 2R_\mathrm{w} \tag{3}$$

The size of the core is sufficiently large so that there is only contact between core wire and helical wires and not between the helical wires. This means that the following inequality is strictly respected [3]:

$$R_\mathrm{w} \sqrt{1 + \frac{\tan^2(\frac{\pi}{2} - \frac{\pi}{m})}{\cos^2\alpha}} < R_\mathrm{h} \tag{4}$$

where R_w is the radius of the helical wire, R_h is the helix radius, m is the number of wires in the layer and α is the lay angle. The geometrical parameters of the simple strand model are presented in table 1. Using the values in table 1, the inequality condition in equation 4 is checked and proved:

$$1.865 \sqrt{1 + \frac{tan^2(\frac{\pi}{2} - \frac{\pi}{6})}{cos^2(\frac{11.83\pi}{180})}} \cong 3.791 < 3.835 \tag{5}$$

Table 1. Geometrical parameters of a ”1+6” simple strand.

Geometrical Parameters	Value
Strand Diameter (d)	11.4 mm
Centre Wire Diameter ($2R_\mathrm{c}$)	3.94 mm
Outer Wire Diameter ($2R_\mathrm{w}$)	3.73 mm
Pitch Length (p)	115 mm

3. Numerical Study under axial loading and torsion

While modelling a ”1+6” type cable numerically, the most important issues that need to be addressed are pitch length, minimum cable length to ensure enough contact between center and outer wires of the cable and eliminate boundary condition errors, contact condition, boundary condition and material properties. The pitch length of the cable is defined as $p = 115mm$. The other geometrical parameters are defined in Table 1. For the contact condition, initially there is contact only between core wire and outer helical wires, but once the conductor is subjected to tension and torsion, there is wire-wire and core-wire interactions and hence general contact is defined. Tangential behaviour with penalty friction formulation with different friction coefficients ($\mu = 0.1, 0.2, 0.3$ and 0.4) and normal contact properties are defined.

The two ends of cable are attached to a clamp on which a radial pressure of magnitude 50 MPa is applied. The boundary conditions includes an end fixed in all directions and the other end is constrained to an axial strain of 3.5 mm in z direction and rotation of 0.35 radians around z axis, while it is restrained to not move along and rotate around x and y axes. The material properties used for finite element analysis are: Young's Modulus $E = 117$ GPa, poisson's ratio $\nu = 0.3$, Density = 8.93 g/cm^3 and plastic domain is implemented as data point interpolated function to link yield stress to yield strain. Solid rectangular elements with reduced integration and hourglass control (C3D8R) were selected to mesh all the wires.

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The 1+6 model is created by assembling a single core wire and 6 outer helical wires. Quasi-static simulations are performed using dynamic explicit module of ABAQUS due to non-linearity. This non-linearity is due to the complexity of the geometry and interactions between the wires of the cable. In order to carry-out a quasi-static analysis with dynamic module in ABAQUS, it is required to manage energy balance:

$$\frac{ALLKE}{ALLIE} * 100 < 10\% \tag{6}$$

where ALLKE is kinetic energy and ALLIE is internal energy of the model.
To ensure a quasi-static analysis to follow the energy inequality in equation 6 is not enough, a smooth kinetic energy curve is also important with absence of oscillations. This can be achieved by subjecting the loading and boundary conditions to a smooth amplitude step.

4. Results and Discussion

A ”1+6” wires straight strand of pitch length 115 mm is modelled in ABAQUS and results that are obtained under quasi-static loading compared with Costello’s (1990) and Labrosse’s (1998) models [3-4]. In the numerical model, there is no contact between the outer wires but only between the center wire and outer wires. Contact condition is defined as both frictionless and frictional with varying friction coefficients. Geometric non-linearity is also taken into account. An axial strain ϵ of 3.5 and a rotation, θ_z of 0.35 radians was applied using a smooth amplitude. Rotation and displacement is not allowed in x and y directions. In Figure 4, it can be seen that linear analytic results from Costello’s and Labrosse’s solution are in good agreement with linear FEA results. The non-linear results will be compared once we have the experimental results which are currently under progress. Variation of axial force with moment is presented in Figure 5. In both Figures 4 and 5, FEA analysis with varying friction coefficients is performed and it is seen that the results are the same for different friction coefficients which is in accordance with global loading regime of cables.

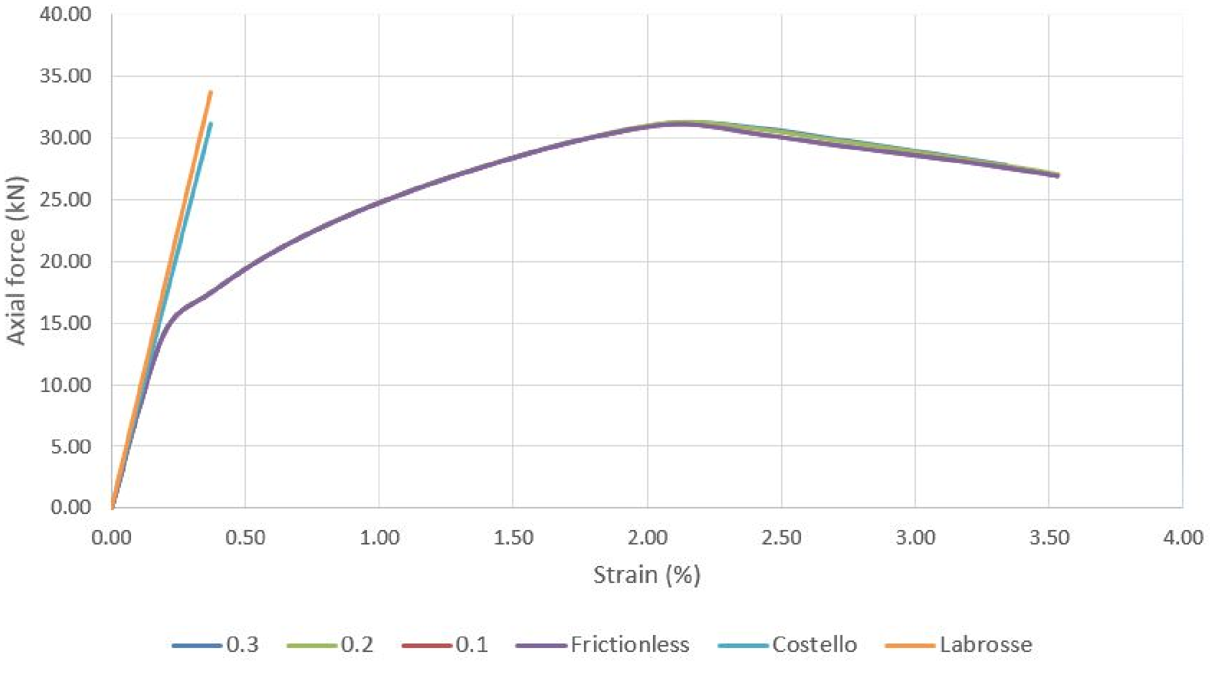

Figure 4. Variation of axial force with strain.

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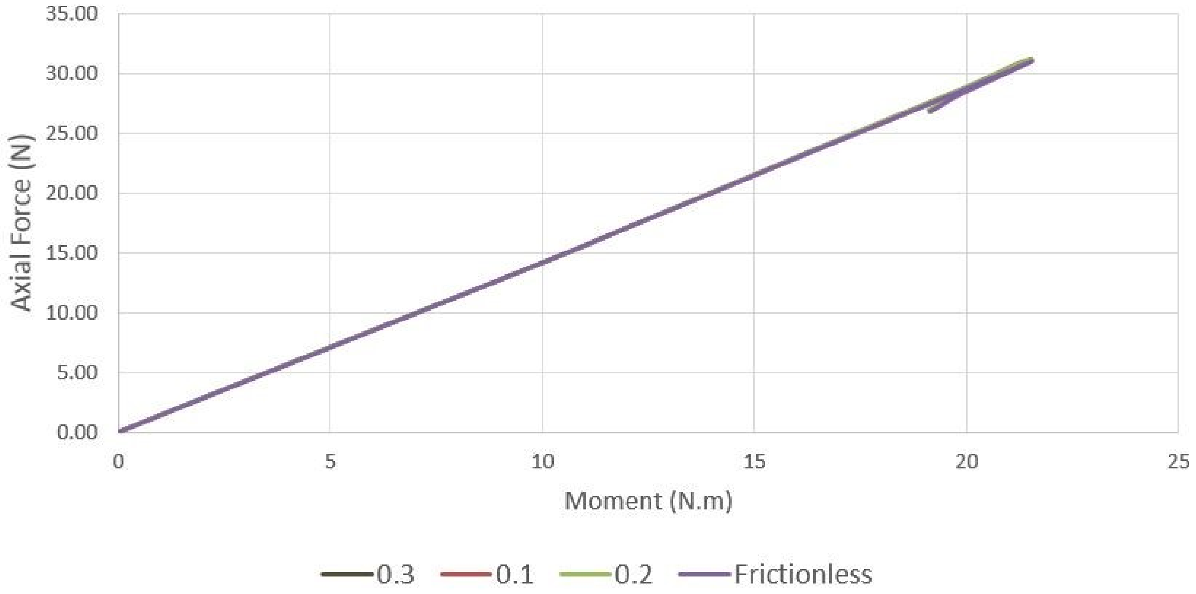

Figure 5. Variation of axial force with moment.

Similarly, in Figure 6, variation of moment versus rotation angle is emphasized. For linear region of the figure, FEA results for different frictional conditions are in better agreement with Costello's theory compared to Labrosse's theory. In this figure too, FEA results are the same for different frictional conditions which is because of considering the conductor as a single system for FEA results. The stress versus strain for the conductor is shown in Figure 7. The results for frictionless and frictional with varying

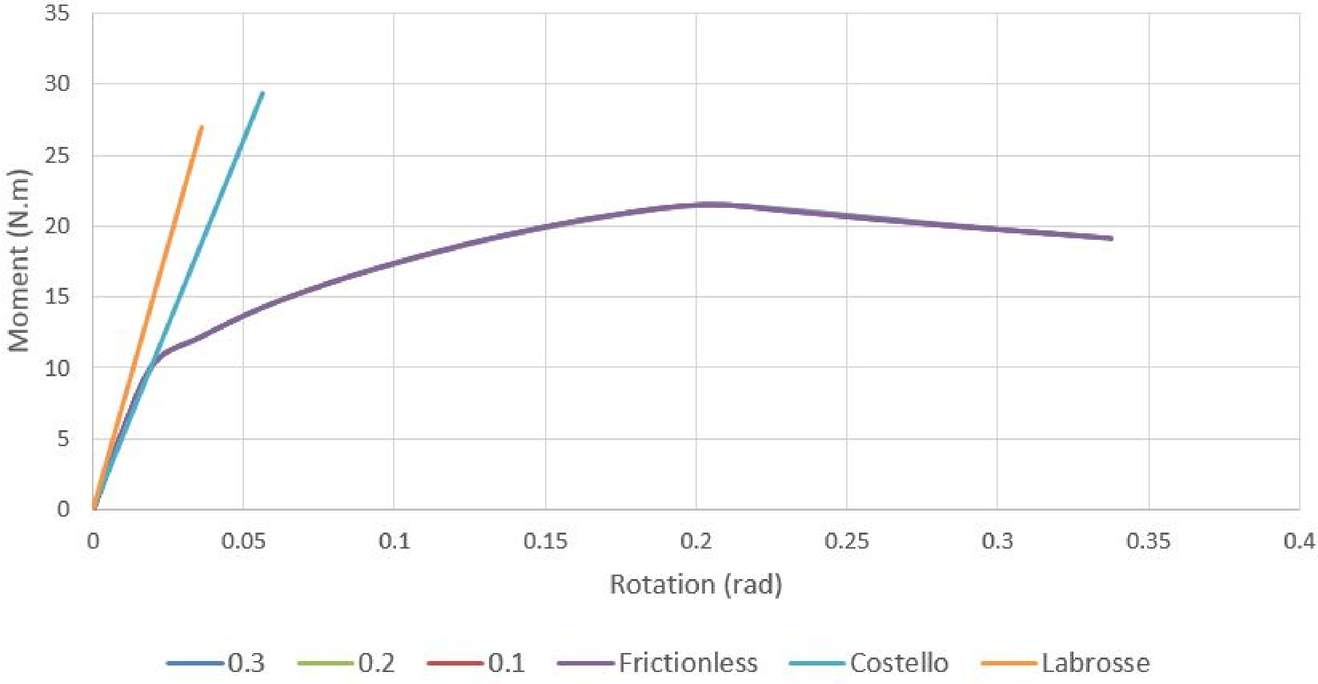

Figure 6. Variation of moment with rotation

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friction coefficients are equal for most part of the graph except a small variation after 2.1% of strain. The frictional dissipation versus strain for different friction coefficients (Fig.8) graph is interesting as normally it is expected to obtain higher frictional dissipation for bigger friction coefficients, but instead it is maximum for 0.2 and minimum for 0.3.

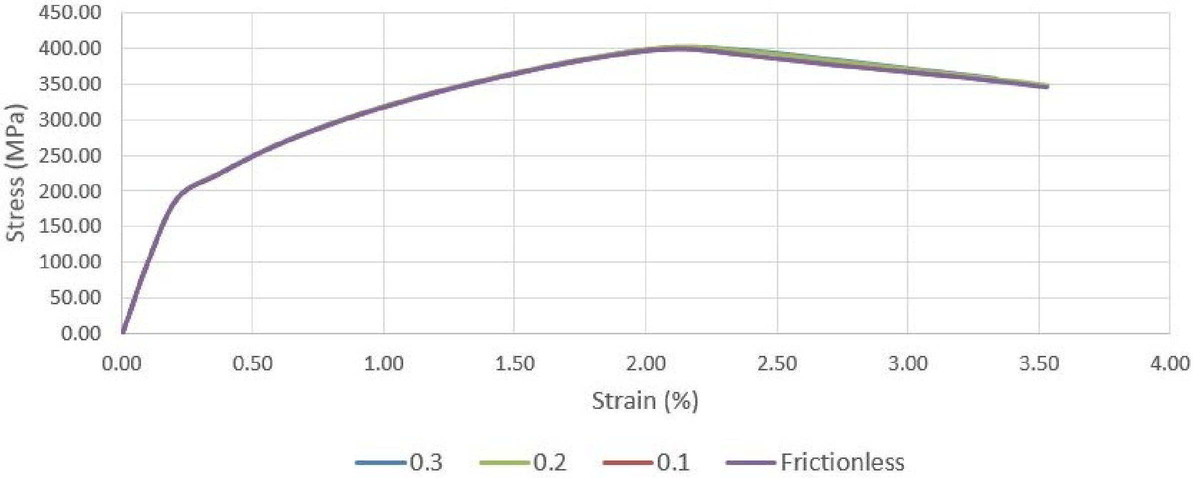

Figure 7. Variation of stress with strain (%).

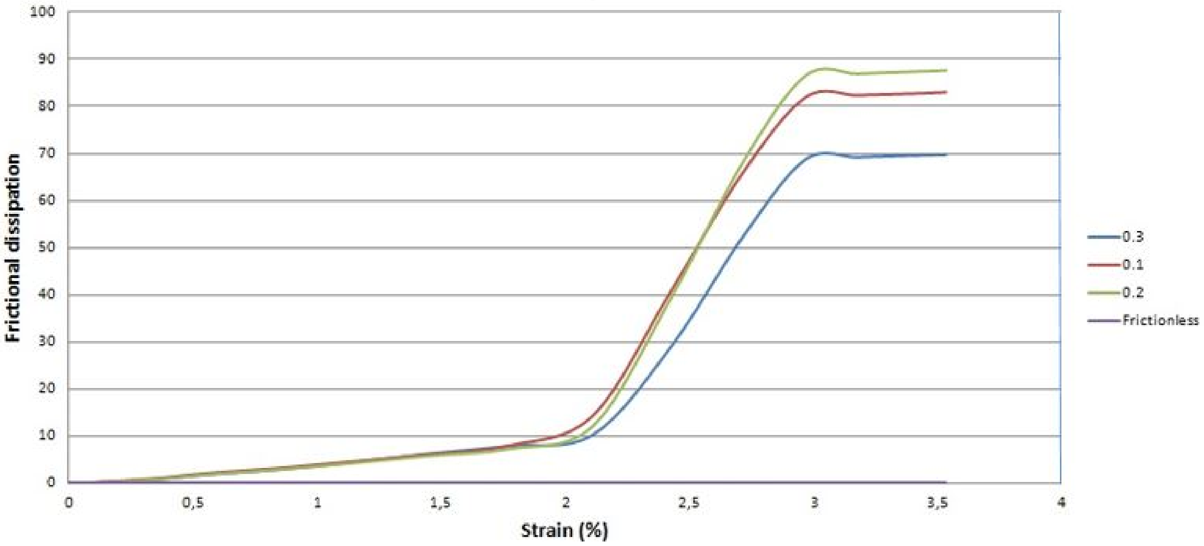

Figure 8. Variation of frictional dissipation with strain (%).

5. Conclusion

This paper has described the tension - torsion quasi-static behaviour of ”1+6” strand of a copper conductor with particular reference to submarine power cables. Finite element analysis of the strand is performed in ABAQUS taking into account material non-linearities and interwire friction.
The results presented show that varying friction coefficient does not affect strain(%) and rotation angle (rad) in the ”1+6” strand for a quasi-static analysis. To complete this work fatigue analysis of the same conductor is under progress, with varying friction coefficients and analyze the effect on the material properties. The frictional dissipation versus strain (%) results shows that friction coefficients does play a

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role in the material behaviour of conductors and copper being a mechanically deformable material, it is important to perform more analysis on it and understand its behaviour under different types of load and internal conditions.

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