Electric cables design using Tea Pipe

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I would like to dedicate this thesis to my loving parents, for all the support they have given me throughout my career.

Abstract

At the present time, cable design is based on trial and error tests and experimental data obtained from long-time experience of previous models. Because of that, there can be found some limitations in their design as well as time consuming tests with low reproducibility.

In this work is studied the nonlinear behavior of two electric cables types, a single and a double twisted cable, under three different loading conditions: traction, bending and torsion. Results from experimental tests under same loading conditions were analyzed in order to simulate similar force-deformation curves. Several material models were applied to both cable types, finding the most accurate results with a viscoplastic model based on Chaboche law with isotropic hardening. Unknown material parameters required for each model were established comparing simulated models with experimental results.

A parametric study was accomplished in order to determine which geometric and material parameters had a greater influence on both models. Double cable lay angle was also studied, having the more influence in traction and bending tests. In this study, internal friction and slipping conditions were neglected since the final goal of this work is oriented to define a homogeneous cable section.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Electric cables are destined to fulfill a huge variety of functions in a wide range of applications, from small devices to large power station, and as consequence, they are composed from single to multiples conductors disposed in different types of configurations. Moreover, they must accomplish particular characteristics like have good flexibility, have a specific preform or follow a determined path. Depending on each circumstances, designers have to impose some constraints to satisfy their requirements: avoid or not contact with other parts, be attached along determined points or be located close to other components.

In addition, their section may be composed of various materials, since they have to be well isolated from contact with the rest of conductors that form the cable, and its core may contain some separators to display the proper configuration. For all these reasons, it is not enough to know the electrical properties of the cable but the mechanical ones also, and for that, a complete analysis of the behavior of electric cables, facing multiple loading conditions and setups, is required. The purpose of this research is to analyze the behavior of different types of electric cables using results obtained from experimental tests, and develop a model that behaves like the real one and that can be parametrized, to implement it in a software package called Tea Pipe.

Tea Pipe is a software package for mechanical nonlinear simulation analysis focused on hoses, cables and pipes. With this software, it is possible to analyze the behavior of different kind of pipes using a wide manufacturer database of materials, connectors and supports. It lets us to optimize parameters such as optimal length, orientations, curvatures, etc. However, in Tea Pipe, the field of electric cables design is now in development and it is not well defined for electric cable and wire harness. Until now, there are limitations in the lack of plasticity in the materials and contact definition, and some other conditions that are missed in regard to the boundary conditions. Thus, this research is intended to enhance the simulation and analysis of electric cables and to find a base model that can serve for multiple configurations of electric cables. Finally, it is important to take into account that the different materials that composes the cables follow a nonlinear behavior, and consequently, the entire model. Thus, to model this nonlinear behavior, a deep study of the available material models is required.

1.1 Motivation

Multiples studies about electric cables and wire harness were done as a response of the increasing demand. With the growth on electric cables manufacturing, rivalry between manufacturers is higher and, because of that, they are constantly looking for a way to improve their models. These improvements are not only referred to electric properties but also to mechanical ones, since in the last years, there have produced important advances in regard to materials science. Although multiples researches and studies about electric cables have been done, they are mainly focused on their electric behavior and ways to improve their conduction capacity, resistance, and isolation ways, above all. Until now, there is not consistent solutions for wire harness design and they are based on trial and error, experimental testing and long-time experience of previous models.

This work is motivated by the necessity of developing a solution for electric cables design, that can be used for multiple combinations and configurations of electric cables, to easily model a grid for different systems. The analysis of geometrical and material parameters define the base to develop a cable model that can serve for all kind of applications, modifying easily parameters of interest.

1.2 Challenges

The simplest electric cable is composed by the conductor, usually copper, and the insulating layer, normally a thermoplastic composite. Since requirements for both industrial and engineering applications are more complex, electric cables are more complex too, and because of that, their design. It is common to find multi-core cables (composed by more electric cables in its core), having each one different geometry. Thus, electric cables sections may have multiple configurations and be composed from two to dozens of wires. In addition, the core may contain separators or spacers to avoid contact between wires. All these core components define an heterogeneous section that is precise to analyze meticulously to find an homogeneous or quasi-homogeneous one to let define a similar model as the real one, or at least, to find which parameters such thickness material, geometry or material properties have a grater impact in the model.

The first challenge is to design with program code an equivalent model for two particular cables, their parameterization and determination of parameters that affects the most both models. For that, it is needed to execute multiples iterations varying a wide range of parameters. Since the section has not a linear behavior but a nonlinear one, the second challenge is to design a nonlinear material model that simulates the real behavior obtained in samples used in experimental tests. This is particularly difficult since most part of data available is based on experimental tests and not on precise material parameters. Thus, it is required to find a material model that fits the most the real material behavior among available ones (viscoplastic, viscoelastic, etc).

1.3 Objectives

Multiple studies about flexible hoses and wire harness design have done, and current models are based on a mix between these tests and data collected during the time based on experience. Although mechanical properties of components with internal helical structure have been investigated in several scientific papers, most of them are focused on steel wire ropes, and because of that, there are little published studies about mechanical behavior of electric cables under external conditions like bending, traction or torsion.

The main objectives of this work are firstly, develop a parametric model of a multiple twisted wire, that can be used to design different configurations of multi-core wires, depending on the choice of the manufacturer. And Secondly, find an equivalent nonlinear model for the single and double cable with enough accuracy respect the real ones, and evaluate how affects to these models a variation of some geometric and material parameters like material thickness, Young's modulus or Poisson's ratio. Finally, it is expected that this work broadens the knowledge of electric cables and wire harness design and serves to develop a complete tool for Tea Pipe software.

1.4 Research approach

To accomplish these objectives, there was created some models of different types of electric cables. Their analysis and simulations were carried out with the aid of some SAMCEF suite solvers: BACON, MECANO and BOSS-Quattro. These solvers let to develop a model applying to it the boundary and loading conditions, its post-processing and finally, checking the most influential parameters.

The main task are the following:

- Design a parametric model of a multi-core wire which may be composed from one to multiples wires.
- Analyze experimental curves corresponding to a single and double twisted cable for each loading condition (traction, bending and torsion), and identify characteristic parameters.
- Study different types of material models and find one that behaves like the real one, trying to combine different models among elastic, viscoplastic and viscoelastic.

- Design and analyze a single and a double twisted cable model, similar to the ones used in experimental tests and do simulations for all loading cases to find a similar behavior.
- Compare results obtained in simulations with the ones obtained in experimental tests.

Chapter 2

Background and literature review

Electric cables design, referred to their mechanical properties specifically, is a relatively new field of study that is in development and must be highly optimized. Until now, wire harness can be modeled using CAD tools dedicated to design cables and wire harness, nevertheless these tools are conceived to route electrical cables, generate the bill of materials and determine required lengths or geometry, but they do not simulate their real mechanical properties. Besides, wire harnesses installation is becoming much more complex as there are increasingly more electrical and electronic devices present in vehicles and spacecrafts mainly, connected by a huge number of wire harness. Thus, it is of interest to model accurately their mechanical properties.

This literature research encompass diverse studies about cable design and modeling, starting from the firsts attempts to define a cable model to their final modeling with CAD tools. Most of this studies were focused on steel wire ropes, however these results are valuables for the study of electric cables design. Another reviews about cable analysis and modeling were published by Triantafyllou in 1984 [1] and 1987 [2], Starossek in 1994 [3], Rega in 2004 [4],[5] and Spak in 2013 [6] and 2014 [7] among others.

2.1 First studies

Since decades ago, from the early 1950's, cable modeling started to be a field of interest, studying firstly the strain stress response of structural cables and wire ropes mainly. Later diverse studies focusing on particular characteristics and phenomena as damping and friction were developed along the 20^{th} century. Until now, there has been published multiples reviews about cable modeling, in the 1980's Triantafyllou publsihed two papers [1; 2] reviewing the work done form the 1600's until that date, covering different aspects about dynamics of an horizontal elastic cable and linear dynamics and effects of elasticity in elastic cables suspended at the same level between two points.

Focusing in the analytical model, Raoof and Hobbs developed a realistic multi-layered structural strands model [8], determining the pattern of friction forces between layers and wires, and the relative displacement in a twisted wire with the two ends fixed. This proposed model was based on a previous model developed some years before by the same authors, assuming an equivalent continuous model of the averaged nonlinear elastic properties of each wire. The authors of this paper state that, the stiffens in the radial direction is negligible compared with the circumferential one, and this is the base to set up the different nonlinear equations. Wires axial stiffness is shown to be a nonlinear function of the applied condition loads, and for the case of both ends fixed in the torsion case, it can be easily predicted for any configuration of the wires as a function of a parameter called H equal to:

$$H = \frac{E_{full-slip}}{E_{steel}} = \sum_{i=1}^{N} \frac{A_{ni}}{A_T \cos^4 \alpha_i} \tag{2.1}$$

where n is the total number of layers, α_i is the lay angle in layer i whose net steel area is A_{ni} and $A_T = n \sum i = A_{ni}$.

Some years before, Huang [9], analyzed the behaviour under some traction and torsion conditions of an only one layer of wires around a central core including friction and extension of the cable, however difference was noted since it was complicated to extend this single model to a multi-layer case as Raoff and Hobbs presented.

Few years later, in 1991, Starossek studied the dynamic response of an extensible cable and presented a dynamic stiffess matrix whose coefficients were function of the frequency of motion, taking into account damping effects [10], being able to be used in the dynamic analysis of composed systems. However, this approach was valid only for the linear theory and restricted to small displacements (small deformations). In this paper, Starossek compared his study with some that follow the same way, and it was based partially in work done by Irvine and Caughey form 1974 to 1981 obtaining better general statements. In other paper published a while after [3], the same author presents basic equations of linear dynamics of a flexible cable and a dynamic stiffness function, neglecting any bending or torsional stiffness and stated that the linear theory was a powerful tool for vibrating cables and small vibrations of simple cables, taking into account their limitations. So one can conclude that this model had still limitations and could only be applied inside limited conditions, not providing accurate results for bending and torsion.

By the same time, Velinsky developed a model strongly related with this case-study, since loading cases of bending and torsion were included in his model [11]. Velinsky modeled each wire as a slim bar, extending that theory for multiples configurations of cable geometries. Taking strongly into account geometric parameters, bending stiffness was calculated as the sum of the bending stiffness for each individual cable, applying corresponding coefficients and neglecting friction between wires. Cable behavior was determined applying a system of six equations (including forces and moments) and the stiffness matrix.

Following this line and focusing in cable geometry, Chiang analyzed simple cables under axial loadings [12]. Its work was based on the parametric study of axial stress and stiffness analyzing six design factors at both ends and middle section of the cables, applying the finite element methods and accomplishing some experimental tests. These parameters to define were four geometrical, boundary conditions on both ends and the contact condition between the external wires and the core. However, its work not only was limited to study these factors separately but he analyzed interactions between them, showing the impact that they could have in the axial stiffness and stress among others. Chiang remarked that some model used until that date were limited as they did not take into account friction between wires and were only valid for cross-sections far away from the cable ends. The author concluded declaring that the thin rod theory implemented by Raoof et al., could not be an accurate enough assumption for the friction case. Chiang was the first author to apply the finite element method to wires and cables, analyzing 3-D models with complex cross-sections and studying interactions among multiple factors that affected the cable stiffness. In the same way to the work that there will be exposed later, the author accomplished different experiments fixing one wire end for the six degrees of freedom while the other end was loaded with an axial load. Conclusions form this study are of great interest and valuable for the study that will be presented hereinafter.

All the six parameters have strong influence on the axial stiffness of the wire, however boundary conditions on the loaded end and the helical angle parameter were larger than the others as the loaded end rotation was not allowed. Thus, without this restriction, the axial stiffness would be reduced. For both, the loaded and fixed ends, the adhesive friction between the external wires and the core, improve the axial stiffness and, in addition, the larger the cable size the larger the axial stiffness. One factor of real interest was that the cable length was an influential factor on the stress increase, but only had real influence the core wire, while the external ones had little influence. To conclude with the results, it was observed that axial stress rose in the middle cross-section.

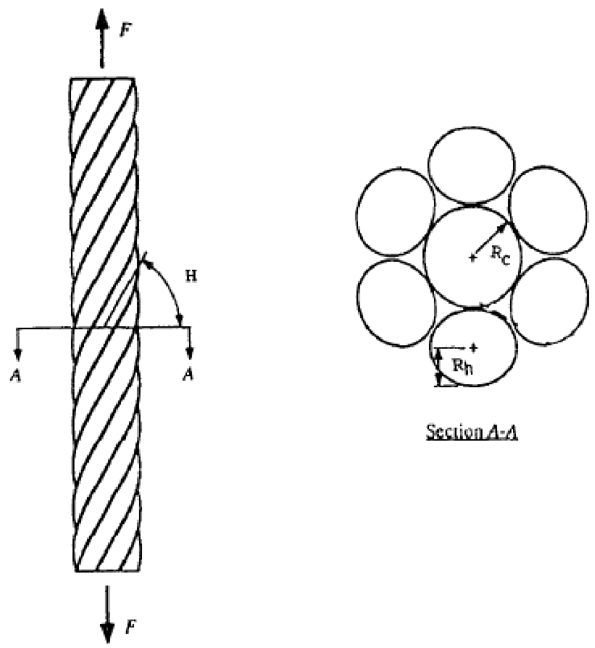

Figure 2.1: Schematic drawing of a 1x7 simple-stranded wire cable under axial loading [12].

Jolicoeur and Cardou proposed a semicontinuous model representing each wire as an orthotropic elastic cylinder [13], treating the cross-section as an homogeneous one under loading cases of bending, traction and torsion. Material was considered orthotropic and transversely isotropic. This model permited to analyze stress, stiffness and contact between layers. The model obtained by the authors adjusted very well with accurate results compared with theoretical and experimental models presented a while before for the torsion and traction loading cases. However for the bending case, it was more difficult to find an accurate result. One year after, in 1997, Jolicoeur published a paper in the same way that the previous one, to enhance the bending stiffness results [14]. Results showed that slip predictions for the Raoof and Hoobs model seemed not to be reliable for a seven wire model as predicted by Costello and Kraincanic, particularly with one end free to rotate, which had an important influence on the stiffness.

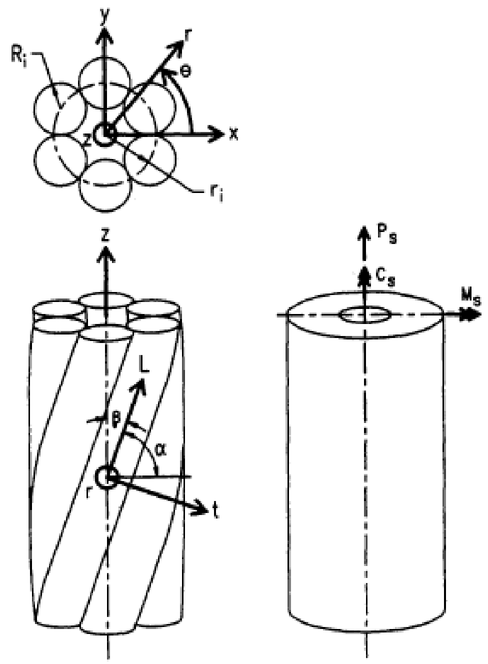

Figure 2.2: Geometry of layer of wires and equivalent orthotropic cylinder [14].

2.2 Recent models

In the early 2000's, wires and cables modeling focused on the nonlinear responses, with a deeper analysis in nonlinear vibration and developing, in a more accurate way, bending and torsion loading cases. Costello presented a compilation of some of his studies and practical experience about mechanics of wire rope, exposing theoretical results for static and dynamic cases and extrapolating these results to real examples, in which there were included electric cables [15]. Furthermore, Costello proposed some practical advices for strands, saying that, if a reduction of stress or an improvement in the strand flexibility was required, it was recommended to leave some space between wires, mainly for the traction loading case. Additionaly, Rega analyzed nonlinear vibrations for suspended cables in two papers [4; 5]. There were presented cable system modeling and methods of analysis, focusing on nonlinear discretized models for the vibration problem analysis with different techniques. Moreover, it was analyzed regular and complex response comparing theoretical and experimental results and bifurcation and chaos phenomena. Rega remarked the importance to determining dimensionality of system in the regular and complex multimodal regime, and to identifying theoretical models of reduced order of cable, to be able to capture the main aspects of its nonlinear dynamics in different operating conditions.

Crossley, Spencer and England analyzed twisted wires modeled as anisotropic elastic cylinders of one single material below bending cases, in addition to the tensile and torsion loads, using the continuum approach [16]. Furthermore, the method used for this single material cylinder was extended to a composite cylinder formed by multiple layers of cables surrounding the core wire. Crossley et al. also stated that there were found no coupling between bending and torsion solutions and for that, it was expected to occur uncoupled wave phenomena. The values for frictionless and bonded cases were considered but it was necessary to model interwire friction to obtain more precise results.

A computational model for synthetic-fiber rope response was developed by Rungamornrat, Beltran, Williamson and Asce [17]. For this model, a classical equilibrium approach was used as well as kinematics of deformation assumptions and frictional forces on rope response. For the loading case, cyclic loads were applied and incorporated to the software using a three parameter damage model. Following the same line, another paper was published in 2003 by Beltran et al. presenting the formulation of a computational model for the analysis of damaged ropes [18].

In regard to finite element modeling Jiang, Warby and Hensall developed a finite element model of a simple cable formed by a core wire surrounding symmetrically by a layer of wires in contact between them and with the core wire, and studied the extension of the cable with both ends fixed against rotation [19]. For the case in which the radius of the core wire was enough larger than the radius of surrounding wires, contact only occurred between the core and each of the external wires. In the finite element model presented by Jiang et al., contact deformations between the adjacent helical wires were not neglected unlike other authors, which stated that for an axial loading case and wires of the same material, the extension of the strand always caused a separation between helical wires. In addition, more parameters were taken into account for their model as the local contact, friction, plastic deformation and the exact geometry, since the finite element model proposed allowed to analyze in detail all these parameters. The authors showed that contact may happens at the same time between the core and helical wires, and between neighbouring helical wires, despite the fact that the conventional assumption neglected the local contact deformation in analytical models, which might lead to wrong conclusions. Another remarkable thing was observed, hysteric behaviour was found when friction was included in the analysis. This model was of great importance as it was one of the few that stated wire-core contact and wire-wire contact simultaneously.

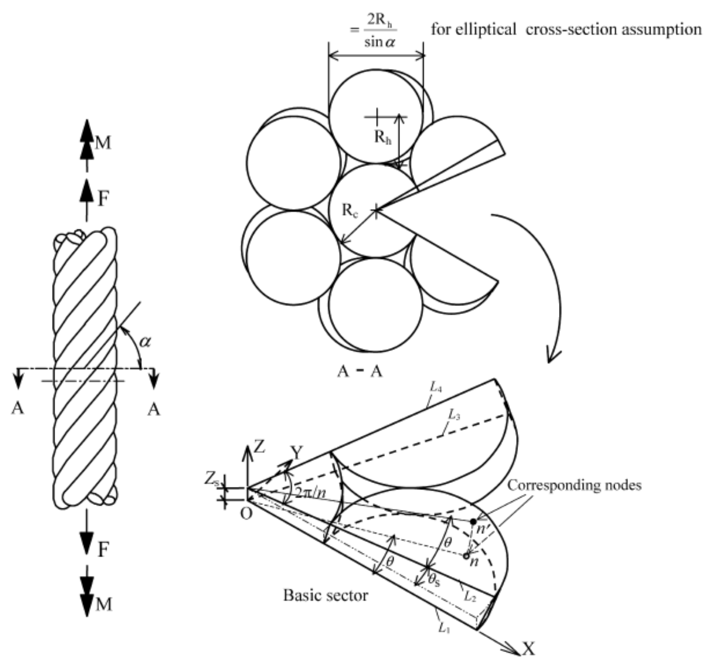

Figure 2.3: Simple wire rope strand and basic sector for the finite element analysis [19].

Shortly after, Jiang published a paper analyzing specifically the pure bending case using a three-dimensional solid elements for structural discretization [20]. This model was valid for linear elastic regime and nonlinear plastic behaviour of the cable. However in this model, Jiang defined contact only between the core and each of the helical wires but not between the helical wires as in the previous model. Jiang observed that when the global strand is subject to pure bending, all wires within the strand were also subjected to pure bending as well, and also that the maximum bending stress occurred in the centre wire. The friction along contact lines between core and surrounding wires was found to be enough small using different coefficients of friction in the model, and not causing any noticeable influence on the global mechanical behaviour or the relative movements between the contacting wire surfaces.

A finite element analysis of the cable dynamic behavior was accomplished by Ojo and Shindini [21]. The response of the cable under external cyclic loadings was simulated in the time domain, analyzing the transversal vibration of the wire and the effects of varying the axial tension on energy dissipation between the strands. In this model, it was also studied the conductor self-damping and their causes. It was stated that cables can behave as dampers by itself, mainly for two different reasons. The first one was the effect of the energy dissipation by the material at a molecular level and the second one was due to the existent friction between the strands. This effect of self-damping was mainly noted in bending cases. Simulations of three different conductors below traction and bending cases were accomplished to determine the axial displacement and the internal energy dissipation, concluding that dissipation decreases with the increase in wire tension. This model might be extended to a multilayer cables model, noted that for better accuracy the conductor had to be treated as a composite curved beam instead of as a solid beam.

Back to the nonlinear cable modeling, Lacarbonara and Pacitti developed a cable model under bending and tension conditions with a dynamical formulation based on nonlinear viscoelasticity [22]. This nonlinear behaviour was referred to the geometric stiffness terms whereas cable material maintained a linear elastic behaviour. In this study it was also investigated the influence of the flexural stiffness on the nonlinear static responses, comparing the results with those obtained for purely extensible cables. Lacarbonara et al. compared different cable models and their response curves in cases of possessing flexural stiffness and neglecting this flexural stiffness finding that, as the cable tension decreases, the difference in the model curves increased. The model developed was applicable for more general cable regimes concluding that higher frequencies were required for higher values of stiffness, and remarking that further investigations were needed as the nonlinear viscoelasticity had to be better developed.

Hashemi and Roach presented a model of a mesh reduction Dynamic Finite Element (DFE) technique for analyzing vibrations of the coupled tension and torsion of multiple twisted wires and cables configurations [23]. Comparisons between the DFE and FEM models were done, confirming the superiority of the first above the second one. Hashemi et al. exposed that under the action of an axial or a torque load, the element underwent both axial and rotational displacements at the same time. With the proposed DFE method, it was also possible to analyze damping effects, variable structural material and mechanical parameters. Analyses were carried out in wires fixed against rotations in both ends and secondly without this restriction.

A numerical analysis of wire strands was developed in 2009 by Erdönmez [24], considering effects of sliding and friction, unlike most of analytical models at that moment. The author created a complete three-dimensional model of a wire under conditions of axial and bending loadings that could be extended over different cases. His work was not only to analyze a simple wire strand using finite element method and compare it with the experimental solutions, but a complete model of twisted wires was analyzed. Additionally, Erdönmez developed a double helical model. Starting from this double helical model, another paper was published by Erdönmez and Imrak [25], in this case analyzing a complex independent wire rope core (IWRC), wire by wire under axial loading.

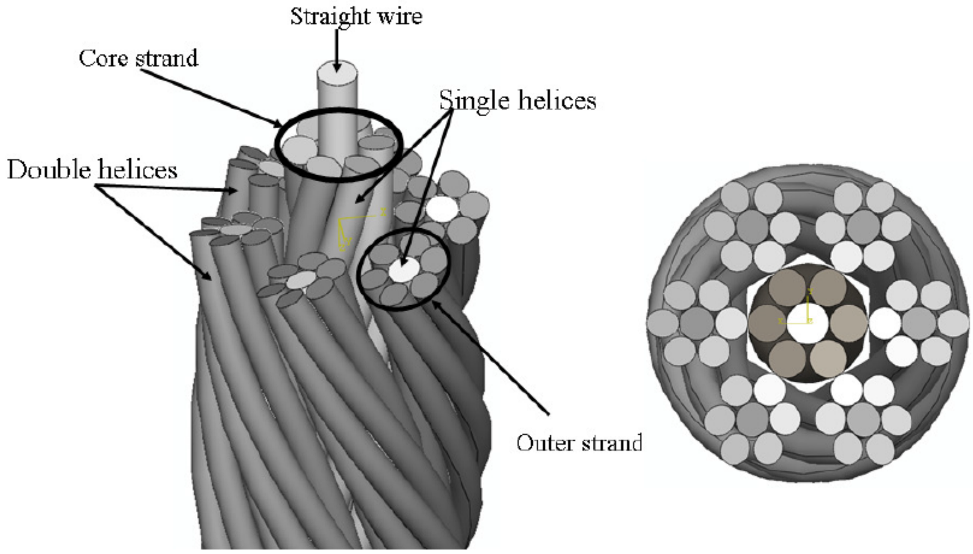

Figure 2.4: A 7x7 wire rope structure with cross section [24].

The most recent study mentioned in this background review is from 2015, accomplished by Xiang, Wang, Chen, Guan, Wang and Dai. The model analyzed [26] was a multi-strand wire rope with a double-helix configuration under axial tension and torque. The study was focused on local deformations and stresses of each wire, proposing a model that predicted with accuracy its global stiffness, assuming that there was no friction between wires and instead of homogenizing the whole model, local bending and torsion were totally computed for each wire. Xiang et al. found that it was irrelevant to consider the Poisson ratio into the axial strain case and the radial wire diameter contraction, as it had not appreciable variation in its global behaviour and when the rope is subjected to an axial tension, torsion stress of a double-helix wire could be neglected. Finally, it was found that the laying angle of both double-helix and single-helix wire was strongly related with the maximum axial stress.

In addition to these papers published by doctors and prominent figures of this field of activity, some dissertations and have been published recently by different students. Zhong studied the dynamic response of cables with variable flexural rigidity with the aid of a CAD software, to determine cable damping due to internal friction [27]. Zhong developed a model neglecting viscous damping, focussing on the internal dry friction effects and simplifying the cable to a continuous beam. In addition, Zhong studied hysteresis cycles regarding relation between instantaneous bending moment and curvature, determining the value of moment at any point in the cable. Following with the dynamic analyses of cables, Sauter studied the dynamical behaviour of slack wire cables measuring their quasi-static properties under bending deformation [28]. Like in the model of Zhong, Sauter analyzed the local moment-curvature relation, measuring local hysteresis cycles simplifying the model to an one-dimensional continuum.

Particularly in the electric cables field, Inagaki studied mechanical properties of electric cables with multi-order helical structure. This is one of few reports published until now that treats exclusively mechanical behaviour of electric cables [29]. Inagaki accomplished different tests upon pure bending cases and a parametric study to see how different parameters, considered of interest, or a change in the loading conditions, affected cable behavior. Furthermore, a complete behavior analysis of different deformations and stresses, taking into account friction between components and variable bending stiffness was given. It was found that radial compressibility of the cable affects strongly its behaviour in bending test, and as mentioned in other papers about wire ropes and steel cables, increasing lay angles generate larger strains.

Special mention to Spak, whose recent work has served to expand the knowledge about cable dynamics. A paper published by Spak et al. [30] expose a method to determine the effective homogeneous beam parameters for a stranded cable and predict both cable damping and resonance. For a cable-beam model, homogeneous parameters were defined calculating effective homogeneous properties of non-homogeneous cables for shear and elasticity modulus. This study was accomplished without taking into account cable damping. In her dissertation published in 2014 [7], Spak studied natural frequencies, frequency response and mode shapes for cables, and developed a method to determine effective homogeneous cable parameters.

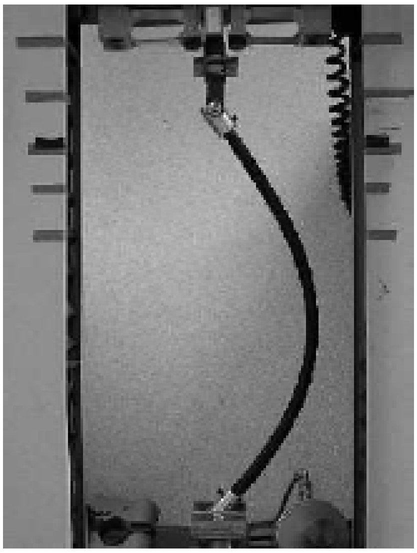

Figure 2.5: Testing bench for bending [29].

In this case, cable damping mechanisms were taken into account, finding that amplitude response was predicted for more cable modes by time hysteric damping than other damping phenomena. Moreover, different types of cables were tested dynamically, identifying some factors that affected dynamical response. Bending stiffens was determined with a developed method that combine bending stiffness for steel cables with properties of composite materials and cable displacements.

2.3 Literature summary

The study of mechanical properties of electric cables and their accurate modeling is an important task for automotive and aeronautical industry and is still in development. Since the mid-twentieth century, cables and wire ropes have been under study, analyzing and testing multiple configurations of cables, determining some properties of interest and relevant parameters. Conclusions obtained in these analyses are useful to understand mechanical properties of electric cables but nonetheless, as they do not behave linearly as steel cables do, there are difficulties determining a model that can serve for all kind of electric cables.

Until now, mechanical parameters definition is based on trial and error, experimental testing and long-time experience of previous models, thus is necessary determine the most impact parameters in cable behavior and find a set of cable models that can serve for multiple configurations. Published studies recently have focused on electric cables modeling and homogenization of the whole model, making easier their study and parameterization. This work is based on these studies, expanding knowledge about determinant parameters that affect mechanical behavior of electric cables and modeling accurately some type of cable configurations.

Chapter 3

Electric cable models

Most of time wire and cable terminology are used to refer the same thing, however they are actually different concepts. While a wire is a single electrical conductor, a cable is a group of two or more wires configured in different ways and isolated from each other, covered by a common insulating structure. Conductors are usually made of copper and the insulation on these cables is often a synthetic polymer or a thermoplastic one. Electric cables are used for multiple purposes, from small electronic devices to huge electrical installations, and each must be adapted for that purpose. Robustness of electric cables is directly related with the voltage that they can carry, and because of that, domestic cables are not as robust as the industrial ones. Electric circuits may be composed by thousands of cables and a typical configuration of wire harness is adapted, attaching multiple cables for different functions.

If a flexible behavior is required, electric cables must be twisted. Assembling small wires before its configuration adds more flexibility to the design, thus if a small number of individual wires are grouped together and twisted, they will be more flexible than solid wires of the same size. In this chapter a brief summary of different types of electric cables and their configurations is given. Moreover, it is exposed the different materials that compose the cable structure and their behavior, finalizing with a description of the models that have been used in this work.

3.1 Types and configurations

3.1.1 Wire sizes

To select the adequate wire size, it is important to take into account the ampacity and wattage that a wire can carry per gauge. Wire gauge is the size in diameter of the wire, ampacity is the amount of electricity that can flow through the wire and wattage is the amount of power that a wire can take. Each application requires a specific wire size for its use, and it is determined by the wire gauge. Sizing of wire is done by the American Wire Gauge (AWG) system, that is the most extended for diameter classification. The most used wire sizes are 10, 12 and 14 (a higher number means a smaller wire size, and affects the amount of power it can carry). To classify the different types, the number of wires follows the wire gauge, for instance, 14/4 indicates a cable composition of 4 wires of 14 gauge each.

3.1.2 Electric cable types

There are different types and configurations of electric cables according to required purposes, in fact, there are more than twenty different types of cables available, designed for different uses from domestic to heavy industrial use, fulfilling requirements of insulation or different loading cases. Some of the most commonly used are described below:

- Coaxial cable: it is formed by conductor core surrounded by a tubular insulating layer and additionally, by a tubular conductor made of copper too, displayed as a woven shield, surrounded finally by another outer dielectric insulator. The core conductor is responsible for transmitting information and the woven shield serves as ground reference and current return. It is called coaxial since the two inner shields share the same geometric axis. There are multiple types of coaxial cables which accomplish different applications, they are used to connect audio and video devices, television and networks. A variant of this cable is called twinaxial cable and consists of a coaxial cable which core is formed by two conductors instead of only one, used for short high speed signals.

- Ribbon cable: called like that for its resemblance to flat ribbons, is composed by multiple insulated conductors running parallel to each other on a flat plane. This parallel configuration allows the simultaneous transmission of multiple data signals of low voltage. It is commonly used to interconnect network devices and computer devices like the motherboard with other core CPU components as they are quite flexible.

- Twisted pair: it is formed by simple pairs of insulated copper wires which are twisted together to avoid electromagnetic interference due to external sources. Wire diameter does not exceed 1 mm, and the number of pairs vary in different types of twisted pair cables. The greater the number of pairs, the higher the resistance of the cable will be to external noise and crosstalk. Their flexible and inexpensive characteristics are used for telephone cabling and local area networks.

- Shielded cable: it is made of one or more insulated wires that can be twisted by pairs or collection of pairs (also called screening) and are collectively attached by a conductive layer or woven braid shielding as in the coaxial cable type. The shielding reduces electrical noise, providing to the cable a barrier from external radio and power frequency interference, attenuating external electromagnetic waves . This conductive layer is may be also insulated.

- Unshielded twisted pair cable: this type of cable consists of two wires that are twisted together to reduce interference conditions. The individual wires are not insulated and it is mainly used for communications. Since they are not insulated, they are more affordable than coaxial cables and are often used in telephones, audio video and data networks. For indoor use, UTP cables are an extended option since they are flexible and can be easily bent for in-wall installations.

- Multi-conductor cable: they are composed by two or more individually insulated cables that are insulated in addition by an external insulation layer that attaches all the wires and confers an extra security.

3.2 Wire harness

This type of cable assembly is exposed separately form the others since cables studied in this work would be part of this kind of configuration and deserves a deeper explanation. A wire harness is an assembly of insulated wires, attached all together by a tubular insulation or a special insulating tape that may contain cables for different applications and multiple configurations. A wire harness is often confused with a cable assembly, however the main difference between these configurations is that a cable assembly usually has just two ends while a wire harness has multiple ends distributed in many different directions with multiple terminations on each branch. The wire harness simplifies the building of larger components by integrating the wiring into a single or several units, for an easier installation. By binding the many wires, cables, and sub-assemblies into a harness, the installer only has one component to work with. In addition, a wire harness allows the completed assembly to be better secured against the abrasion and vibration effects, and by constricting the wires into a non-flexible beam, usage of space is optimized.

This type of cable assembly is commonly used in automobiles, aircraft and also spacecrafts since they have a wide range of electric and electronic systems that must be connected all together, and be capable to transmit signals between them with the added problem that these devices can be located several meters away from each other. Furthermore, as aircraft usually contain several hundred kilometers of electric cables, this configuration lets to manage better their installation and to optimize the space occupied by all the cables. Wire harness configuration prevents from different vibration conditions that affects the performance of the system and also provides a better insulation from abrasion or moisture. The time invested in cable network installation is highly reduced and standardizes the process.

Electric cables manufacturing is still done by hand despite the increase and improvement of the automatized process. This fact is due to several reasons that make the process difficult to standardize and automatize:

- Large longitudes and little diameters.
- Routing wires through insulation hoses.
- Multiple categories of cables and specific characteristics.
- Cable assembly and terminals connection.
- Cable fastening.

Additionally, wire harness design is a complex process too:

- Wire harness design process requires taking into account parameters for both electrical and mechanical engineering.
- As new material compositions are developed, their analysis and modeling requires time.
- There are a huge number of constraints due to safety rules and regulations imposed by different organisms.
- It is subject to a large number of superimposed effects as electromagnetic interference, corrosion, abrasion and degradation among others.
- It suffers continuous changes due to airlines and automotive companies customization.

It can be concluded that wire harness configuration is the best option when a vast quantity of electric cables is needed to be connected between multiple devices and systems that perform different functions, as in the case of complex machines like automobiles and aircraft, and requires different conditions of voltage and power.

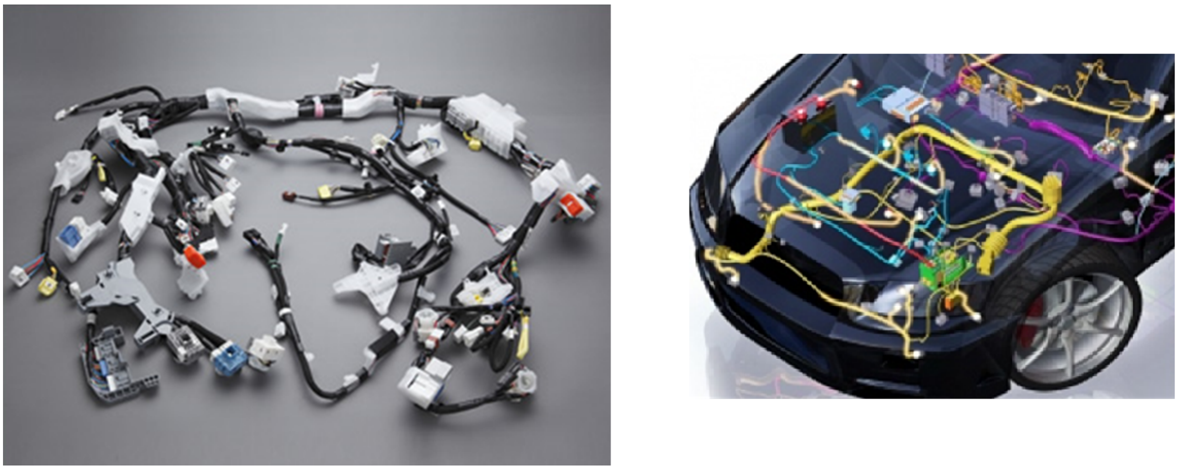

Figure 3.1: Wire harness and its automobile implementation.

3.3 Materials

Electric cables are made of multiple materials since they have not only to transmit the current but also accomplish other conditions like be insulated or stand different loads. Electric cable core is formed by multiple wires and it is in charge of carry electric power. It is made usually of copper, although it can be made of aluminium or aluminium alloys since it less conductive but cheaper and lighter. There are two criteria for measuring copper conductors, the American criterion that defines the number of wires and their diameters (AWG) and the European criterion that defines the conductor maximum resistance in Ω/km.

Cable isolation is made of some type of polymer, normally a thermoplastic or thermostable one and its thickness will depend on the level of working voltage, the nominal current, ambient temperature and conductor temperature. Some of the most frequently used insulation polymers are:

- Thermoplastic:
  - PVC: the most used as it is cheap and durable.

- PE: has lower dielectric losses than PVC and is sensitive to moisture under voltage stress. It is used mainly for high voltages.

- Thermostable:
  - XLPE: is used for high temperature applications as it helps to prevent the polymer from melting or separating at elevated temperatures.
  - ERP: is more flexible than PE and XLPE, but has higher dielectric losses than both.

If the cable is composed at the same time by more cables, they must be attached by a filling layer whose mission is to insulate the set of cables and maintain its circular section. In addition, cables may be separated by some metallic strands, made of tin usually, that confer a rigid structure to the cable and maintain each wire in its determined position. Finally, there may be a cover to protect the whole opposite to mechanical deformations.

3.4 Analyzed models

In this work, two different type of cables were modeled and analyzed. Firstly, a single cable composed by a copper core and an insulation layer and secondly, a double twisted cable composed by two twisted wires separated by two tin strands, attaching the whole by an insulation layer. A third cable composed by multiple twisted wires was modeled and parametrized, whose number of cables can be selected. In this section, a geometric description of modeled cables is given, as well as their configuration and material identification, nevertheless this last task will be treated in a more extensive way in the next chapter, since it requires a deeper analysis.

3.4.1 Single cable

The tested model is composed by a simple core made of cooper and an insulation layer made of PVC. Core diameter is 1.4 mm and the insulation layer thickness is 0.65 mm. Different cable lengths were tested depending on the loading conditions.

Thus, different cables with these parameters were modeled and analyzed to obtain similar force-deformation curves to experimental ones. In addition, this cable was parametrized to study the impact of a variation in its diameter and thickness.

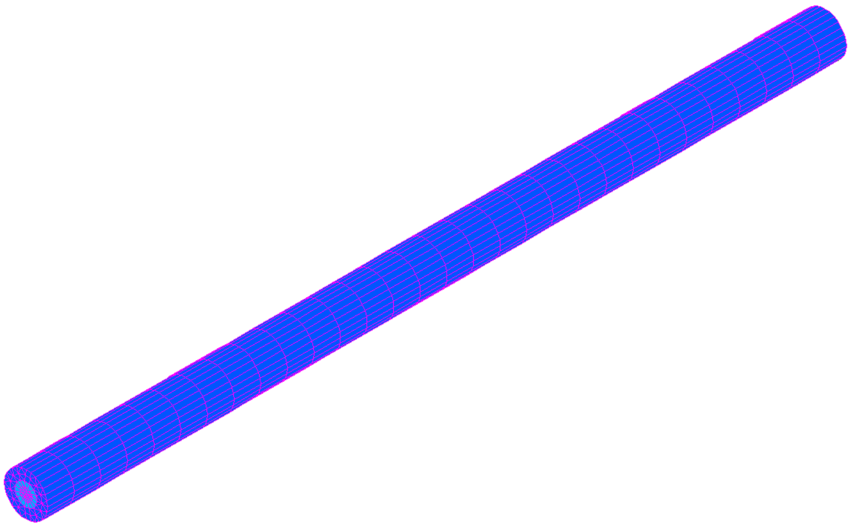

Figure 3.2: Single cable model.

3.4.2 Double twisted cable

This second model is more complex and it is composed by two twisted cables with a simple copper core, a PVC insulation layer and two spacers made of tin. All this ensemble is finally covered by an external insulation layer. Core diameters of simple cables are 2.5 mm and their insulation layer thickness is 0.40 mm. Spacers diameter are 1.10 mm and the outer diameter of the external insulation layer is 8.90 mm. Thickness of the external insulation varies around the core as it attaches cables of different sections. Various cable lengths were tested, as in the single cable case, depending on the loading conditions.

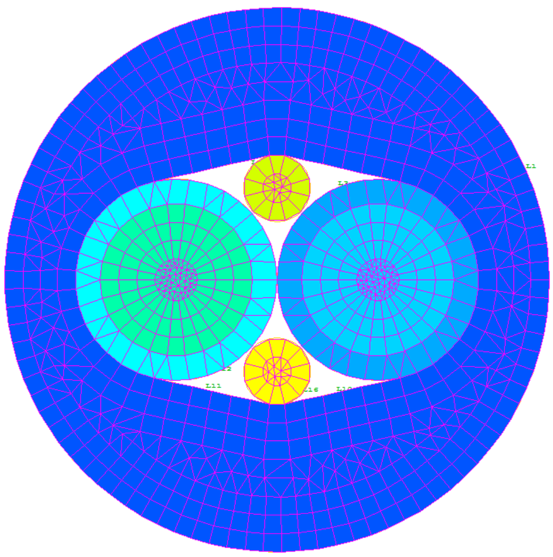

Figure 3.3: Composition of the double cable cross section.

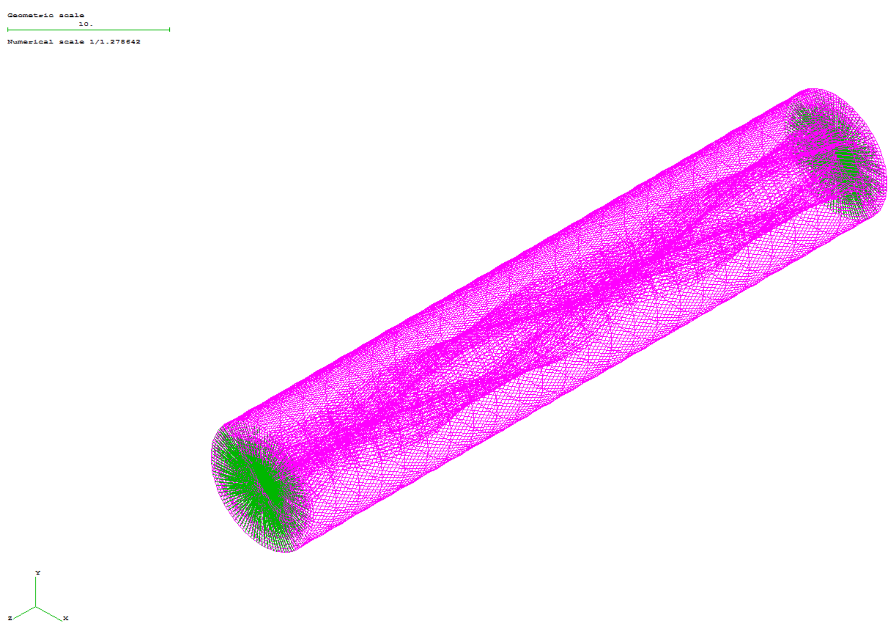

Figure 3.4: Double cable internal and external mesh.

3.4.3 Multiple twisted cables

A final model was developed to easily add wires of different types to the cable core. This model was not tested in a testing bench, however it was developed with the purpose of improving Tea Pipe tool, to create any kind of electric cable in a simpler way. To parametrize the model, some data is required as an input. User must introduce diameter, their center positions and thickens parameters for the geometric configuration. In regard to the material parameters it is necessary to introduce the Young's modulus, Poisson's ratio and the mass density. Figure 3.5 shows the core of a three twisted cable model.

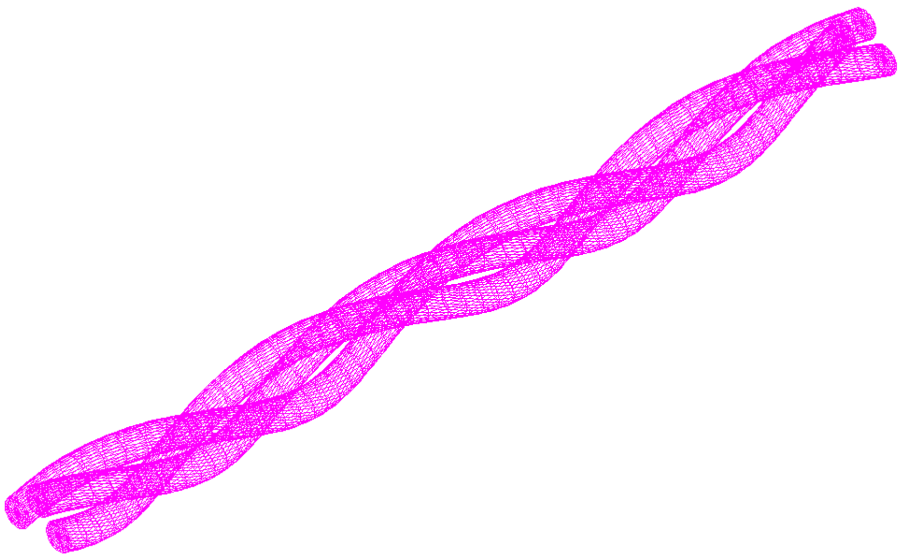

Figure 3.5: Cable core composed of three twisted wires.

Chapter 4

Markets

In this chapter are analyzed different markets interested in implementing a CAD software tool dedicated to electric cables design, that can be used in the design process of industrial machines. At present, almost all engineering industries take advantage of CAD software tools to design their products, and with industries development, they look increasingly for more accuracy in the analysis and design process, to save time and cost invested in experimental tests.

Due to the constant increase of electrical and electronic systems integrated in all kind of machines, there are multiple industries in which their product design requires to model thousand of meters of electric cables. Further, this vast quantity of electric cables not only interferes in the space distribution, but affect the whole mechanical behavior of the machine. Looking for the prefect design, companies work to find models that behaves the more accurate possible as real ones, and this pursuit of perfection has derived in a need for a tool that be capable of representing mechanically electric cables behavior. Thus, a tool to design electric cables easily and in an intuitive way is required. The most interested in such tool are automotive and aeronautic industries, however there are some others interested in it.

4.1 Automotive

Decades ago, automobile was a machines purely mechanic, transmitting all movements by means of gears, chains and straps. At present time, automobiles are made of thousand of electrical systems and electronic devices, connected by multiple electric cables transmitting information continuously that create a vast cable network. Furthermore, it is required to allocate precisely this cable mass to optimize room available, interact as less as possible with other vehicle parts and be completely insulated for passengers safety. In addition, it is required to model conditions of flexibility, rigidity and response, opposite to different vibration and loading conditions that vehicle undergoes.

Automotive companies are one of the most interested in a tool that aid them in the design process of electric cables. Besides, electric vehicles are the future, a future that is getting closer. Electric vehicles are full of electric cables and devices, and a good distribution of all connections may derive in a save of several kilograms, giving the vehicle a better behavior. Conditions of flexibility and adaptability are important too, since connection parts may suffer from excessive loading and vibration conditions, causing damages and possible disconnections between devices. To maintain a prefect performance of the system vehicle, wire harness has to be enough strong to withstand any adverse situation. For that, a tool to analyze each loading case or a combination of them is mandatory for any automotive company, to develop a perfect design as real as possible.

4.2 Aeronautics

Some aviation accidents happened in the past due to cable failures following common patterns, and because of that, the term of Electrical Wiring Interconnect System (EWIS) was created, to analyze in a deeper way problems derived from aging effect, wrong insulation or deteriorated wiring among others. A correct performance of an aircraft is directly related with its electric system reliability. This electric system reliability is based on the correct behavior and configuration of the cable wiring. A proper installation of the aircraft components and the manufacturing procedures are requirements of the EWIS regulations.

In aeronautic industry, there are more complex problems than in the automotive one, since electric cables have a more complex configuration following stricts conditions and connection distances are much larger. However, the main problem is the cable routing. Since multiple parts of the aircraft are normally designed and manufactured for different companies, a precise cable routing to connect all these different parts is required. Costly problems can be originated due to the lack of feedback between two companies designing two depending parts of the aircraft. There have been cases, concerning cable routing between the main body and the wings, in which a wrong cable routing design has derived to a huge money loss. Correct engineering design, planning and coordination with the manufacturers of each electrical component will secure the proper installation of each component.

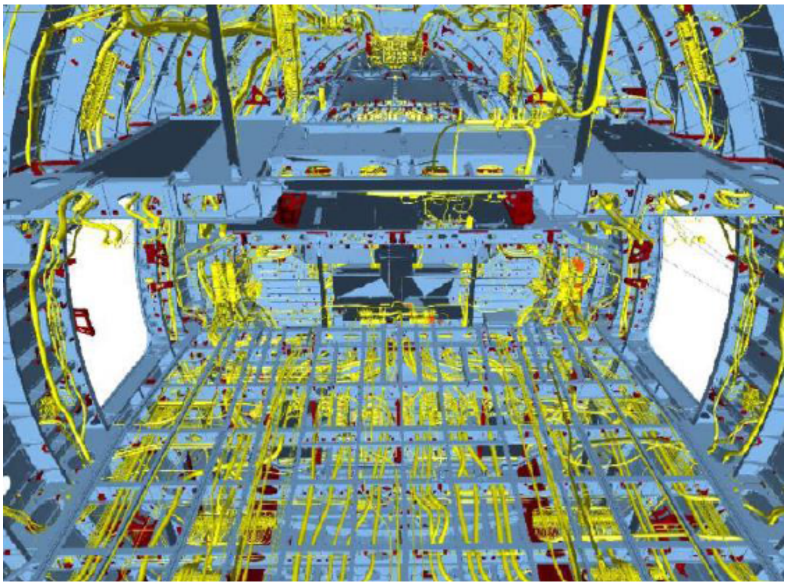

Figure 4.1: Cable routing of an A380 model.

As an example, to see dimensions of the problem in one of the biggest aircraft manufactured until now, an Airbus A380 has more than 500km of electric cables, 100.000 wires and 40.000 connections. This vast quantity of cables and connections requires a perfect design of the aircraft wire harness, and for that a specific tool is needed.

Here are listed some different kind of electric cables required for a common aircraft:

- Coaxial cables for high frequency transmission.
- Fire resistant cables in engine.
- Special cables in engine environment.
- Special cables assemblies for satellite communication.
- Hook-up wires in wings.

4.3 Other industries

Owing to machine technology increasing, their equipment has become more complex. Actually, few machines do just one task and most of them require some degree of connection between other equipment. In almost every industry, from agricultural development to energy sector, an extensive network of elecrtic cables is present, and to optimize these process and their usage is required a wire harness optimization.

Wiring harness is one of key components used in various industrial machines and manufacturing equipment for power supply and signal/data exchange. Industrial cable harnesses are used to connect a wide range of manufacturing equipment like industrial robots and FA machines such as CNCs and PLCs. Wire harness assembly is also used for wiring inside those machinery. For each industry a custom wiring harness is required since they have to accomplish their tasks in different environments, so for instance, in oil and gas industry, apart from a cable routing optimization, special characteristic of waterproof, corrosion and abrasion resistant are required and must be analyzed and optimized.

Chapter 5

Experimental tests

In this chapter are described the different kind of experimental tests accomplished by Daimler AG. This company tested some cable types and provided Siemens-PLM experimental force-deformation curves for two models, in order to reproduce them by simulation. As mentioned previously, the two models under analysis were a single core cable and a double twisted cable. Three loading cases were tested for both models: traction, bending and torsion. Notice the fact that, since the single cable has a much smaller diameter compared with the double cable one, taken measurements have a less uniform behavior than for the double cable, in bending and torsion cases above all.

5.1 Traction

For the traction test, cable was placed in vertical position and fixed by both ends. Traction load was provided by a servo hydraulic cylinder that pulls one cable end down keeping the other fixed. In addition to this servo, the testing bench was composed by force and displacement sensors in order to establish loading conditions and constraints, and to take desired measures accurately. Traction tests was done by loading the cable up to a determined force and then unloading to 0 N, following this process until five loading cycles. Loading speed was the same for loading and unloading and the maximum displacement allowed was restricted to a determined percentage of the total length.

Obtained force-displacement curves for the single and double cable show that there is produced a constant deformation from the first cycle for both models, so plasticity occurs, although in a small quantity. For the single cable there are two differentiated slopes with a quasi-linear behavior, and from the yield point, the slope increase notably starting the hardening. In the double cable case, plasticity phenomenon occurs too, but in this case loading cycles are quasi-linear from the beginning to the end of the force application.

5.2 Bending

For the bending test, cable was placed in vertical position and only fixed by one end. The bending load was placed some millimeters away form the fixed end applied in horizontal direction. Bending force was not placed in the cable end so as to avoid contact problems. Force was provided by a metal plate with a circular hole that guarantee the force to be perpendicular to the cable initial central axis any time. Testing bench was composed by force and displacement sensors so as to establish loading conditions and impose desired constraints.

Bending test was done by imposing to the cable a displacement with a maximum defined force, and going back to a position where residual cable force is null. With this kind of loading cycle it is possible to observe if plastic deformation happens. The loading and unloading cycle was repeated five times. Loading speed was ten times slower than traction test.

Obtained force-displacement curves for the single and double cable show that in both tests appear a phenomenon called ratcheting, that occurs when certain materials are cyclically loaded. Ratcheting effect is defined as the accumulation of plastic deformation with increasing the number of loading cycles, also called cyclic creep. It should also be noted the effect of cyclic softening, since in both cases, the force needed to reach the fixed displacement is decreasing with the cycle increase. For both cases, plastic deformation occurs in a considerable range, being about a half of the imposed displacement.

5.3 Torsion

In regard to torsion test, cable was placed in horizontal position and fixed by both ends. Torsion load was provided by a servo hydraulic cylinder that turns one cable end keeping the other fixed. In addition to this servo, the testing bench was composed by moment and turn sensors in order to establish loading conditions and constraints, and to take desired measures accurately.

Torsion test was accomplished by turning the cable up to a determined degrees quantity and then unloading to a 0 Nm moment, following the same procedure that in bending case, in order to check if plastic deformation occurs. The cycle was carried out five times, as in the other tests, and loading speed was the same for loading and unloading. Obtained moment-turn curves for the single and double cable show, as previously discussed, that for the single cable, variability of the curve is highly noted due to the fact that cable diameter is quite small and thus, moment measurements can not be enough accurate, since an accuracy to the thousandth is required. In this case, the shape of the curve has certain degree of similarity to the traction curve, since there is a linear trend in all cycles, despite the fact that plastic deformation occurs. Plastic strain were a third of the total cable displacement.

In the double cable case the shape of the curve is more clear. In this case the shape is similar to the bending test curve. The same ratcheting effect with accumulation of plastic deformations and the same cyclic softening occurs, obtaining a decreasing moment in each cycle. The maximum moment in this case is around ten times higher than for the single cable. Plastic deformations comprise a range about a third of total displacement, so it is quite similar than for the single cable case.

Chapter 6

Methodology

In this chapter it is described in detail the work done to analyze and design electric cable models proposed. The accomplished work was divided in three phases: design, material selection and parameterization. In the first phase were designed two different cable model, a single cable and a double twisted cable. These models correspond with the ones tested by Daimler AG. In addition, a third model was developed as a base of a future project. With this last model it is possible to create different electric cable configurations giving some geometric parameters. The second phase was the material identification and validation of a model that simulates a similar behavior as the real one, and reproduce shapes of the curves obtained in experimental tests. Finally, the last phase was to parametrize designed models and identify parameters of interest, varying them in a selected range and observing their influence in the model. Part of this phase was done simultaneously with material selection as parameterization lets to test in a faster way if a material is valid to or not.

6.1 Design

In this section it is exposed how were designed cable models developed with BACON. It is described in detail the design process for three different models: single cable, double twisted cable and multiple twisted cables. For each model can be found its developed BACON code in appendices section.

There were designed two type of electric cables based on geometric parameters given by Daimler AG and afterwards, these two models were parameterized to analyze their behavior facing some parameters variation. So firstly, models were designed starting from specific given values to reproduce stress-strain curves and subsequently, these models served as the base to analyze the impact of some parameters in both models. Design of electric cables was done using SAMCEF software, concretely the BACON programming module. BACON is a programming environment that lets develop any kind of single or multibody solid model and apply to it all type of boundary conditions, constraints and external and internal loading such as friction conditions, temperature dependency, compression or torsion among others. BACON was the base to develop the different cable models to post-process them before. As has been commented above, an additional design was developed. It is a very basic model that has to be completed but it is also a good starting point for future developments in Tea Pipe. Below, all these models are described in more detail.

6.1.1 Single cable

The single cable model is the simplest model studied in this work. However, it was interesting to study, as more complex one were composed of multiple of these cables. As mentioned in Chapter 3, this model is composed by a copper core and a PVC insulation. As mentioned above, the model was designed by programming code, which permits develop a precise model, making easier to do changes and letting parameterize the whole model for its subsequent analysis.

The design process started with cable section definition. Firstly was defined the core section and the insulation thickness, then the section was extruded up to desired length and finally was applied the mesh to the whole body. Parameters of the mesh size and different conditions are showed in Table 6.1 and 6.2. Mesh size was selected regarding to a compromise between results accuracy and time cost. Different types of material parameters were applied to the core and insulation. Basic elasticity parameters were defined for each body, these parameters are the

Young's modulus, Poisson's ratio and mass density. In addition, for each material were applied different material models corresponding to the one that fits the best with the real behavior. For material definition, the SAMCEF database has multiple combinations of elastic, viscoplastic or viscoelastic models among others and some of these were applied for each cable component. Material selection is explained in a deeper way in the next section as it requires some theoretical approach.

Table 6.1: Single cable design parameters.

Single Cable	Length [mm]	Number of elements	Mesh size
Traction	100	50	0.3
Bending	50	30	0.3
Torsion	50	30	0.3

Table 6.2: Single cable material parameters.

Single Cable	Young's Modulus [MPa]	Poisson's ratio	Mass density [kg/mm^3]
Cu	120000	0.4	$1.40 \cdot 10^{-6}$
PVC	2800	0.34	$8.96 \cdot 10^{-6}$

For each kind of test (traction, bending and torsion) there was applied a cyclic function of loading and unloading to simulate real test conditions. Speed time deformation was estimated from data provided by Daimler AG. Thus, for the model, equivalent parameters were calculated for each loading-unloading cycle and are listed below:

Table 6.3: Test parameters for each case.

Test	Deformation	Time for each semi-cycle
Traction	0.134 mm	1,61 s
Bending	7 mm	8.4 s
Torsion	45°	20 s

Additionally, there were defined different loading and fixation conditions for each case (for all cases one end is fixed against displacements and rotations):

- Traction:
  - Load: Applied load of 80 N in z axis direction (central cable axis).
  - Constraints: Fx, Fy, Mx, My, Mz.
- Bending:
  - Load: Imposed displacement of 7 mm in y axis direction.
  - Constraints: Fx, My, Mz.
- Torsion:
  - Load: Applied turn of 45° around z axis.
  - Constraints: Fx, Fy, Mx, My.

In addition to these loading conditions, there was applied the gravity force to each case and all analyses were carried out applying a dynamic response to the model.

6.1.2 Double twisted cable

The double twisted cable model is a more complex model composed by two single cables similar to the previous model, two twisted tin rods acting like spacers between the two cables and a final insulation layer attaching the whole assembly. As in the single cable model, geometric dimensions were taken from tests accomplished by Daimler AG and the complete model was designed with BACON.

Cable section was defined by two copper cores insulated, in parallel and in contact by one side and two small spacers, one above and another behind. Friction between bodies was neglected in this study. Then the section was extruded and these four bodies were twisted around an imaginary axis up to the desired length. This axis was the central axis of the whole ensemble and pass through the center of the insulation external circumference. The four bodies were twisted 360° along the total length. Finally the whole was surrounded by another insulation layer that fits to internal bodies and has a circular external shape. Characteristic of the mesh and further details of the model are given in Table 6.4 and 6.5.

Different types of material parameters were applied to each body that compose the twisted cable. Apart from the basic elasticity parameters given to each body (Young's modulus, Poisson's ratio and mass density), different response models were applied to each material. Materials that compose the ensemble were tin for the separators, PVC for the external and internal insulation and copper for each single cable core. Although there were applied different response models for each type of material, one of the scopes of this work was to observe the influence of each material in the whole body and determine if it would be possible to design an homogeneous section, assuming that it was composed of bodies of the same material.

Table 6.4: Double cable design parameters.

Double Cable	Length [mm]	Number of elements	Mesh size
Traction	100	50	0.3
Bending	50	30	0.3
Torsion	50	30	0.3

In this model, there were applied same loading and fixation conditions as in the single cable. For each test, there was applied a cyclic loading function to simulate real test conditions. Speed deformation time was the same as in the previous model.

Table 6.5: Double cable material parameters.

Double Cable	Young's Modulus [MPa]	Poisson's ratio	Mass density [kg/mm^3]
Cu	120000	0.4	$1.40 \cdot 10^{-6}$
PVC	2800	0.34	$8.96 \cdot 10^{-6}$
Sn	55000	0.33	$7.20 \cdot 10^{-6}$

Finally, gravity force was applied in the positive z axis to each case with a dynamic response of the model. This complex model was more time consuming than the previous one when post-porcessing with MECANO, and as a consecuence, affected notably to BOSS-Quattro analyses.

6.1.3 Multiple twisted cables

The multiple twisted cables design is a model composed by a number of twisted simple cables defined by the user, simple cables are the same that the ones designed in single cable section. The model showed in Fig 6.1 is the one corresponding to a four twisted cables configuration. This cable model has a simpler configuration comparing with the double twisted cable (simple configuration here is referred to a composition only by simple insulated wires without separators or spacers). However, this model was designed with the purpose of adding easily wires of different types and geometries to a common assembly. It is a model destined to make easy the design of electric cables within Tea Pipe interface and facilitate its modeling to the user.

Input parameters for this model are the number of wires composing the inner configuration, cable center x and y coordinates, copper and insulation radii for each inner wire, external insulation thickness, Young's modulus, shear modulus and mass density for each material. To add any number of wires to this model, a loop was developed in BACON programming code. The main loop sequence for each wire is the following:

- Definition of the inner and outer insulation radii and core center.
- Section mesh generation.
- Twisted extrusion around z axis (z axis pass through external insulation center).
- Material parameters assignment.

This process continues for each cable until the number or desired wires are created and finally is defined the external insulation attaching all the inner cables. This model was not analyzed under loading conditions as the purpose was only the design of the model. However, to apply loads and restrictions, the procedure to follow is the same as in the single and double cable.

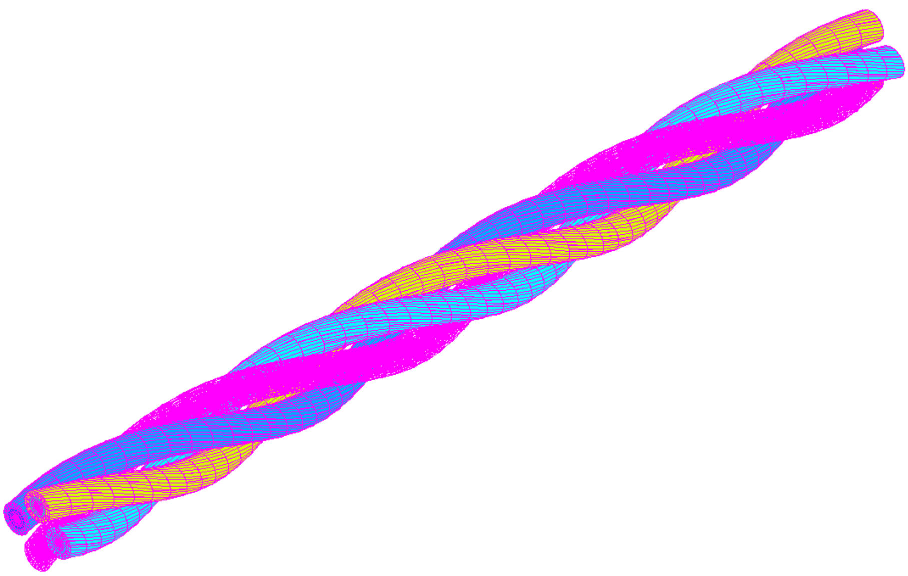

Figure 6.1: Multiple twisted cable model composed of four single cables.

6.2 Material selection

In this section it is described the material selection process followed to select the material behavior model that best represent the curves obtained in experimental tests. For each model, it is given some theoretical approach to well understand how the model works. In this selection process, there were tried multiple material models available in the SMACEF library, emphasising the following ones: elastic, viscoelastic, elsto-plastic and viscoplastic.

For the firsts parametric analyses, there was chosen the simplest material model (linear elastic model) in order to obtain some data related with the basic influential parameters. Despite the fact that analyzed models do not follow a linear elastic behavior, to define more complex models, it was required to establish an elastic behavior as the base of each model. Thus, a linear analysis was useful to define the rest of materials. To simulate as close as possible the real cable behavior there were used nonlinear models, taking into account speed deformation. It should be noted that complex models required a much higher processing time, for the double cable above all, hence this part of the work was one of the most time-consuming.

6.2.1 Elastic model

The linear elastic behavior is the simplest model available in SMACEF library. There may be defined three different types of elastic laws: isotropic, orthotropic or anisotropic material. For each one it is required different parameters, however for all of them, there must be selected the type of strain/stress measurement. In Table 6.6 is listed available laws for strain and stress.

Table 6.6: Stress-strain laws.

Law	Stress measure	Strain measure
2^{nd} Piola Kirchhoff	$S = P/A_0 \times L_0/L$	$E = (L/L_0 - 1) + +0.5(L/L_0 - 1)^2$
Cauchy	$\sigma = P/A$	$\varepsilon = ln(L/L_0)$
Kirchhoff	$\tau = P/A_0 \times L_0/L$	$\varepsilon = ln(L/L_0)$
Biot	$h = P/A_0$	$e = L/L_0 - 1$

Hence, the strain/stress couples are Cauchy stress with natural strain and deformed volume, Kirchhoff stress with natural strain and initial volume, 2^{nd} Piola Kirchhoff with Green strain and initial volume and Biot stress and Biot strain with initial volume. In nonlinear analyses, the choice of one of these strain/stress couples will give different results so, as the general material behavior was one associated with plastic deformations, the best option was to work with natural strains that respect incompressibility in large strains. The choice of one of these relations was important for linear analyses also, since in bending especially, there were large deformations. For that, the couple used for all analyses was Cauchy stress with natural strain, as for Cauchy stress the initial geometry is replaced by the deformed geometry.

When designing cable models, there were used isotropic and orthotropic configurations. For the two used configurations it was necessary to define the following parameters:

- Isotropic material: Young's modulus and Poisson's ratio or bulk modulus and shear modulus.
- Orthotropic material: Three values for the Young's modulus, three values for the shear modulus and three values for Poisson's ratio in the x, y, and z directions.

Common parameters to define for all configurations, in addition to the specific ones were: thermal expansion coefficient, mass density of the material, strain/stress measurement and reference temperature. Moreover thermal dependency of some parameters may be defined.

To accomplish individual tests, it was used an isotropic configuration since only was studied one component of the model. For the final models an orthotropic configuration was chosen. There was not used an anisotropic configuration since none of materials that compose the cables behaves as pure anisotropic material.

6.2.2 Viscoelastic model

The main characteristic of this model is the introduction of the velocity dependence with which the load was imposed. In the SAMCEF library were available three different viscoelastic models, composed by serial or parallel combinations of simple Hooke and damping laws. These models are: Kelvin, Maxwell and Zener.

Kelvin law models the behavior of the material as an elastic stiffness in parallel with a damping. This model predicts deformations with accuracy under constant stresses and works well for rubber like behaviors, since it predicts very well the creep. However, the relaxation is much less accurate. Fig 6.2 depicts the Kelvin model configuration.

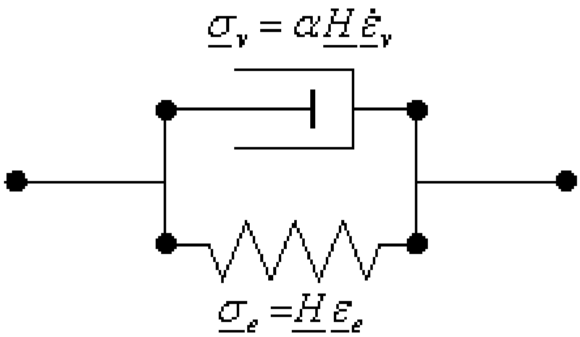

Figure 6.2: Kelvin viscoelastic model configuration.

Equations associated to this model are:

$$\sigma = \sigma_e + \sigma_v \tag{6.1}$$

$$\varepsilon = \varepsilon_e = \varepsilon_v \tag{6.2}$$

Maxwell law models the behavior of the material as an elastic stiffness in series with a damping. This model predicts with accuracy for the exponential stress decreasing of a polymer under constant strain. However, creep behavior is not well represented since plastic deformations are supposed to be linear. Figure 6.3 shows the Maxwell model configuration.

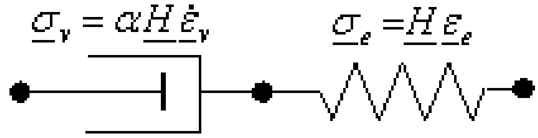

Figure 6.3: Maxwell viscoelastic model configuration.

Equations associated to this model are:

$$\sigma = \sigma_e = \sigma_e \tag{6.3}$$

$$\varepsilon = \varepsilon_e + \varepsilon_v \tag{6.4}$$

Zener law models the behavior of the material as the Kelvin model (elastic stiffness and structural damping in parallel) in series with an elastic spring. Figure 6.4 shows the Zener model configuration.

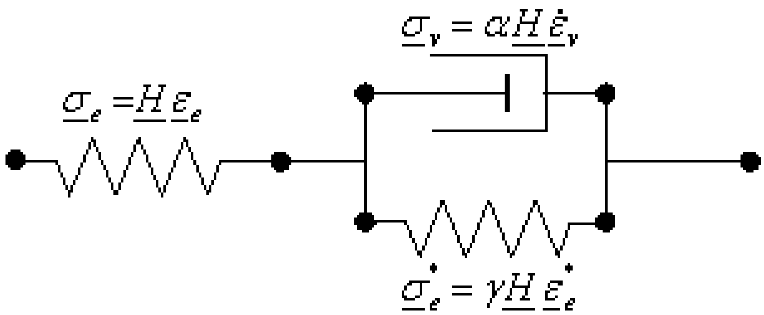

Figure 6.4: Zener viscoelastic model configuration.

Equations associated to this model are:

$$\varepsilon_v = \varepsilon_e^* \tag{6.5}$$

$$\varepsilon = \varepsilon_e + \varepsilon_e^* \tag{6.6}$$

$$\sigma = \sigma_v + \sigma_e^* = \sigma_e \tag{6.7}$$

Since Maxwell model does not predicts well enough creep and Kelvin model does not predicts with accuracy relaxation, Zener model is the most complete of the three available and, as it is a combination of the two previous models, thus predicts both phenomena.

The viscoelastic model was studied in regard to the simulation of the PVC insulation behavior, since it has an elastic component between a considerable range and it is dependent of the velocity. It was not possible to apply this material response over the whole model as there were plasticity phenomena. Among the models presented it was chosen the Zener model, since it is the most complete characterizing both phenomena. To define this model, in addition to establish elastic parameter, there must be given values of the damping (α) and 2^{nd} Hooke coefficient (γ) for each material.

6.2.3 Elasto-plastic model

Since in all tests occurred both elastic and plastic deformations, another model that was tried was the elasto-plastic one. This is a more complex model than the seen previously and it takes into account the kinematic hardening. In this model there must define hardening parameters instead of define the hardening curve. Equations associated with this model are the following:

$$\boldsymbol{\sigma} = H(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon_{pl}} - \boldsymbol{\varepsilon_{therm}}) \tag{6.8}$$

$$\boldsymbol{\beta} = \boldsymbol{\sigma} - \sum_i \mathbf{X_i} \tag{6.9}$$

$$f(\boldsymbol{\beta}) - Y \leqslant 0 \tag{6.10}$$

$$Y = k + \sum_j Q_j(1 - e^{-b_j \varepsilon_{eq}}) \tag{6.11}$$

$$\dot{\boldsymbol{\varepsilon}}_{pl} = \dot{p}\frac{\partial f}{\partial \boldsymbol{\beta}} \tag{6.12}$$

$$\boldsymbol{\beta}^T \dot{\boldsymbol{\varepsilon}}_{pl} = \dot{\varepsilon}_{eq} f(\beta) \tag{6.13}$$

$$\dot{\mathbf{X}}_\mathbf{i} = \dot{p}\left(\frac{2}{3}C_i\frac{\partial f}{\partial \boldsymbol{\beta}} - D_i\mathbf{X}_\mathbf{i}\right) = \frac{2}{3}C_i\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{pl}} - \dot{p}D_i\mathbf{X}_\mathbf{i} \tag{6.14}$$

In uniaxial loading, the stress in function of plastic strain is given by:

$$\sigma = k + \sum_j Q_j(1 - e^{-b_j \varepsilon_{eq}}) + \sum_i \frac{C_i}{D_i}(1 - e^{-D_j \varepsilon_{eq}}) \tag{6.15}$$

In addition, there must define the yield criteria among three available: Von Mises, Raghava and anisotropic Von Mises. For all models were chosen Von Mises and Raghava criteria as both are vaild when plastic deformations exist.

- Von Mises criterion:

$$\sigma_{eq}(\sigma) = \sqrt{\frac{1}{2}((\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2))} \leq Y \tag{6.16}$$

- Raghava criterion:

$$\sigma_{eq}(\boldsymbol{\sigma}) = \frac{I_1(S-1) + \sqrt{I_1^2(S-1)^2 + 12I_{2D}S)})}{2S} \leq Y \tag{6.17}$$

where $I_1 = \sigma_x + \sigma_y + \sigma_z$ is the first invariant of stress tensor,

$$I_{2D} = \frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2}{6} \tag{6.18}$$

is the second invariant of the deviatoric stress tensor, and S is a material dependent parameter.

This material model was imposed for all the cable components to simulate a complete elasto-plastic behavior, since what it was looking for, is the characterization of the entire model instead of a component by component modeling. To define this model there must be defined values of the initial elastic limit (k), parameters for isotropic hardening (b,Q) and parameters for kinematic hardening (C,D) for each material.

6.2.4 Viscoplastic model

Finally, the last material that was tested was the viscoplastic one. In this model, as in the viscoelastic one, material laws depend on the strain velocity. This model is similar to the plastic model but taking into account time effect. Damage effects were not taken into account as those data were not available from experimental tests.
Equation related to stress is:

$$\boldsymbol{\sigma} = (1-d)\mathbf{H} : \boldsymbol{\varepsilon_{ela}} = (1-d)\mathbf{H} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon_{vp}} - \boldsymbol{\epsilon_{th}}) \tag{6.19}$$

where ε_{ela} is the elastic strain, $\boldsymbol{\varepsilon_{vp}}$ is the viscoplastic strain, $\boldsymbol{\epsilon_{th}}$ is the thermal strain and d is a damage variable. Viscoplastic strains are defined by the following equation,

$$\dot{\boldsymbol{\varepsilon}}_{vp} = \dot{\varepsilon}_{eqvp} \frac{\partial \sigma_{eq}^{d}(\boldsymbol{\beta})}{\partial \boldsymbol{\beta}} = \dot{\varepsilon}_{eqvp} \frac{\partial}{\partial \boldsymbol{\beta}} \left(\frac{\sigma_{eq} \boldsymbol{\beta})}{1-d} \right) \tag{6.20}$$

where $\dot{\varepsilon}_{eqvp}$ is the equivalent viscoplastic strain rate and σ_{eq} is an equivalent stress. $\boldsymbol{\beta}$ is a stress tensor measured from a criterion center,

$$\boldsymbol{\beta} = \boldsymbol{\sigma} - \sum_{i=1}^{n_{hard}} \boldsymbol{\alpha_i} \tag{6.21}$$

for the superposition of n_{hard}, kinematic hardening. For i=1 to n_{hard}, center positions are driven by:

$$\boldsymbol{\alpha_i} = \frac{2}{3} c_i f_i(\varepsilon_{eqvp} \mathbf{x_i}) \tag{6.22}$$

$$\dot{\mathbf{x}}_{\mathbf{i}} = \dot{\boldsymbol{\varepsilon}}_{\boldsymbol{vp}} - \left(c_i f_i(\varepsilon_{eqvp}) \dot{\varepsilon}_{eqvp} + \frac{\gamma_{kin}}{\alpha_{eq}} \left(\frac{\alpha_{eq}}{M} \right)^{m_{r,kin}} \right) \mathbf{x}_{\mathbf{i}} \tag{6.23}$$

where $\dot{\mathbf{x}}_{\mathbf{i}}$ are variables associated to kinematic hardening, α_{eq} is an equivalent center and ca_i, c_i, γ_{kin}, M and $m_{r,kin}$ are material parameters depending on the model. The system is closed by a law which gives a relation between the equivalent viscoplastic strain rate and the equivalent stress:

$$\dot{\varepsilon}_{vp} = \left\langle \frac{\sigma_{eq}^d - \sigma_r}{\sigma_c} \right\rangle^n \tag{6.24}$$

where, σ_r is the radius criterion, σ_c is a comparision stress which is an image of the material resistance and n is a viscosity coefficient.
Isotropic hardening equations characterized by the radius criterion are the following:

$$\sigma_r = k + bQr \tag{6.25}$$

$$\dot{r} = \dot{\varepsilon}_{eqvp} - br\dot{\varepsilon}_{eqvp} + \frac{\gamma_{iso}}{bQ} \left| Q_r - bQr \right|^{m_{r,iso}} sign\left(Q_r - bQr \right) \tag{6.26}$$

where r is a variable related with isotropic hardening, k, b, Q, γ_{iso}, Q_r and $m_{r,iso}$ are material parameters.

For this model were tested three different approaches based on Chaboche law: Chaboche law with isotropic hardening (5 parameters), Chaboche law with nonlinear kinematic hardening (5 parameters) and Chaboche law with isotropic and nonlinear kinematic hardening (7 parameters). Parameters to define for each model are the following:

- Chaboche law with isotropic hardening:
  - n: viscosity coefficient.
  - K, k: material parameters related with creep.
  - b, Q: material parameters related with isotropic hardening.

- Chaboche law with nonlinear kinematic hardening:
  - n: viscosity coefficient
  - K, k: material parameters related with creep.
  - ca_i, c_i: material parameters related with kinematic hardening.
- Chaboche law with isotropic and nonlinear kinematic hardening:
  - n: viscosity coefficient.
  - K, k: material parameters related with creep.
  - b, Q: material parameters related with isotropic hardening.
  - ca_i, c_i: material parameters related with kinematic hardening.

In addition to this model, there are available in SAMCEF libraries more complex models based on Chaboche law adding nine or sixteen parameters, however, since there were not such information about material parameters, it was not possible to test them.

6.3 Analysis and parameterization

Both models, the single and the double cable were parameterized with the aim of analyzing the importance of some of them and observe which were the ones that produce a higher impact in the model, and if there were parameters that could be neglected. To analyze all variables in an iterative way, there was used a software that launches automatically multiple analyses varying each time specified parameters, this is BOSS-Quattro software. BOSS-Quattro is a parametric application manager and multi disciplinary optimization environment that lets to manage iterative loops of analysis. It builds and runs chains of tasks involving different applications, and collects results automatically. Thanks to this software was easier to determine the importance of some parameters in the model since it executes multiple analyses varying a wide range of values for these parameters. An interesting option inside this tool is the possibility of combining a variation of parameters and observe their interaction. To process the designed model in

BACON, the MECANO post-processor was used. MECANO is a nonlinear static and dynamic module of analysis with the ability of enabling the integration of multi body simulation features in the models, this software is the one that make all computations and gives the results required for the model.

The interest in using BOSS-Quattro also came from the automatic handling of iterative studies, which rapidly becomes impracticable "by hand" as the number of needed analyses grows. In that context, BOSS-Quattro is powered by a set of engines which provide parametric, statistical, design of experiments, optimization, and updating features. Among the multiples engines that BOSS-Quattro has, cable analyses were carried out using the parametric studies engine. With this engine was possible to give a set of values for a subset of parameters, and describe desired system responses. For that, it was required to establish the parametric variables with its variation range and the desired parametric function to analyze. Moreover there had to be defined the iteration mode among serial, parallel or combine. For this analysis the combine iteration mode was chosen, in which BOSS-Quattro performed all possible combinations.

In this work, there were accomplished two different type of analyses, a linear and a nonlinear one, both over the two main designed models, single and double cable. On one hand, linear analyses were carried out in order to obtain some approximated data about material, Young's modulus and Poisson's ratio influence. Although a linear behavior did not correspond with the cable behavior, it was interesting to see in a faster way how a variation of these parameters affect to the model, as the linear analysis is much less time consuming than the nonlinear one. On the other hand, as nonlinear analyses provide more accurate results comparing with experimental tests, these results were useful to set up final values to define material modeling parameters and, like in linear analysis, to observe the influence of a variation in some parameters over the model. Hereinafter are explained in more detail both kind of analyses.

6.3.1 Linear analyses

In the parametric linear analyses phase, the material model selected was the elastic one. For the single cable model, geometric and material parameters were analyzed. Regarding geometric variation, there was applied a core radius *R1* and an insulation thickness T variation from 0.1 to 1 mm with a step of 0.225 mm, keeping a PVC and copper Young's modulus of 2.8 GPa and 120 GPa respectively. It is important to remark that there was applied the same geometric variation to both wire components (PVC and Cu) to see which of them is more influential in the cable behavior.

With respect to material parameters variation, there was applied a copper Young's modulus variation from 100 GPa to 130 GPa with a step of 7.5 GPa, for PVC there was applied a variation from 2000 MPa to 3500 MPa with a step of 375 MPa. Cable section size is kept for these variations with a core radius of 0.7 mm and a thickness of 0.65 mm, the same that in experimental tests. All these combinations and their percentage difference in quantity can be seen in Apendix A. In geometric analyses first four variation values correspond to the thickness variation and the next four to the core radius variation. In material analyses first four values correspond to the copper Young's modulus variation and next four to the PVC Young's modulus variation. Copper Young's modulus range variation was much smaller than PVC one since plastic material insulation may vary easily than copper, and since insulation may not always be PVC.

Poisson's ratio variation does not appear in these tables since, as it is explained in Chapter 7, its variation did not cause any perturbation in the wire behavior, as was found in [26]. Range variation of the Poisson's ratio for the PVC was from 0.35 to 0.45 and for the copper from 0.3 to 0.4.

For each test there were measured different kind of parameters:

- Traction: Maximum displacement in component $+z$ in mm.
- Bending: Maximum force in component $+y$ in N.

- Torsion: Maximum moment in component $-z$ in Nmm.

For each parameter there were obtained 25 values corresponding to combinations of 2 parameters in a 5 values range.

For the double twisted cable model, only material parameters were analyzed, since geometric parameters could not be parameterized because of the complexity of this model. Geometric parameters for simple wires were a 2.5 mm diameter for copper core and 0.40 mm for PVC thickness, a tin diameter of 1.10 mm for both spacers and an outer diamter of 8.90 mm for the external insulation. The Young's modulus variation range parameters and their steps were the following:

- Copper (*Y1*): From 100 to 130 GPa, step of 7.5 GPa.
- PVC (*Y2*): From 2000 to 3500 MPa, step of 375 MPa.
- Tin (*Y3*): From 40000 to 60000 MPa, step of 5000 MPa.

In Appendix B there can be seen parameter combinations Young's modulus for each material. Variation column shows percentage difference in quantity for Sn (first four values), PVC (next four values) and Cu Young's modulus (last for values).

As in the single cable model, Poisson's ratio variation do not produce any appreciable effect in the model. In this case range variation was:

- Copper (*NT1*): From 0.3 to 0.4, step of 0.25.
- PVC (*NT2*): From 0.35 to 0.45, step of 0.25.
- Tin (*NT3*): From 0.3 to 0.4, step of 0.25.

Parameters measured in each test were the same than in the previous case, maximum displacement for traction, maximum force for bending, and maximum moment for torsion. Each test had different output parameters since there were applied different loading conditions. For traction, a force was imposed measuring the displacement associated to this imposed force in one cable end. For bending, a displacement was imposed measuring the corresponding residual force in the maximum displacement point. Finally for torsion, a turn was imposed and measuring its corresponding moment at 45°.

In these analyses, obtained numeric data did not correspond accurately with the ones obtained in experimental tests, however they provided important information about which were the parameters that had grater impact over the model and between what range there had to be established material parameters.

6.3.2 Nonlinear analyses

In the parametric nonlinear analyses phase, were tested nonlinear models exposed in the previous section. Since most of the parameters associated to these models must be obtained from experimental tests, the parametric analysis served to try and iterate different combinations of this parameters (between a logical range) and verify if it was a valid model or not.

The material model selected to analyze in a deeper way was the viscoplastic, concretely the Chaboche law with isotropic hardening. This material model was the one that most accurate curve shapes and numeric values provided among the four tested. With this model was possible to simulate plasticity as well as viscosity effects. Although kinematic hardening is a model used usually for cyclic loading, isotropic hardening is the one that better simulate plasticity phenomena. As time-cost was a decisive factor, nonlinear analyses were focused on bending test, since is the case that it is produced with more frequency in real conditions, and the principal effect that was required to be tested. Hence, viscoplastic parameters obtained in bending test were established for the three loading cases.

Firstly, for the single cable, the parametric study was focused on varying material parameters to find an accurate cable response. There were selected two different criteria for Chaboche law, the Ragahava and the Von Mises criterion. Same variation range was applied for both, analyzing displacements for the first loading cycle in the maximum and minimum values of the force. Observing these two values, it was possible to determine whether the obtained curve associated to the tested material model resemble the experimental curves or not. Values selected for n, K and k parameters were 5, 8, 11 and 14 for each variable and for b and Q were kept values of 10 and 100 respectively. Hence, for the parametric analysis combining three variables in a range of four values, 64 iterations were done. Accepted values for both displacements were 7 mm for the maximum and between 3 mm and 4 mm for the minimum one. The variable combinations that showed more accurate results, were selected to analyze them and tune values to obtain the final model.

Once material parameters tuning was done, in regard to two material models, same analysis as in the linear case were accomplished. For bending test, copper Young's modulus selected range was from 100 GPa to 130 GPa with a step of 7.5 GPa and for PVC a range from 2 GPa to 3.5 GPa with a step of 0.325 GPa, finding enough accurate results for displacement-force curves. For traction test the range selected was different as it was found that single cable with a nonlinear material model behaves like an orthotropic material (discussed in Chapter 7). Thus, the range for copper Young's modulus was from 30 GPa to 70 GPa with a step of 10 GPa and for PVC a range from 5 GPa to 12 GPa with a step of 7.5 GPa.

Results obtained from these nonlinear analyses were valuable to find the best cable model and determine force-displacement curves with accuracy for both curve shape and numeric data.

Chapter 7

Resluts and Discussion

In this chapter are presented results obtained from the cable behavior study in the simulation process and from the parametric analyses by means of an iterative method. In addition, it is exposed a comparison between simulated curves and the ones obtained from experimental tests under the three loading cases, as well as a discussion about the final material model selected. It is also analyzed the influence of geometric and material parameters that most affect the cable behavior and the design limitations. For each analysis are showed different tables and charts. Finally it is commented the influence of the lay angle for an elastic behavior.

7.1 Parametric analyses results

In this section are presented and discussed results obtained for both linear and nonlinear parametric analyses. Linear analyses are referred to analyses done for both cable models with a linear elastic behavior, and nonlinear analyses are referred to analyses done with a viscoplastic model. For the single cable results are presented for both, geometric and material parameters and for the double cable are presented material analyses results. Nonlinear analyses were focused mainly in the single cable, since it was a much less time consuming model than double cable, hence results regarding this case are presented largely for the single cable model.

7.1.1 Linear analyses results

Results obtained in the geometric and material analysis of the single cable traction test are showed in Table 7.1 and Figures 7.1 and 7.2. Copper geometric variation had a higher influence than PVC in the cable behavior whit same radius alteration for copper and PVC. Although for the minimum copper radius, an increase of PVC thickness has strong influence, when this value is increased in a small quantity, PVC has not relevant influence compared with copper. As it can be observed in Table 7.1, maximum impact caused by PVC with a geometric variation of 69% is 32% and minimum, associated to a variation of 23%, is 2%. Comparing same values in copper case, maximum is 92% and minimum 39% with same geometric alteration. Thus, it can be noted that copper was the more influential material in this analysis. In addition it should also be noted that from the first increase of copper radius, percentage difference between copper and PVC is highly considered.

Young's modulus variation had an impact of less magnitude in this case, however it is considerable. As it can be seen in Figure 7.2, a copper Young's modulus alteration causes almost same impact percentage in the maximum displacement. However, a PVC Young's modulus increase only caused 1% of displacement decrease (Figure 7.1). In this analysis, copper was also the material that had the most influence in maximum displacements, despite the fact that its Young's modulus variation was half of the PVC. Hence, it may be concluded that for single cable traction test, copper is the material that establish the cable behavior.

Table 7.1: Geometric variation influence for the single cable traction test.

R1 [mm]	T [mm]	Y1* [MPa]	Y2* [MPa]	Disp. [mm]	PVC	Cu	G. var.
0.1	0.1	2800	120000	2.95616			
0.1	0.325	2800	120000	2.01365	32%		69%
0.1	0.55	2800	120000	1.30201	35%		41%
0.1	0.775	2800	120000	0.868735	33%		29%
0.1	1	2800	120000	0.607295	30%		23%
0.325	0.1	2800	120000	0.223322		92%	69%
0.325	0.325	2800	120000	0.210521	6%	90%	
0.325	0.55	2800	120000	0.194802	7%	85%	
0.325	0.775	2800	120000	0.177543	9%	80%	
0.325	1	2800	120000	0.160307	10%	74%	
0.55	0.1	2800	120000	0.072051		68%	41%
0.55	0.325	2800	120000	0.0701132	3%	67%	
0.55	0.55	2800	120000	0.0677355	3%	65%	
0.55	0.775	2800	120000	0.065033	4%	63%	
0.55	1	2800	120000	0.0621361	4%	61%	
0.775	0.1	2800	120000	0.0356876		50%	29%
0.775	0.325	2800	120000	0.0350631	2%	50%	
0.775	0.55	2800	120000	0.0343236	2%	49%	
0.775	0.775	2800	120000	0.0334866	2%	49%	
0.775	1	2800	120000	0.0325804	3%	48%	
1	0.1	2800	120000	0.0212379		40%	23%
1	0.325	2800	120000	0.0209646	1%	40%	
1	0.55	2800	120000	0.0206499	2%	40%	
1	0.775	2800	120000	0.0202963	2%	39%	
1	1	2800	120000	0.0199138	2%	39%	

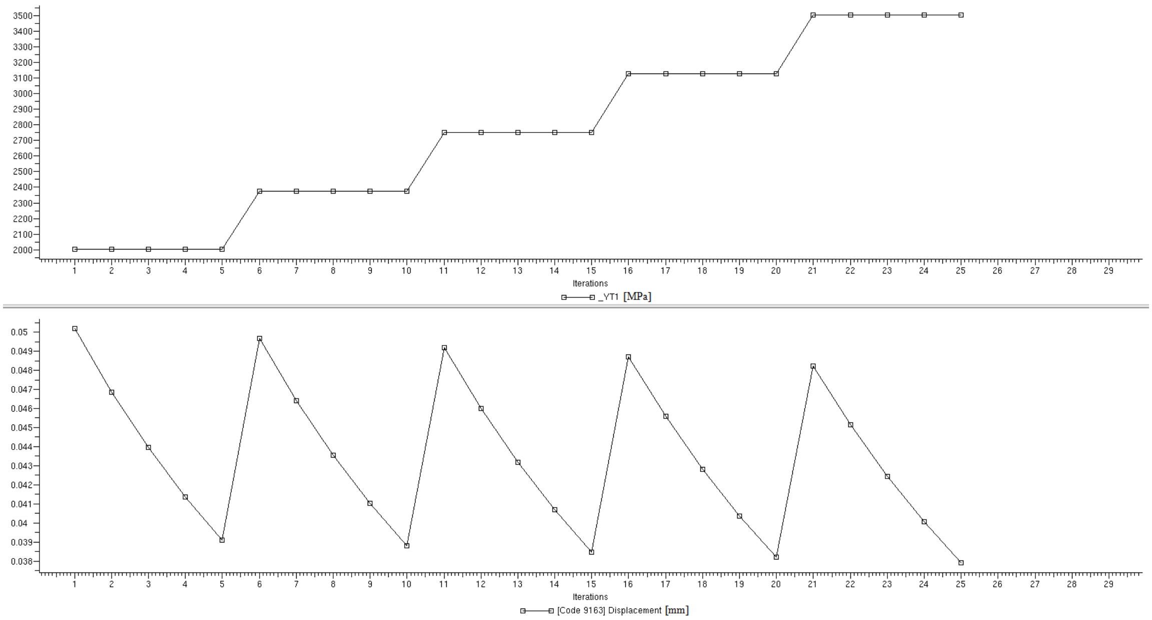

Figure 7.1: Influence of PVC Young's modulus in maximum displacement.

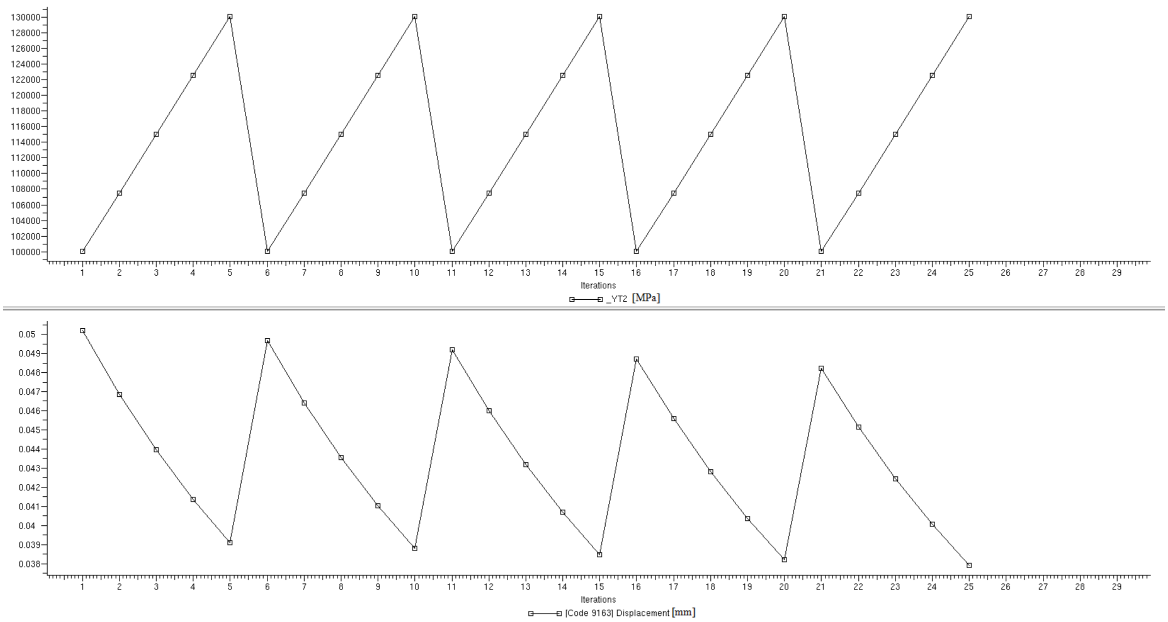

Figure 7.2: Influence of copper Young's modulus in maximum single cable displacement.

Results obtained in the geometric and material analysis of the single cable bending test are showed in Table 7.2 and Figures 7.3 and 7.4. In this analysis what was measured was the maximum residual fore. For geometric analysis case, results follow same pattern than for traction test but with a higher impact for both PVC and copper. Copper influence is highly appreciated and in most cases is clearly the dominant material. The influence of PVC decrease drastically with the first copper increase, however it can not be neglected in all cases at it reaches a 30%. Notice the fact that a geometric modification in the cable design is quite sensible for the bending case.

Table 7.2: Geometric variation influence for the single cable bending test.

R1 [mm]	T [mm]	Y1* [MPa]	Y2* [MPa]	Force [N]	PVC	Cu	G. var.
0.1	0.1	2800	120000	0.00472259			
0.1	0.325	2800	120000	0.148205	97%		69%
0.1	0.55	2800	120000	0.554617	73%		41%
0.1	0.775	2800	120000	1.50161	63%		29%
0.1	1	2800	120000	3.07482	51%		23%
0.325	0.1	2800	120000	3.10885		100%	69%
0.325	0.325	2800	120000	3.54324	12%	96%	
0.325	0.55	2800	120000	4.49466	21%	88%	
0.325	0.775	2800	120000	6.38445	30%	76%	
0.325	1	2800	120000	9.09625	30%	66%	
0.55	0.1	2800	120000	8.25383		62%	41%
0.55	0.325	2800	120000	9.14318	10%	61%	
0.55	0.55	2800	120000	11.1235	18%	60%	
0.55	0.775	2800	120000	14.5027	23%	56%	
0.55	1	2800	120000	19.0621	24%	52%	
0.775	0.1	2800	120000	29.7708		72%	29%
0.775	0.325	2800	120000	31.3625	5%	71%	
0.775	0.55	2800	120000	34.7508	10%	68%	
0.775	0.775	2800	120000	40.3083	14%	64%	
0.775	1	2800	120000	47.4675	15%	60%	
1	0.1	2800	120000	81.633		64%	23%
1	0.325	2800	120000	84.8194	4%	63%	
1	0.55	2800	120000	90.1639	6%	61%	
1	0.775	2800	120000	98.5126	8%	59%	
1	1	2800	120000	109.352	10%	57%	

In the material analysis case, although it can be observed a higher influence of PVC than for the previous case (Figure 7.3), the alteration of the copper Young's modulus is which causes the biggest impact, as it is showed in Figure 7.4. A variation of the copper Young's modulus has almost the same proportional effect for all PVC combinations. In Appendix A there can be seen numerical data associated to both charts.

Results obtained in the geometric and material analysis of the single cable torsion test are showed in Table 7.3 and Figures 7.5 and 7.6. Geometric variation results show that copper has a much higher influence than PVC in all cases but in the first copper range. From a copper radius of 0.325 mm the variation of PVC has almost no effect, thus for this analysis PVC influence can be neglected.

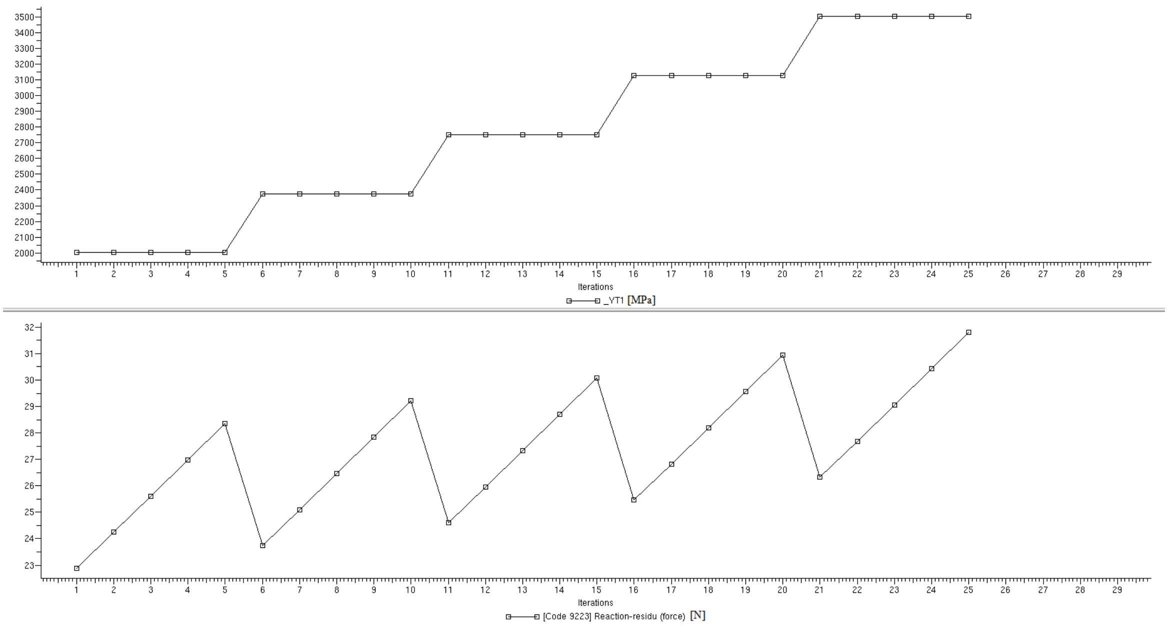

Figure 7.3: Influence of PVC Young's modulus in maximum force.

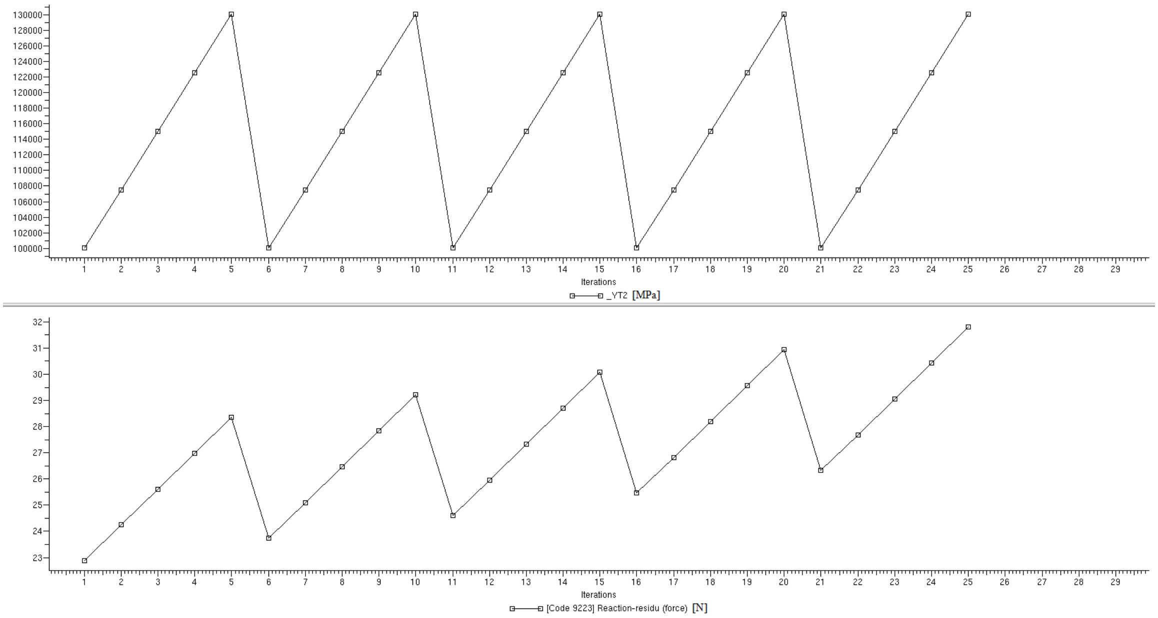

Figure 7.4: Influence of copper Young's modulus in maximum single cable residual force.

Regarding material analysis, same results were obtained, copper is once again the material that defines the cable behavior. Hence for torsion case the only material that had relevant importance in the whole cable behavior was copper. Poisson's ratio results can be fund in Appendix A. This parameter was tested for each case obtaining same results for all of them: Poisson's ratio variation did not cause any effect in single cable model, as was found in [26]. Same results were obtained for the double cable model.

As mentioned previously, for the double cable are exposed results concerning material analyses. Figure 7.7 shows the influence of each material in traction test. Same color lines depict the impact that has each Young's modulus increase for three different materials. It may be observed that copper is the one that introduces a greater displacement decrease and tin is the less influential. Hence, for this kind of test, tin influence may be neglected. It should be noted that, in addition, copper Young's modulus variation was the smallest one, thus copper is the material that defines cable behavior in this case.

Table 7.3: Geometric variation influence for the single cable torsion test.

R1 [mm]	T [mm]	Y1* [MPa]	Y2* [MPa]	Moment [Nmm]	PVC	Cu	G. var.
0.1	0.1	2800	120000	-0.09			
0.1	0.325	2800	120000	-0.54	83%		69%
0.1	0.55	2800	120000	-3.24	83%		41%
0.1	0.775	2800	120000	-11	71%		29%
0.1	1	2800	120000	-28	61%		23%
0.325	0.1	2800	120000	-8		99%	69%
0.325	0.325	2800	120000	-10	20%	95%	
0.325	0.55	2800	120000	-19	47%	83%	
0.325	0.775	2800	120000	-36	47%	69%	
0.325	1	2800	120000	-68	47%	59%	
0.55	0.1	2800	120000	-94		91%	41%
0.55	0.325	2800	120000	-100	6%	90%	
0.55	0.55	2800	120000	-120	17%	84%	
0.55	0.775	2800	120000	-150	20%	76%	
0.55	1	2800	120000	-203	26%	67%	
0.775	0.1	2800	120000	-382		75%	29%
0.775	0.325	2800	120000	-400	5%	75%	
0.775	0.55	2800	120000	-430	7%	72%	
0.775	0.775	2800	120000	-483	11%	69%	
0.775	1	2800	120000	-565	15%	64%	
1	0.1	2800	120000	-1080		65%	23%
1	0.325	2800	120000	-1112	3%	64%	
1	0.55	2800	120000	-1164	4%	63%	
1	0.775	2800	120000	-1246	7%	61%	
1	1	2800	120000	-1366	9%	59%	

For bending test, results are completely different than in the previous case, as it can be seen in Figure 7.8. In this case, PVC is the material that exert a higher influence in the obtained maximum residual force. It may be observed that the gap introduced by PVC is between six and ten times the introduced by copper with same Young's modulus variation and in this case, tin influence can be completely neglected too. Notice the fact that for bending analyses, Young's modulus for all materials was reduced in a big quantity in order to obtain more similar results to experimental test. Hence, it can be seen that it is not possible to apply an isotropic material model for double cable design and should be applied an othotropic one, defining a different Young's modulus for each x, y and z direction.

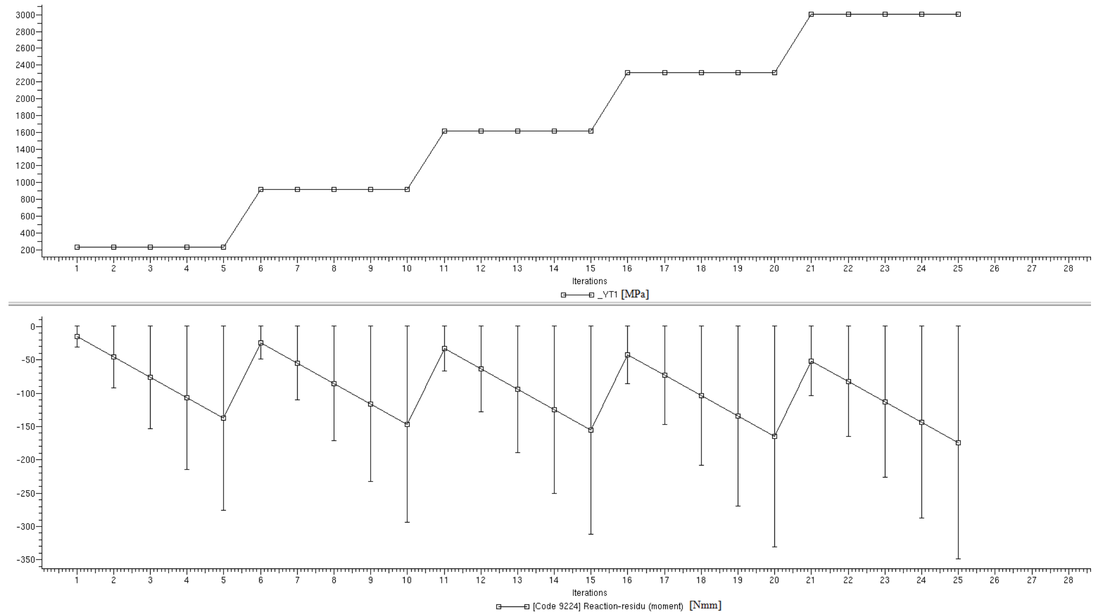

Figure 7.5: Influence of PVC Young's modulus in maximum single cable residual moment.

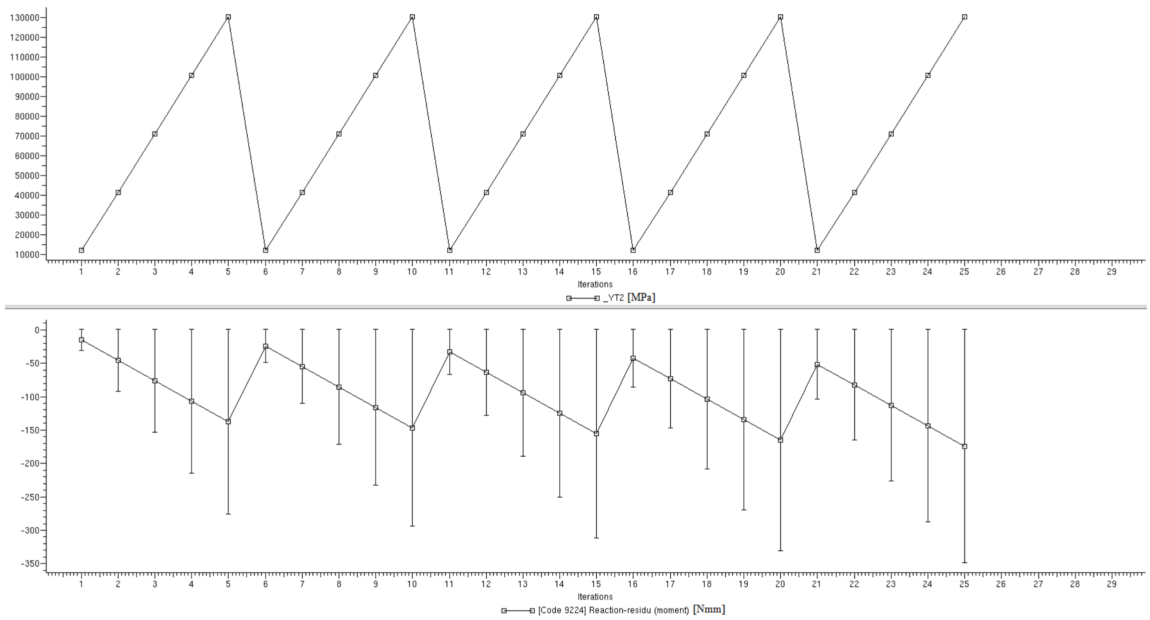

Figure 7.6: Influence of copper Young's modulus in maximum single cable residual moment.

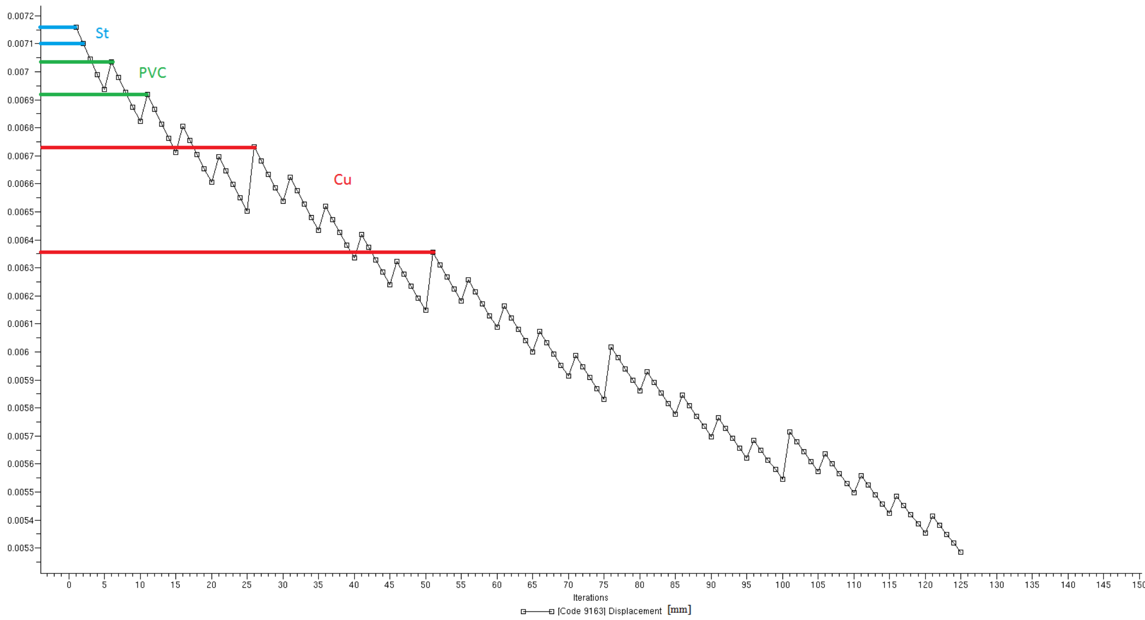

Figure 7.7: Influence of Young's modulus in maximum double cable displacement.

For torsion test, results follow the same line that the ones obtained in bending case, being the PVC the more influential. Figure 11 shows the gap introduced by each Young's modulus increase. Notice the fact that the tin gap is too small and thus, it is not depicted. For the same Young's modulus variation, the impact of PVC is between three and four times the the impact of copper. It can be concluded that for the double cable the effect of tin can be neglected and copper and PVC have a different impact for each test.

In Appendix B are available tables associated to these analysis with all numeric data and the percentage of influence of each material.

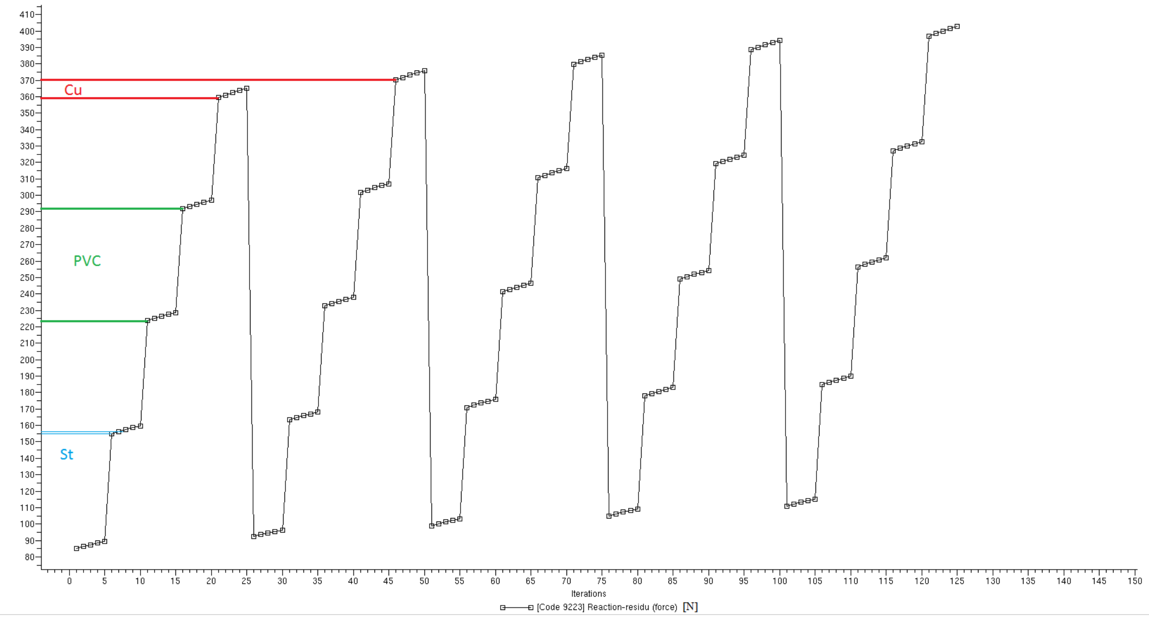

Figure 7.8: Influence of Young's modulus in maximum double cable residual force.

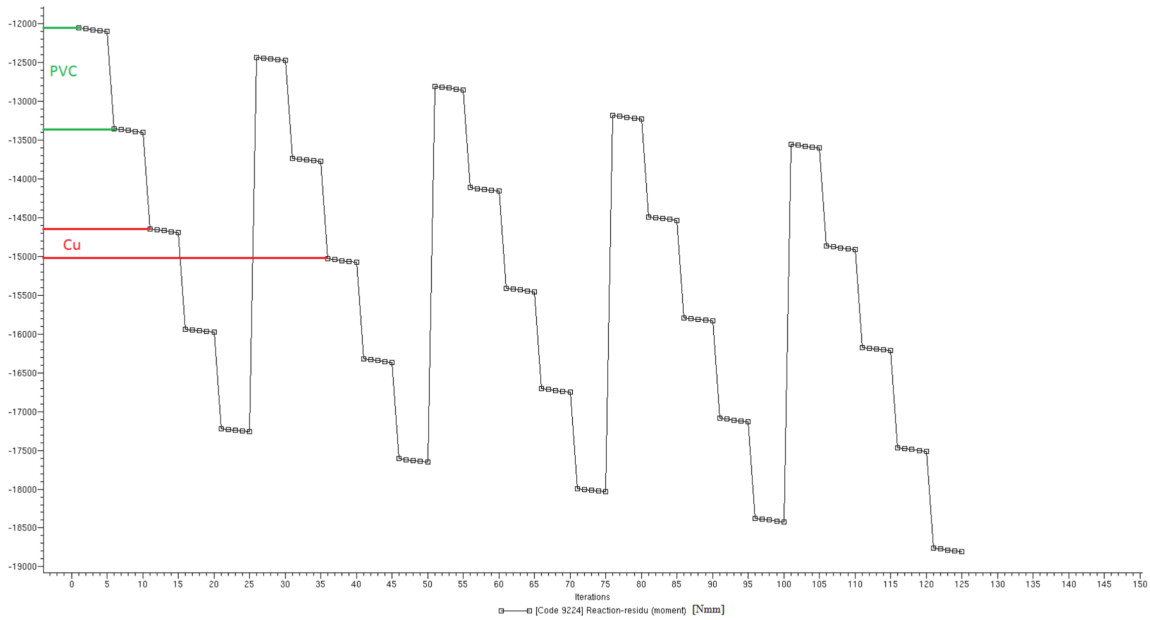

Figure 7.9: Influence of Young's modulus in maximum double cable residual moment.

7.1.2 Nonlinear analyses results

Results obtained concerning nonlinear analyses results are centered on traction and bending tests for single cable model. In this case results evaluation is focused on numeric values of displacement and force instead of the impact of each material in the model, however their influence is also discussed.

In Table 7.4 are listed data concerning traction test analysis. The parameter of interest in this case was the maximum displacement reached by the cable under 80 N force. Maximum displacement looked for is around 0.14 mm. It may be observed that better results are found in the bottom part of the table, with a PVC Young's modulus of 12 GPa and a copper Young's modulus between 40 GPa and 70 GPa. Notice the fact that copper Young's modulus variation has almost no effect in the maximum displacement obtained. It should also be noted that unlike traction linear analysis, with a nonlinear model, material influence changes radically being the PVC the more influential in the cable behavior.

Table 7.5 shows data in regard to bending test analysis. In this case was studied the maximum residual force for each loading cycle corresponding with a displacement of 7 mm. This time there looked for a residual force of around 3.5 N. Among different Young's modulus combinations, the most accurate corresponds with a PVC Young's modulus of 2.75 GPa and a copper Young's modulus of 130 GPa. It may be observed that again PVC is the material that most affects cable behavior, however this time with much less intensity since in addition, its Young's modulus variation is twice that of the copper.

As can be seen from obtained results, they get closer to numeric data obtained in experimental test, however this in not the only thing to take into account, since curve shape is another material characteristic that have to be simulated.

Table 7.4: Nonlinear parametric analysis of single cable traction test.

R1* [mm]	T* [mm]	Y1 [MPa]	Y2 [MPa]	Disp. [mm]	Cu	PVC	Y var.
0,7	0,65	5000	30000	0,272146			
0,7	0,65	5000	40000	0,26956	1%		25%
0,7	0,65	5000	50000	0,267834	1%		20%
0,7	0,65	5000	60000	0,266548	0%		17%
0,7	0,65	5000	70000	0,265524	0%		14%
0,7	0,65	6750	30000	0,215007		21%	26%
0,7	0,65	6750	40000	0,212551	1%	21%	
0,7	0,65	6750	50000	0,210944	1%	21%	
0,7	0,65	6750	60000	0,209761	1%	21%	
0,7	0,65	6750	70000	0,208824	0%	21%	
0,7	0,65	8500	30000	0,181233		16%	21%
0,7	0,65	8500	40000	0,178887	1%	16%	
0,7	0,65	8500	50000	0,177383	1%	16%	
0,7	0,65	8500	60000	0,176294	1%	16%	
0,7	0,65	8500	70000	0,175441	0%	16%	
0,7	0,65	10250	30000	0,158837		12%	17%
0,7	0,65	10250	40000	0,156569	1%	12%	
0,7	0,65	10250	50000	0,155137	1%	13%	
0,7	0,65	10250	60000	0,154115	1%	13%	
0,7	0,65	10250	70000	0,153326	1%	13%	
0,7	0,65	12000	30000	0,142864		10%	15%
0,7	0,65	12000	40000	0,140647	2%	10%	
0,7	0,65	12000	50000	0,139266	1%	10%	
0,7	0,65	12000	60000	0,138292	1%	10%	
0,7	0,65	12000	70000	0,137547	1%	10%	

Table 7.5: Nonlinear parametric analysis of single cable bending test.

R1* [mm]	T* [mm]	Y1 [MPa]	Y2 [MPa]	Force [N]	Cu	PVC	Y var.
0,7	0,65	2000	100000	3,16743			
0,7	0,65	2000	107500	3,17039	0%		7%
0,7	0,65	2000	115000	3,1733	0%		7%
0,7	0,65	2000	122500	3,17616	0%		6%
0,7	0,65	2000	130000	3,17899	0%		6%
0,7	0,65	2375	100000	3,33825		5%	16%
0,7	0,65	2375	107500	3,34119	0%	5%	
0,7	0,65	2375	115000	3,34409	0%	5%	
0,7	0,65	2375	122500	3,34693	0%	5%	
0,7	0,65	2375	130000	3,34974	0%	5%	
0,7	0,65	2750	100000	3,47405		4%	14%
0,7	0,65	2750	107500	3,47697	0%	4%	
0,7	0,65	2750	115000	3,47984	0%	4%	
0,7	0,65	2750	122500	3,48267	0%	4%	
0,7	0,65	2750	130000	3,48546	0%	4%	
0,7	0,65	3125	100000	3,58498		3%	12%
0,7	0,65	3125	107500	3,58788	0%	3%	
0,7	0,65	3125	115000	3,59073	0%	3%	
0,7	0,65	3125	122500	3,59353	0%	3%	
0,7	0,65	3125	130000	3,5963	0%	3%	
0,7	0,65	3500	100000	3,67763		3%	11%
0,7	0,65	3500	107500	3,68051	0%	3%	
0,7	0,65	3500	115000	3,68334	0%	3%	
0,7	0,65	3500	122500	3,68612	0%	3%	
0,7	0,65	3500	130000	3,68887	0%	3%	

7.2 Material selection results

In this section are presented simulated force-displacement curves of the single cable for bending and traction tests. As it has been commented in Chapter 6, there were accomplished multiples tests trying different material models to define as accurate as possible curves obtained from experimental tests, and the model found that better simulated these curves was the viscoplastic.

Among tried laws within available for the viscoplastic model, the one that showed the best results was Chaboche law with isotropic hardening. Firstly, this model was applied to copper and a viscoelastic model to PVC, since PVC has a more elastic behavior than copper. However, results were not accurate enough since the elastic component of PVC imposed against the plastic strain. Thus, the same viscoplastic model was applied for both materials and with same viscoplastic parameters. Once selected this concrete model, there were carried out multiple trial and error tests and parametric analysis with material parameters as variables to tune the curves obtained. These tests were focused on bending case since that was the more relevant case which must be defined. Finally, parameters that best approached to looked for results were:

- Viscosity coefficient, n: 11
- Material parameter related with creep, K: 5 MPa
- Material parameter related with creep, k: 11 MPa
- Material parameter related with isotropic hardening, b: 10
- Material parameter related with isotropic hardening, Q: 100 MPa

Figure 7.10 depicts the force-displacement curve obtained with the model described above. Values of displacement and force are quite accurate and the plastic strain obtained is slightly larger than obtained in experimental tests. Regarding curve shape, it simulates with some accuracy loading-unloading cycles, however from the second loading cycle it is obtained a larger part of elastic strain, so this part must be improved. Nonetheless, overall results are good enough taking into account the difficulty of simulating an exact curve of a nonlinear model.

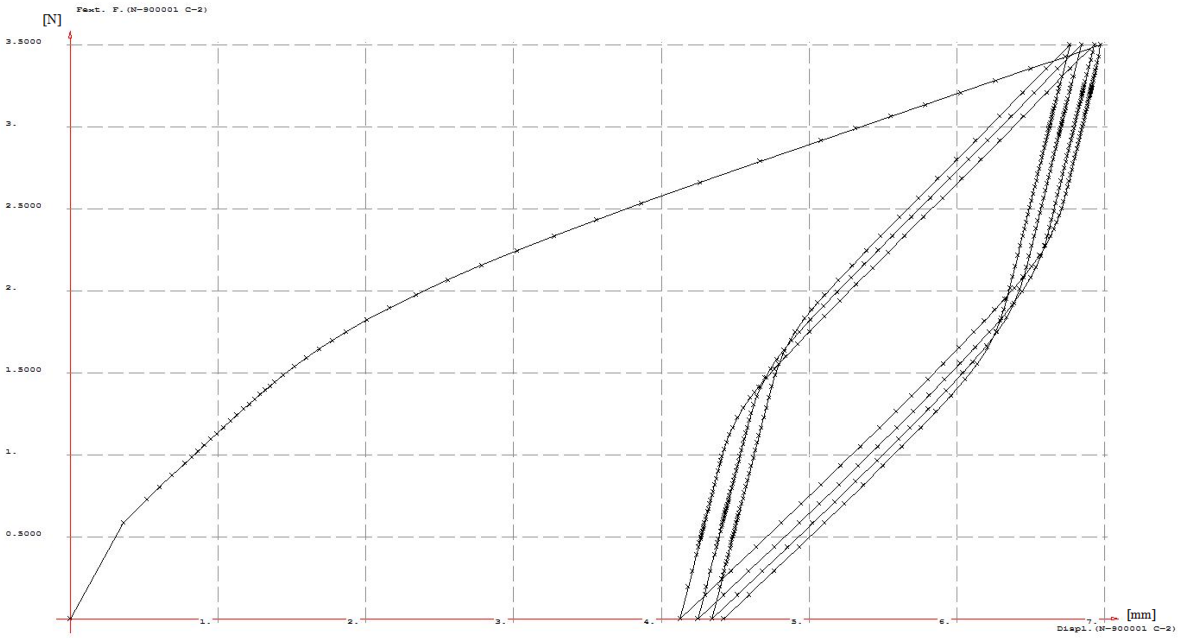

Figure 7.10: Single cable bending test Force-Displacement curve with viscoplatic behavior.

With same parameters of the viscoplastic model in bending case, there was simulated the traction test. First results showed a curve that did not describe its real behavior. As it has discussed, that happened since there had to define an orthotropic model instead of an isotropic one. Thus, there must be redefined Young's modulus for each material. This process has been described in the previous section, finding a combination that approaches to experimental test. Figure 7.11 shows force-displacement curve obtained with these parameters. Maximum force-displacement values are accurate enough, however there is obtained a larger plastic strain as occurred in bending case. In addition, shape of first loading cycle is not accurate enough. Nevertheless, following cycles have a similar behavior to experimental test and this model can simulate both cases with some accuracy.

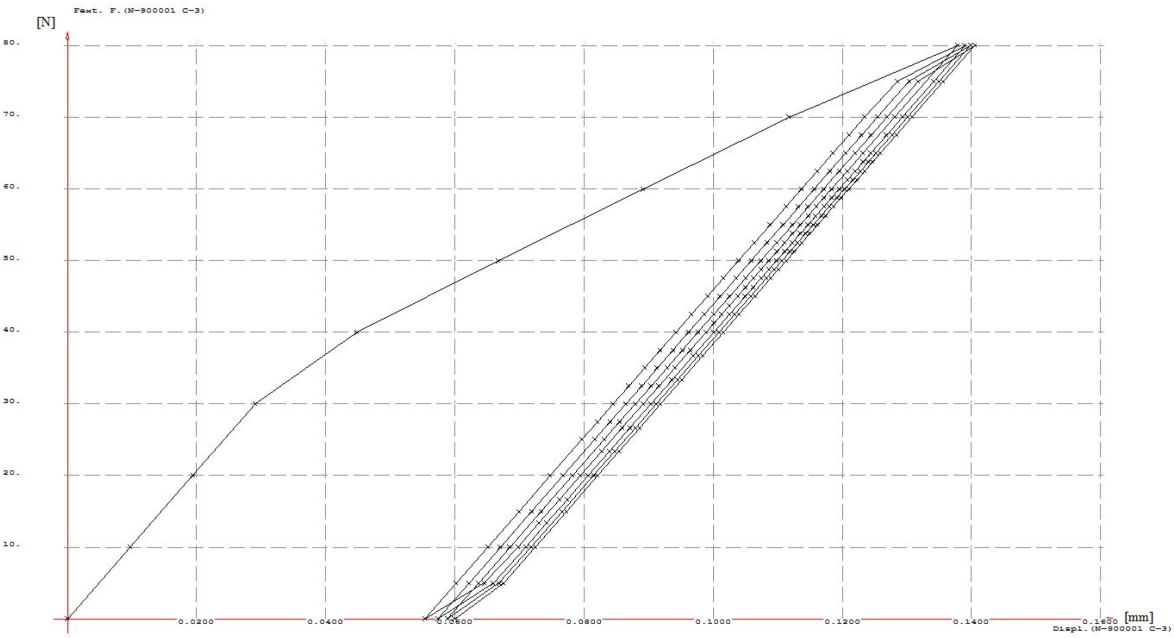

Figure 7.11: Single cable traction test Displacement-Force curve with viscoplatic behavior.

For torsion case, there also were redefined Young's modulus parameters, as results with bending parameters were not accurate enough. Figure 7.12 shows the moment-turn curve obtained with a PVC Young's modulus of 1.5 GPa and a copper Young's modulus of 20 GPa.

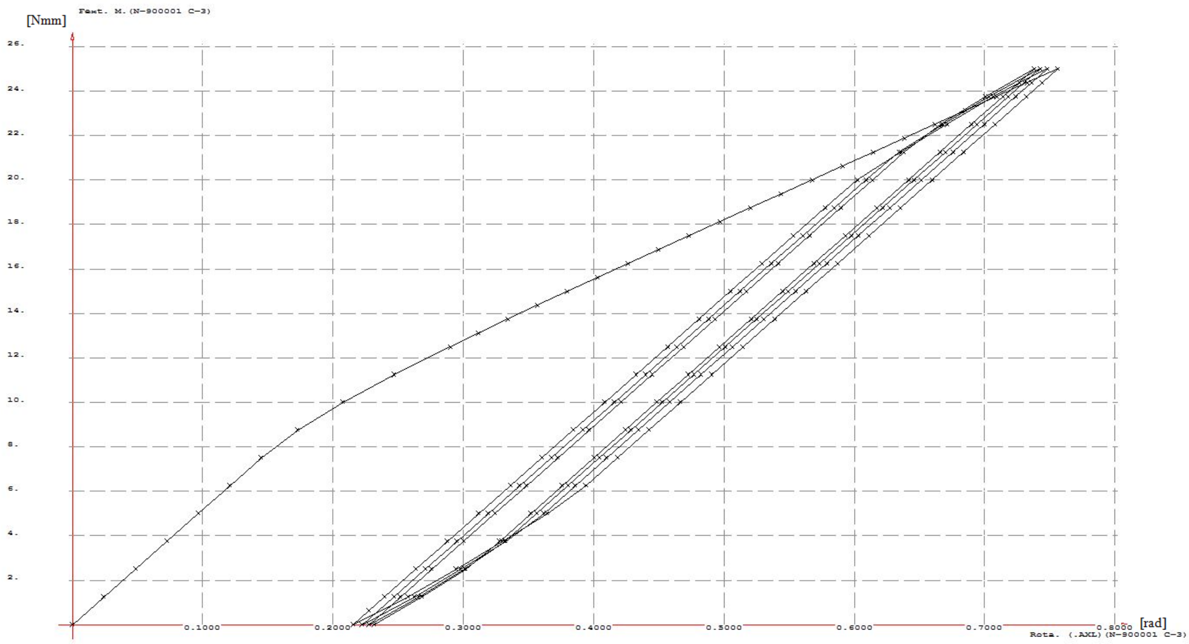

Figure 7.12: Single cable torsion test Moment-Turn curve with viscoplatic behavior.

7.3 Lay angle

The lay angle effect was studied in regard to the double cable core, and is the angle between the twisted wire and the central core (in this case the cable central axis). Although it is common to study this parameter for cables surrounding a core, in this case the core is composed of twisted cables and it was studied the lay angle associated to this twisted pair of cables. The effect of the lay angle was studied for each loading case varying the cable turns along the cable length. Turns were done around the z central axis of the cable. Tables 7.6, 7.7 and 7.8 show results obtained for each case. It should be noted that since the cable length for the traction test was twice the length for bending and torsion, a bigger range was taken. For that, it is also showed the lay length, defined as the distance required to complete one turn of the wire around the central axis. With this parameter it was possible to compare clearly what was its impact over the three cases.

For traction test, variation column shows the percentage with which maximum displacement increases with respect to the previous value. Minimum value of the displacement corresponds with one wire turn along the cable length and maximum value with six turns. Displacement difference of these two values is 71.43%, thus it may be observed that each turn, maximum displacement increases although in a smaller quantity each time. It can be concluded that, for traction test, a lay angle increase supposes a maximum displacement increase, as was tested in [29].

For bending test, cable behavior follows the same way that for traction case. There was obtained a maximum force decrease as the lay angle increased (lay length decrease). Force difference between the two extreme values is 33.33% so, it is interesting to note that the cable elastic behavior is increased. In this case the effect has a greater impact with a variation increase of almost twice, regarding traction case variation for two turns along total cable length. It should be noted that the decrease of the force follows a decreasing trend. Finally, it should also be noted that although in this case wires turn three times around central axis, maximum lay length is the same to the previous case since cable length is half.

Table 7.6: Lay length for traction case.

Traction	Lay length [mm]	Max. dispalcement [mm]	Variation
360°	100	0.0058	
720°	50	0.0066	12%
1080°	33	0.0084	21%
1440°	25	0.0115	27%
2160°	17	0.0203	43%

Table 7.7: Lay length for bending case.

Bending	Lay length [mm]	Max. force [N]	Variation
360°	50	1500	
720°	25	1200	20%
1080°	17	1000	17%

Table 7.8: Lay length for torsion case.

Torsion	Lay length [mm]	Max. moment [Nmm]	Variation
360°	50	16000	
720°	25	15800	1%
1080°	17	15500	2%

For torsion test it was noted no effect in the cable behavior. The maximum moment obtained decreases scarcely with the increase of the lay angle. Data showed in Table 7.8 was obtained applying a positive moment over the cable, however similar results were obtained applying a negative moment. Notice the fact that lay length is the same as in the previous two cases in order to compare data under same conditions.

Lay angle can be increased or decreased to modify the elasticity of the cable for traction and bending cases. For torsion case, it has no effect in both application directions. To conclude, it should be remarked that the lay angle effect was studied under a linear elastic material model, thus for a viscoplastic behavior results may be different.

Chapter 8

Conclusions

This research has analyzed the nonlinear behavior of two basic electric cable models under three different loading cases: traction, bending and torsion. For both designs, there were tested multiple material models finding that, the one that represented in a more accurate way their behavior, taking into account elasticity, plasticity and viscosity phenomena was the viscoplastic model. Among multiple viscoplastic models studied, the one that resulted to simulate better curves obtained in experimental test was Chaboche law with isotropic hardening. With this model, the ratcheting effect could be simulated with accuracy. In addition, it was found that basic elastic parameters were different for each kind of test, hence an othotropic material model was defined.

In this cable behavior analysis, required material parameters for each model were defined comparing theoretical models with experimental results by means of trial and error tests. In a parallel way, same cable models were tested under the assumption of a linear elastic behavior, in order to compare both results and verify if it was possible to appraise some similarities. For some core sizes of the single cable model, the influence of PVC can be neglected. However, material parameters variation did not affect in the same way than for nonlinear behavior model. On the other hand, for the double cable model, the influence of tin can be neglected for all the cases, and PVC is the one that imposes the cable behavior for bending and torsion cases. Finally, for this cable model, different basic elastic parameters had to be defined for each main axis, as in nonlinear model.

The lay length effect was studied for the linear model having an important influence for traction and bending cases, increasing the flexible behavior with the increase of the lay length. For torsion test this parameter had no effect. In any cable model was not studied the slipping or friction effects as for future work the main goal of this cable modeling is to find an homogeneous section composed of one material that could simulate the whole cable behavior.

8.1 Further work and considerations

Electric cables mechanical design is a growing filed of study that is in the firsts development phases. Because of that, the accomplished work is a good starting point to continue developing this cable models and design, basing on these ones, different cable assemblies. A logical next step for these models is, firstly, find some vicoplastic parameters that let simulate exactly the same curves obtained in experimental test, and secondly, continue developing the nonlinear model for the double cable design, taking into account data obtained from the single cable model and study the effect of lay angle in the nonlinear model, checking if same results as in the linear model are obtained.

In addition, it would be interesting to design an equivalent material model that may replace the heterogeneous cable cross section by a homogeneous, or at least by a quasi-homogeneous one, composed of one or two different materials that behaves as the real cable model. This is the most interesting point, since the final goal of electric cables design is to find some equivalent models that may be used to design all kind of cables with different configurations.

Chapter 9

Timeline

In this chapter are commented some aspects about invested time in each task, remarking the most time consuming tasks and some critical parts. This work can be divided in two general tasks, modeling and analysis. Modeling tasks are focused on the cable models design and parameterization, and concerning analysis tasks it is referred to parametric and material analysis. However, it should be noted that material analysis was a combination of modeling and analysis, since the material model must be designed previously to start with its analysis. For this two main tasks some training were accomplished intended to learning of two SAMCEF softwares, concretely BACON and BOSS-Quattro.

In regard to modeling tasks, they include the three different cable models, highlighting the multiple twisted cable model time cost, since it was required to develop a complex loop with multiple variables. Concerning analysis part, linear parametric analyses and material analysis tasks were carried out in parallel, studying elastic parameters while a nonlinear model was found. Nonlinear parametric analyses started when material analysis provided good enough results to approach to experimental curves. Notice the fact that analysis part was more time consuming since the model must be analyzed for each parameters combination, that supposed, in the most extreme case, an execution time of one week. Figure 9.1, shows the Gantt chart with the main tasks accomplished during the whole work.

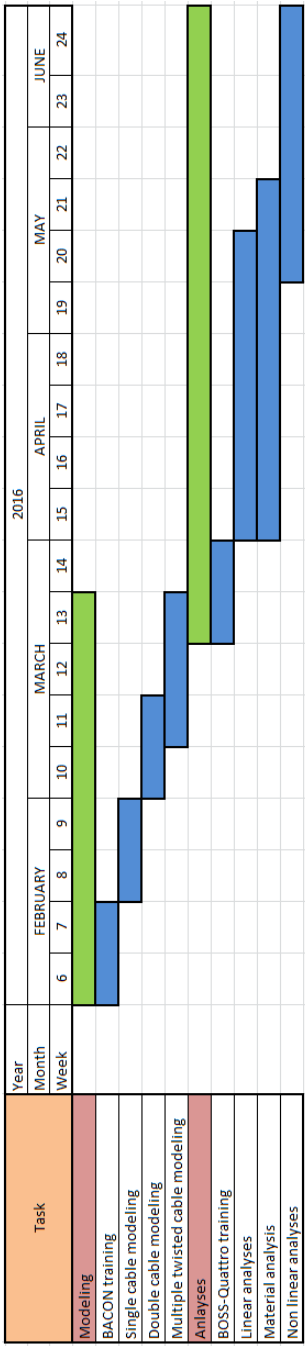

Figure 9.1: Gantt chart.

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Appendix A. Parametric linear analyses results for the single cable model

In this appendix are listed results obtained in linear analyses for the single cable model and some figures regarding Poisson's ratio influence.

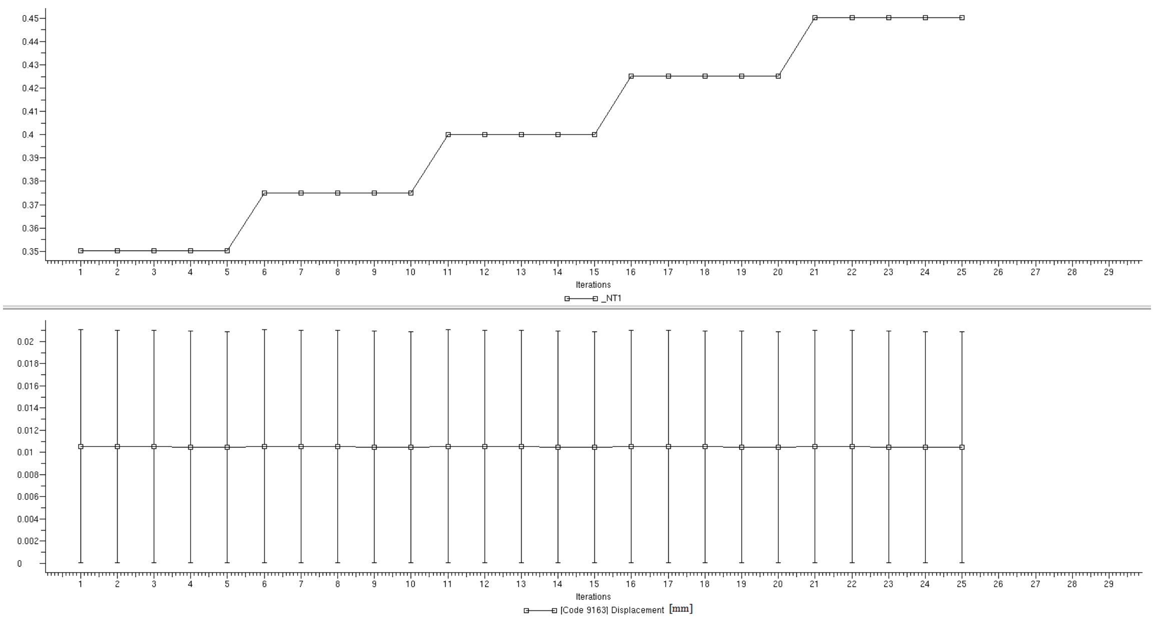

Figure 2: Influence of PVC Poisson's ratio in maximum single cable displacement.

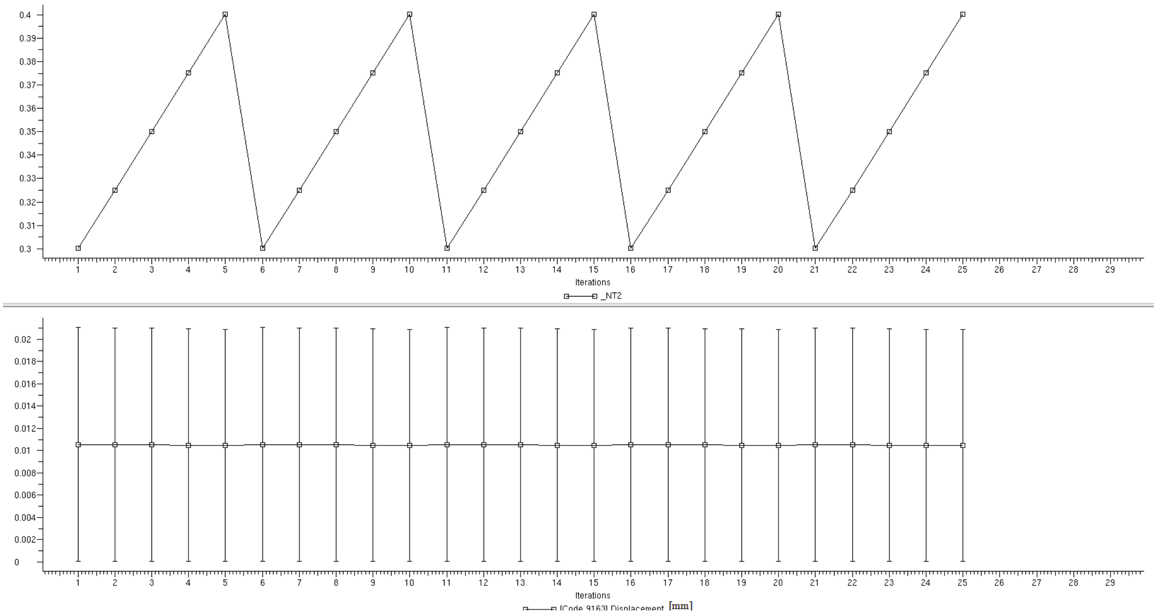

Figure 3: Influence of copper Poisson's ratio in maximum single cable displacement.

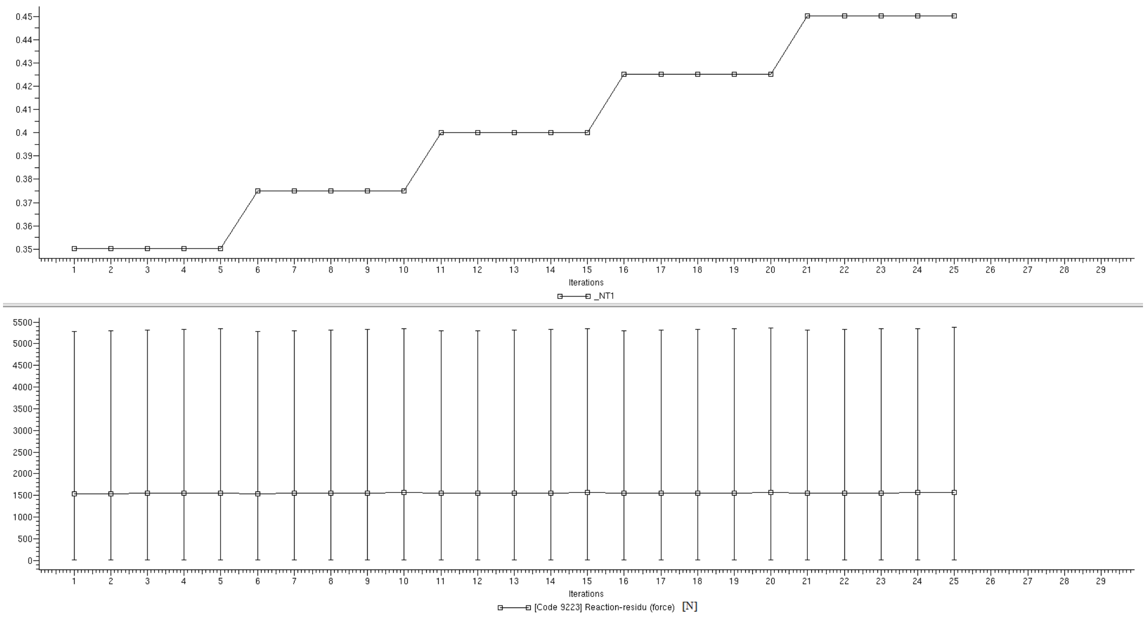

Figure 4: Influence of PVC Poisson's ratio in maximum single cable residual force.

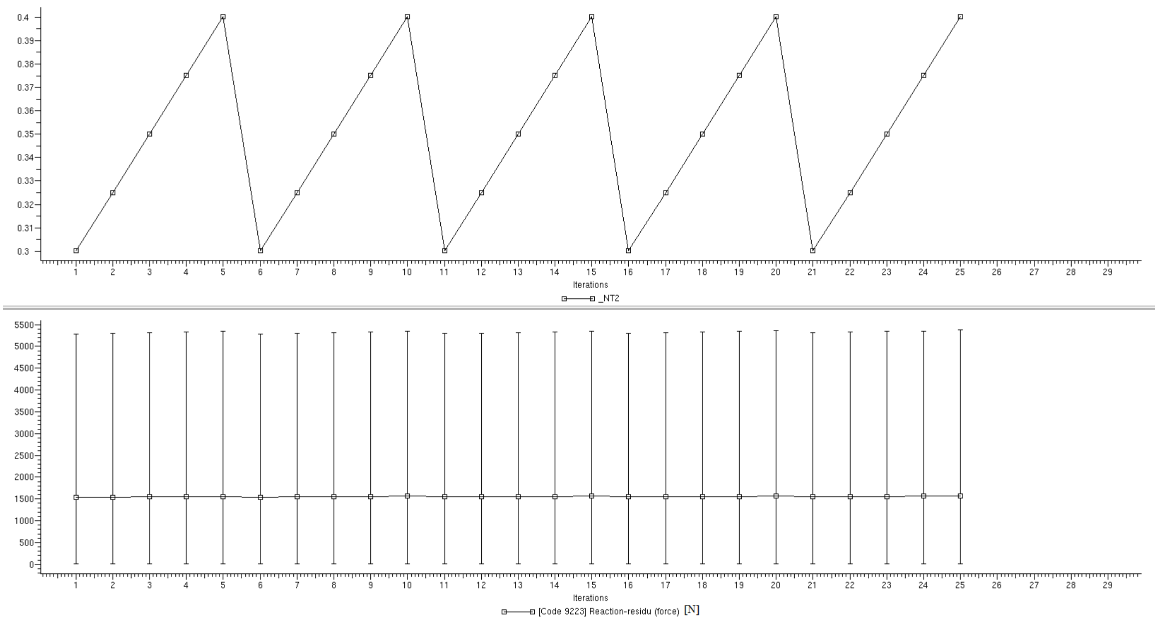

Figure 5: Influence of copper Poisson's ratio in maximum single cable residual force.

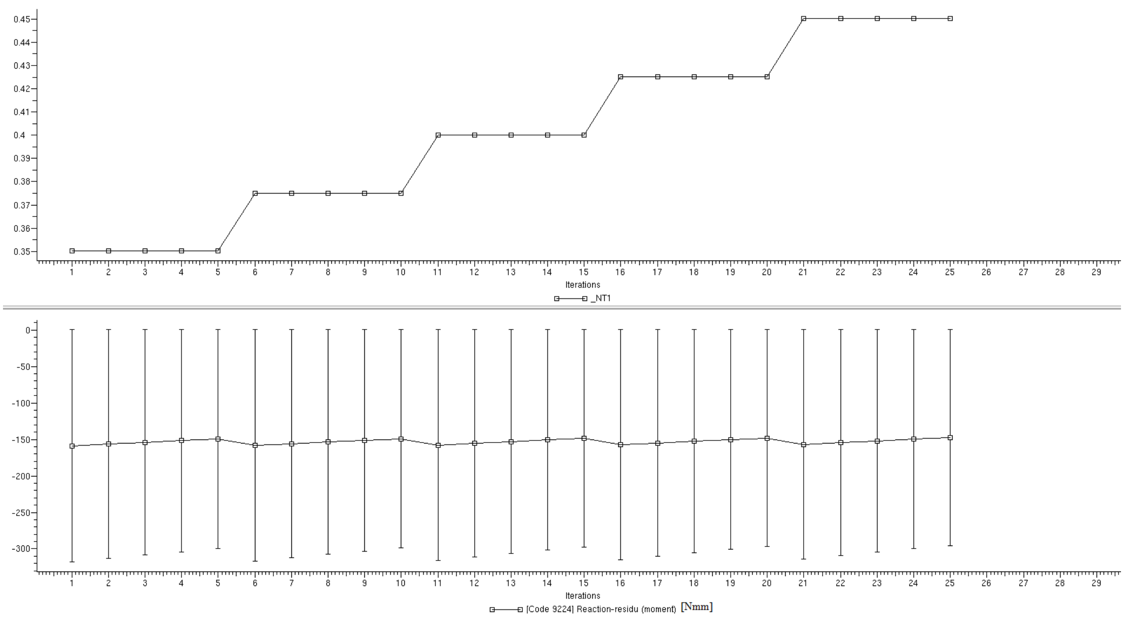

Figure 6: Influence of PVC Poisson's modulus in maximum single cable residual moment.

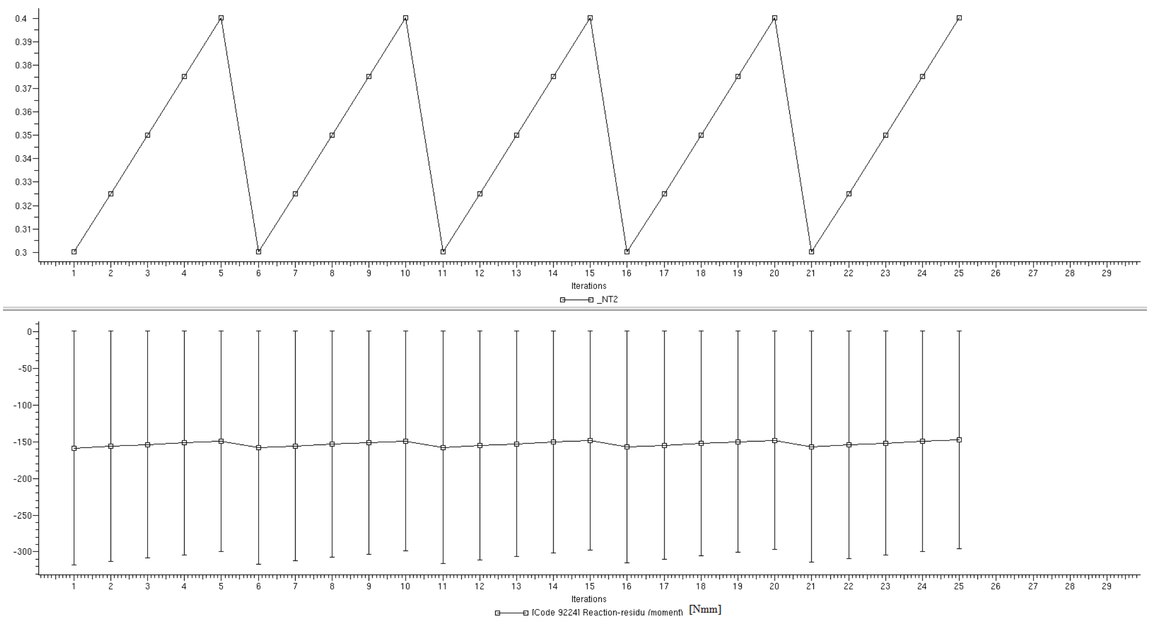

Figure 7: Influence of copper Poisson's ratio in maximum single cable residual moment.

Table 1: Young's modulus variation influence for the single cable traction test.

R1* [mm]	T* [mm]	Y1 [MPa]	Y2 [MPa]	Disp. [mm]	Cu	PVC	Y var.
0.7	0.65	2000	100000	0.0501605			
0.7	0.65	2000	107500	0.0468386	7%		7%
0.7	0.65	2000	115000	0.0439294	6%		7%
0.7	0.65	2000	122500	0.0413604	6%		6%
0.7	0.65	2000	130000	0.0390753	6%		6%
0.7	0.65	2375	100000	0.0496612		1%	16%
0.7	0.65	2375	107500	0.046403	7%	1%	
0.7	0.65	2375	115000	0.043546	6%	1%	
0.7	0.65	2375	122500	0.0410204	6%	1%	
0.7	0.65	2375	130000	0.0387717	5%	1%	
0.7	0.65	2750	100000	0.0491718		1%	14%
0.7	0.65	2750	107500	0.0459754	7%	1%	
0.7	0.65	2750	115000	0.0431692	6%	1%	
0.7	0.65	2750	122500	0.0406858	6%	1%	
0.7	0.65	2750	130000	0.0384727	5%	1%	
0.7	0.65	3125	100000	0.0486919		1%	12%
0.7	0.65	3125	107500	0.0455556	6%	1%	
0.7	0.65	3125	115000	0.0427989	6%	1%	
0.7	0.65	3125	122500	0.0403567	6%	1%	
0.7	0.65	3125	130000	0.0381783	5%	1%	
0.7	0.65	3500	100000	0.0482214		1%	11%
0.7	0.65	3500	107500	0.0451434	6%	1%	
0.7	0.65	3500	115000	0.0424349	6%	1%	
0.7	0.65	3500	122500	0.0400329	6%	1%	
0.7	0.65	3500	130000	0.0378883	5%	1%	

Table 2: Young's modulus variation influence for the single cable bending test.

R1* [mm]	T* [mm]	Y1 [MPa]	Y2 [MPa]	Force [N]	Cu	PVC	Y var.
0.7	0.65	2000	100000	22.8583			
0.7	0.65	2000	107500	24.2277	6%		7%
0.7	0.65	2000	115000	25.597	5%		7%
0.7	0.65	2000	122500	26.9663	5%		6%
0.7	0.65	2000	130000	28.3356	5%		6%
0.7	0.65	2375	100000	23.7207		4%	16%
0.7	0.65	2375	107500	25.0902	5%	3%	
0.7	0.65	2375	115000	26.4595	5%	3%	
0.7	0.65	2375	122500	27.8289	5%	3%	
0.7	0.65	2375	130000	29.1983	5%	3%	
0.7	0.65	2750	100000	24.583		4%	14%
0.7	0.65	2750	107500	25.9525	5%	3%	
0.7	0.65	2750	115000	27.322	5%	3%	
0.7	0.65	2750	122500	28.6914	5%	3%	
0.7	0.65	2750	130000	30.0608	5%	3%	
0.7	0.65	3125	100000	25.4452		3%	12%
0.7	0.65	3125	107500	26.8148	5%	3%	
0.7	0.65	3125	115000	28.1843	5%	3%	
0.7	0.65	3125	122500	29.5537	5%	3%	
0.7	0.65	3125	130000	30.9232	4%	3%	
0.7	0.65	3500	100000	26.3073		3%	11%
0.7	0.65	3500	107500	27.6769	5%	3%	
0.7	0.65	3500	115000	29.0465	5%	3%	
0.7	0.65	3500	122500	30.416	5%	3%	
0.7	0.65	3500	130000	31.7855	4%	3%	

Table 3: Young's modulus variation influence for the single cable torsion test.

R1* [mm]	T* [mm]	Y1 [MPa]	Y2 [MPa]	Moment [Nmm]	Cu	PVC	Y var.
0.7	0.65	1000	100000	-31			
0.7	0.65	1000	107500	-92	66%		7%
0.7	0.65	1000	115000	-153	40%		7%
0.7	0.65	1000	122500	-217	29%		6%
0.7	0.65	1000	130000	-275	21%		6%
0.7	0.65	1500	100000	-49		37%	33%
0.7	0.65	1500	107500	-111	56%	17%	
0.7	0.65	1500	115000	-172	35%	11%	
0.7	0.65	1500	122500	-233	26%	7%	
0.7	0.65	1500	130000	-294	21%	6%	
0.7	0.65	2000	100000	-68		28%	25%
0.7	0.65	2000	107500	-128	47%	13%	
0.7	0.65	2000	115000	-190	33%	9%	
0.7	0.65	2000	122500	-252	25%	8%	
0.7	0.65	2000	130000	-313	19%	6%	
0.7	0.65	2500	100000	-86		21%	20%
0.7	0.65	2500	107500	-148	42%	14%	
0.7	0.65	2500	115000	-218	32%	13%	
0.7	0.65	2500	122500	-270	19%	7%	
0.7	0.65	2500	130000	-331	18%	5%	
0.7	0.65	3000	100000	-104		17%	17%
0.7	0.65	3000	107500	-165	37%	10%	
0.7	0.65	3000	115000	-227	27%	4%	
0.7	0.65	3000	122500	-288	21%	6%	
0.7	0.65	3000	130000	-350	18%	5%	

Appendix B. Parametric linear analyses results for the double cable model

In this appendix are listed results obtained in linear analyses for the double cable model. For the three cases (traction, bending and torsion) tables are divided in some parts due to their extension.

Table 4: Young's modulus variation influence for the double cable traction test.

Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Disp. [mm]	St	PVC	Cu	Variation
100000	2000	40000	0.00715701				
100000	2000	45000	0.0071004	1%			11%
100000	2000	50000	0.00704471	1%			10%
100000	2000	55000	0.0069899	1%			9%
100000	2000	60000	0.00693597	1%			8%
100000	2375	40000	0.00703451		2%		16%
100000	2375	45000	0.00697982	1%	2%		
100000	2375	50000	0.006926	1%	2%		
100000	2375	55000	0.00687302	1%	2%		
100000	2375	60000	0.00682086	1%	2%		
100000	2750	40000	0.00691729		2%		14%
100000	2750	45000	0.0068644	1%	2%		
100000	2750	50000	0.00681234	1%	2%		

Continuation of Table 4							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Disp. [mm]	St	PVC	Cu	Variation
100000	2750	55000	0.00676107	1%	2%		
100000	2750	60000	0.00671059	1%	2%		
100000	3125	40000	0.00680463		2%		12%
100000	3125	45000	0.00675345	1%	2%		
100000	3125	50000	0.00670304	1%	2%		
100000	3125	55000	0.0066534	1%	2%		
100000	3125	60000	0.0066045	1%	2%		
100000	3500	40000	0.00669607		2%		11%
100000	3500	45000	0.0066465	1%	2%		
100000	3500	50000	0.00659767	1%	2%		
100000	3500	55000	0.00654957	1%	2%		
100000	3500	60000	0.00650218	1%	2%		
107500	2000	40000	0.00673174			6%	7%
107500	2000	45000	0.00668162	1%		6%	
107500	2000	50000	0.00663227	1%		6%	
107500	2000	55000	0.00658366	1%		6%	
107500	2000	60000	0.00653577	1%		6%	
107500	2375	40000	0.00662267		2%	6%	
107500	2375	45000	0.00657416	1%	2%	6%	
107500	2375	50000	0.00652638	1%	2%	6%	
107500	2375	55000	0.0064793	1%	2%	6%	
107500	2375	60000	0.00643291	1%	2%	6%	
107500	2750	40000	0.00651824		2%	6%	
107500	2750	45000	0.00647125	1%	2%	6%	
107500	2750	50000	0.00642494	1%	2%	6%	
107500	2750	55000	0.00637931	1%	2%	6%	
107500	2750	60000	0.00633434	1%	2%	6%	
107500	3125	40000	0.00641779		2%	6%	
107500	3125	45000	0.00637223	1%	2%	6%	
107500	3125	50000	0.00632733	1%	2%	6%	
107500	3125	55000	0.00628307	1%	2%	6%	

Continuation of Table 4							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Disp. [mm]	St	PVC	Cu	Variation
107500	3125	60000	0.00623944	1%	1%	6%	
107500	3500	40000	0.00632089		2%	6%	
107500	3500	45000	0.00627669	1%	1%	6%	
107500	3500	50000	0.00623312	1%	1%	6%	
107500	3500	55000	0.00619016	1%	1%	5%	
107500	3500	60000	0.0061478	1%	1%	5%	
115000	2000	40000	0.00635444			6%	7%
115000	2000	45000	0.00630975	1%		6%	
115000	2000	50000	0.0062657	1%		6%	
115000	2000	55000	0.00622228	1%		5%	
115000	2000	60000	0.00617948	1%		5%	
115000	2375	40000	0.00625659		2%	6%	
115000	2375	45000	0.00621327	1%	2%	5%	
115000	2375	50000	0.00617056	1%	2%	5%	
115000	2375	55000	0.00612845	1%	2%	5%	
115000	2375	60000	0.00608692	1%	1%	5%	
115000	2750	40000	0.0061629		1%	5%	
115000	2750	45000	0.00612087	1%	1%	5%	
115000	2750	50000	0.00607942	1%	1%	5%	
115000	2750	55000	0.00603854	1%	1%	5%	
115000	2750	60000	0.00599822	1%	1%	5%	
115000	3125	40000	0.00607273		1%	5%	
115000	3125	45000	0.00603191	1%	1%	5%	
115000	3125	50000	0.00599165	1%	1%	5%	
115000	3125	55000	0.00595194	1%	1%	5%	
115000	3125	60000	0.00591277	1%	1%	5%	
115000	3500	40000	0.00598565		1%	5%	
115000	3500	45000	0.005946	1%	1%	5%	
115000	3500	50000	0.00590688	1%	1%	5%	
115000	3500	55000	0.00586828	1%	1%	5%	
115000	3500	60000	0.00583019	1%	1%	5%	

Continuation of Table 4							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Disp. [mm]	St	PVC	Cu	Variation
122500	2000	40000	0.00601741			5%	6%
122500	2000	45000	0.00597731	1%		5%	
122500	2000	50000	0.00593775	1%		5%	
122500	2000	55000	0.00589874	1%		5%	
122500	2000	60000	0.00586024	1%		5%	
122500	2375	40000	0.00592906		1%	5%	
122500	2375	45000	0.00589013	1%	1%	5%	
122500	2375	50000	0.00585172	1%	1%	5%	
122500	2375	55000	0.00581383	1%	1%	5%	
122500	2375	60000	0.00577643	1%	1%	5%	
122500	2750	40000	0.00584447		1%	5%	
122500	2750	45000	0.00580664	1%	1%	5%	
122500	2750	50000	0.00576932	1%	1%	5%	
122500	2750	55000	0.00573248	1%	1%	5%	
122500	2750	60000	0.00569612	1%	1%	5%	
122500	3125	40000	0.00576302		1%	5%	
122500	3125	45000	0.00572624	1%	1%	5%	
122500	3125	50000	0.00568994	1%	1%	5%	
122500	3125	55000	0.0056541	1%	1%	5%	
122500	3125	60000	0.00561873	1%	1%	5%	
122500	3500	40000	0.00568431		1%	5%	
122500	3500	45000	0.00564853	1%	1%	5%	
122500	3500	50000	0.00561321	1%	1%	5%	
122500	3500	55000	0.00557833	1%	1%	5%	
122500	3500	60000	0.0055439	1%	1%	5%	
130000	2000	40000	0.00571454			5%	6%
130000	2000	45000	0.00567835	1%		5%	
130000	2000	50000	0.00564263	1%		5%	
130000	2000	55000	0.00560737	1%		5%	
130000	2000	60000	0.00557256	1%		5%	
130000	2375	40000	0.00563428		1%	5%	

Continuation of Table 4							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Disp. [mm]	St	PVC	Cu	Variation
130000	2375	45000	0.00559911	1%	1%	5%	
130000	2375	50000	0.00556438	1%	1%	5%	
130000	2375	55000	0.00553009	1%	1%	5%	
130000	2375	60000	0.00549624	1%	1%	5%	
130000	2750	40000	0.00555747		1%	5%	
130000	2750	45000	0.00552325	1%	1%	5%	
130000	2750	50000	0.00548946	1%	1%	5%	
130000	2750	55000	0.00545609	1%	1%	5%	
130000	2750	60000	0.00542313	1%	1%	5%	
130000	3125	40000	0.00548349		1%	5%	
130000	3125	45000	0.00545017	1%	1%	5%	
130000	3125	50000	0.00541727	1%	1%	5%	
130000	3125	55000	0.00538478	1%	1%	5%	
130000	3125	60000	0.00535268	1%	1%	5%	
130000	3500	40000	0.00541197		1%	5%	
130000	3500	45000	0.00537952	1%	1%	5%	
130000	3500	50000	0.00534747	1%	1%	5%	
130000	3500	55000	0.0053158	1%	1%	5%	
130000	3500	60000	0.00528452	1%	1%	5%	
End of Table							

Table 5: Young's modulus variation influence for the double cable bending test.

Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Force [N]	St	PVC	Cu	Variation
1500	300	1000	84.9761				
1500	300	2000	86.1902	1%			50%
1500	300	3000	87.2382	1%			33%
1500	300	4000	88.1631	1%			25%
1500	300	5000	88.9923	1%			20%
1500	600	1000	154.748		45%		50%
1500	600	2000	156.095	1%	45%		
1500	600	3000	157.32	1%	45%		
1500	600	4000	158.449	1%	44%		
1500	600	5000	159.497	1%	44%		
1500	900	1000	223.426		31%		33%
1500	900	2000	224.833	1%	31%		
1500	900	3000	226.139	1%	30%		
1500	900	4000	227.364	1%	30%		
1500	900	5000	228.522	1%	30%		
1500	1200	1000	291.551		23%		25%
1500	1200	2000	292.994	0%	23%		
1500	1200	3000	294.349	0%	23%		
1500	1200	4000	295.632	0%	23%		
1500	1200	5000	296.856	0%	23%		
1500	1500	1000	359.322		19%		20%
1500	1500	2000	360.789	0%	19%		
1500	1500	3000	362.177	0%	19%		
1500	1500	4000	363.501	0%	19%		
1500	1500	5000	364.77	0%	19%		
2375	300	1000	92.0717			8%	37%
2375	300	2000	93.3206	1%		8%	
2375	300	3000	94.3993	1%		8%	

Continuation of Table 5							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Force [N]	St	PVC	Cu	Variation
2375	300	4000	95.352	1%		8%	
2375	300	5000	96.2065	1%		7%	
2375	600	1000	163.076		44%	5%	
2375	600	2000	164.448	1%	43%	5%	
2375	600	3000	165.697	1%	43%	5%	
2375	600	4000	166.848	1%	43%	5%	
2375	600	5000	167.918	1%	43%	5%	
2375	900	1000	232.649		30%	4%	
2375	900	2000	234.076	1%	30%	4%	
2375	900	3000	235.402	1%	30%	4%	
2375	900	4000	236.647	1%	29%	4%	
2375	900	5000	237.824	0%	29%	4%	
2375	1200	1000	301.524		23%	3%	
2375	1200	2000	302.985	0%	23%	3%	
2375	1200	3000	304.357	0%	23%	3%	
2375	1200	4000	305.659	0%	23%	3%	
2375	1200	5000	306.9	0%	23%	3%	
2375	1500	1000	369.96		18%	3%	
2375	1500	2000	371.443	0%	18%	3%	
2375	1500	3000	372.847	0%	18%	3%	
2375	1500	4000	374.188	0%	18%	3%	
2375	1500	5000	375.474	0%	18%	3%	
3250	300	1000	98.5971			7%	27%
3250	300	2000	99.8753	1%		7%	
3250	300	3000	100.98	1%		7%	
3250	300	4000	101.955	1%		6%	
3250	300	5000	102.831	1%		6%	
3250	600	1000	170.682		42%	4%	
3250	600	2000	172.076	1%	42%	4%	
3250	600	3000	173.345	1%	42%	4%	
3250	600	4000	174.515	1%	42%	4%	

Continuation of Table 5							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Force [N]	St	PVC	Cu	Variation
3250	600	5000	175.603	1%	41%	4%	
3250	900	1000	241.022		29%	3%	
3250	900	2000	242.467	1%	29%	3%	
3250	900	3000	243.809	1%	29%	3%	
3250	900	4000	245.07	1%	29%	3%	
3250	900	5000	246.262	0%	29%	3%	
3250	1200	1000	310.523		22%	3%	
3250	1200	2000	311.998	0%	22%	3%	
3250	1200	3000	313.385	0%	22%	3%	
3250	1200	4000	314.701	0%	22%	3%	
3250	1200	5000	315.956	0%	22%	3%	
3250	1500	1000	379.505		18%	3%	
3250	1500	2000	381.002	0%	18%	3%	
3250	1500	3000	382.419	0%	18%	3%	
3250	1500	4000	383.772	0%	18%	2%	
3250	1500	5000	385.071	0%	18%	2%	
4125	300	1000	104.76			6%	21%
4125	300	2000	106.064	1%		6%	
4125	300	3000	107.19	1%		6%	
4125	300	4000	108.185	1%		6%	
4125	300	5000	109.079	1%		6%	
4125	600	1000	177.825		41%	4%	
4125	600	2000	179.239	1%	41%	4%	
4125	600	3000	180.526	1%	41%	4%	
4125	600	4000	181.713	1%	40%	4%	
4125	600	5000	182.817	1%	40%	4%	
4125	900	1000	248.861		29%	3%	
4125	900	2000	250.322	1%	28%	3%	
4125	900	3000	251.679	1%	28%	3%	
4125	900	4000	252.955	1%	28%	3%	
4125	900	5000	254.16	0%	28%	3%	

Continuation of Table 5							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Force [N]	St	PVC	Cu	Variation
4125	1200	1000	318.922		22%	3%	
4125	1200	2000	320.41	0%	22%	3%	
4125	1200	3000	321.81	0%	22%	3%	
4125	1200	4000	323.138	0%	22%	3%	
4125	1200	5000	324.406	0%	22%	3%	
4125	1500	1000	388.386		18%	2%	
4125	1500	2000	389.893	0%	18%	2%	
4125	1500	3000	391.322	0%	18%	2%	
4125	1500	4000	392.686	0%	18%	2%	
4125	1500	5000	393.996	0%	18%	2%	
5000	300	1000	110.67			5%	18%
5000	300	2000	111.995	1%		5%	
5000	300	3000	113.141	1%		5%	
5000	300	4000	114.153	1%		5%	
5000	300	5000	115.062	1%		5%	
5000	600	1000	184.632		40%	4%	
5000	600	2000	186.065	1%	40%	4%	
5000	600	3000	187.368	1%	40%	4%	
5000	600	4000	188.571	1%	39%	4%	
5000	600	5000	189.69	1%	39%	4%	
5000	900	1000	256.317		28%	3%	
5000	900	2000	257.793	1%	28%	3%	
5000	900	3000	259.164	1%	28%	3%	
5000	900	4000	260.453	0%	28%	3%	
5000	900	5000	261.671	0%	28%	3%	
5000	1200	1000	326.895		22%	2%	
5000	1200	2000	328.396	0%	21%	2%	
5000	1200	3000	329.808	0%	21%	2%	
5000	1200	4000	331.147	0%	21%	2%	
5000	1200	5000	332.426	0%	21%	2%	
5000	1500	1000	396.8		18%	2%	

Continuation of Table 5							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Force [N]	St	PVC	Cu	Variation
5000	1500	2000	398.319	0%	18%	2%	
5000	1500	3000	399.758	0%	17%	2%	
5000	1500	4000	401.132	0%	17%	2%	
5000	1500	5000	402.452	0%	17%	2%	
End of Table							

Table 6: Young's modulus variation influence for the double cable torsion test.

Y1 [GPa]	Y2 [GPa]	Y3 [GPa]	Max. Moment [Nmm]	St	PVC	Cu	Variation
100000	2000	40000	-12062.1				
100000	2000	45000	-12072.6	0%			11%
100000	2000	50000	-12082.9	0%			10%
100000	2000	55000	-12093.2	0%			9%
100000	2000	60000	-12103.5	0%			8%
100000	2375	40000	-13360.7		10%		16%
100000	2375	45000	-13371.2	0%	10%		
100000	2375	50000	-13381.7	0%	10%		
100000	2375	55000	-13392.1	0%	10%		
100000	2375	60000	-13402.4	0%	10%		
100000	2750	40000	-14653.3		9%		14%
100000	2750	45000	-14663.9	0%	9%		
100000	2750	50000	-14674.4	0%	9%		
100000	2750	55000	-14684.8	0%	9%		
100000	2750	60000	-14695.2	0%	9%		
100000	3125	40000	-15941.1		8%		12%
100000	3125	45000	-15951.7	0%	8%		
100000	3125	50000	-15962.3	0%	8%		
100000	3125	55000	-15972.8	0%	8%		
100000	3125	60000	-15983.2	0%	8%		
100000	3500	40000	-17224.8		7%		11%
100000	3500	45000	-17235.5	0%	7%		
100000	3500	50000	-17246.1	0%	7%		
100000	3500	55000	-17256.7	0%	7%		
100000	3500	60000	-17267.2	0%	7%		
107500	2000	40000	-12439.1			3%	7%
107500	2000	45000	-12449.5	0%		3%	
107500	2000	50000	-12459.9	0%		3%	
107500	2000	55000	-12470.2	0%		3%	

Continuation of Table 6							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Max. Moment [Nmm]	St	PVC	Cu	Variation
107500	2000	60000	-12480.5	0%		3%	
107500	2375	40000	-13740.5		9%	3%	
107500	2375	45000	-13751.1	0%	9%	3%	
107500	2375	50000	-13761.5	0%	9%	3%	
107500	2375	55000	-13771.9	0%	9%	3%	
107500	2375	60000	-13782.2	0%	9%	3%	
107500	2750	40000	-15035.7		9%	3%	
107500	2750	45000	-15046.3	0%	9%	3%	
107500	2750	50000	-15056.8	0%	9%	3%	
107500	2750	55000	-15067.3	0%	9%	3%	
107500	2750	60000	-15077.7	0%	9%	3%	
107500	3125	40000	-16326		8%	2%	
107500	3125	45000	-16336.6	0%	8%	2%	
107500	3125	50000	-16347.2	0%	8%	2%	
107500	3125	55000	-16357.7	0%	8%	2%	
107500	3125	60000	-16368.2	0%	8%	2%	
107500	3500	40000	-17612.1		7%	2%	
107500	3500	45000	-17622.8	0%	7%	2%	
107500	3500	50000	-17633.4	0%	7%	2%	
107500	3500	55000	-17644	0%	7%	2%	
107500	3500	60000	-17654.5	0%	7%	2%	
115000	2000	40000	-12814.8			3%	7%
115000	2000	45000	-12825.3	0%		3%	
115000	2000	50000	-12835.7	0%		3%	
115000	2000	55000	-12846	0%		3%	
115000	2000	60000	-12856.3	0%		3%	
115000	2375	40000	-14119.1		9%	3%	
115000	2375	45000	-14129.7	0%	9%	3%	
115000	2375	50000	-14140.1	0%	9%	3%	
115000	2375	55000	-14150.5	0%	9%	3%	
115000	2375	60000	-14160.9	0%	9%	3%	

Continuation of Table 6							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Max. Moment [Nmm]	St	PVC	Cu	Variation
115000	2750	40000	-15416.9		8%	2%	
115000	2750	45000	-15427.5	0%	8%	2%	
115000	2750	50000	-15438	0%	8%	2%	
115000	2750	55000	-15448.5	0%	8%	2%	
115000	2750	60000	-15458.9	0%	8%	2%	
115000	3125	40000	-16709.5		8%	2%	
115000	3125	45000	-16720.1	0%	8%	2%	
115000	3125	50000	-16730.7	0%	8%	2%	
115000	3125	55000	-16741.3	0%	8%	2%	
115000	3125	60000	-16751.7	0%	8%	2%	
115000	3500	40000	-17997.8		7%	2%	
115000	3500	45000	-18008.6	0%	7%	2%	
115000	3500	50000	-18019.2	0%	7%	2%	
115000	3500	55000	-18029.8	0%	7%	2%	
115000	3500	60000	-18040.3	0%	7%	2%	
122500	2000	40000	-13189.5			3%	6%
122500	2000	45000	-13200	0%		3%	
122500	2000	50000	-13210.4	0%		3%	
122500	2000	55000	-13220.7	0%		3%	
122500	2000	60000	-13231	0%		3%	
122500	2375	40000	-14496.6		9%	3%	
122500	2375	45000	-14507.2	0%	9%	3%	
122500	2375	50000	-14517.7	0%	9%	3%	
122500	2375	55000	-14528.1	0%	9%	3%	
122500	2375	60000	-14538.4	0%	9%	3%	
122500	2750	40000	-15796.9		8%	2%	
122500	2750	45000	-15807.5	0%	8%	2%	
122500	2750	50000	-15818	0%	8%	2%	
122500	2750	55000	-15828.5	0%	8%	2%	
122500	2750	60000	-15838.9	0%	8%	2%	
122500	3125	40000	-17091.8		8%	2%	

Continuation of Table 6							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Max. Moment [Nmm]	St	PVC	Cu	Variation
122500	3125	45000	-17102.4	0%	8%	2%	
122500	3125	50000	-17113	0%	8%	2%	
122500	3125	55000	-17123.6	0%	8%	2%	
122500	3125	60000	-17134.1	0%	8%	2%	
122500	3500	40000	-18382.3		7%	2%	
122500	3500	45000	-18393	0%	7%	2%	
122500	3500	50000	-18403.7	0%	7%	2%	
122500	3500	55000	-18414.3	0%	7%	2%	
122500	3500	60000	-18424.8	0%	7%	2%	
130000	2000	40000	-13563.2			3%	6%
130000	2000	45000	-13573.7	0%		3%	
130000	2000	50000	-13584.1	0%		3%	
130000	2000	55000	-13594.5	0%		3%	
130000	2000	60000	-13604.8	0%		3%	
130000	2375	40000	-14873.1		9%	3%	
130000	2375	45000	-14883.7	0%	9%	3%	
130000	2375	50000	-14894.2	0%	9%	3%	
130000	2375	55000	-14904.6	0%	9%	3%	
130000	2375	60000	-14915	0%	9%	3%	
130000	2750	40000	-16175.8		8%	2%	
130000	2750	45000	-16186.4	0%	8%	2%	
130000	2750	50000	-16197	0%	8%	2%	
130000	2750	55000	-16207.5	0%	8%	2%	
130000	2750	60000	-16217.9	0%	8%	2%	
130000	3125	40000	-17472.9		7%	2%	
130000	3125	45000	-17483.6	0%	7%	2%	
130000	3125	50000	-17494.2	0%	7%	2%	
130000	3125	55000	-17504.8	0%	7%	2%	
130000	3125	60000	-17515.3	0%	7%	2%	
130000	3500	40000	-18765.6		7%	2%	
130000	3500	45000	-18776.3	0%	7%	2%	

Continuation of Table 6							
Y1 [MPa]	Y2 [MPa]	Y3 [MPa]	Max. Moment [Nmm]	St	PVC	Cu	Variation
130000	3500	50000	-18787	0%	7%	2%	
130000	3500	55000	-18797.6	0%	7%	2%	
130000	3500	60000	-18808.1	0%	7%	2%	
End of Table							

Appendix C. Parametric nonlinear analyses results for the single cable model

In this appendix are listed results obtained in non linear analyses for the single cable model regarding Young's modulus influence in traction and bending.

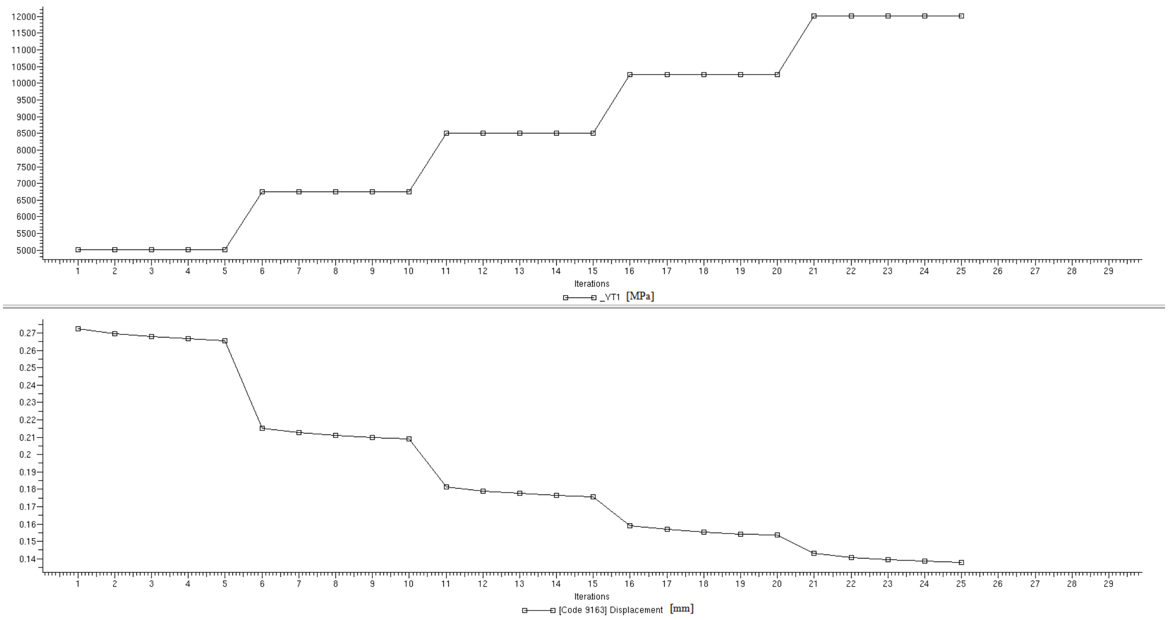

Figure 8: Influence of PVC Young's modulus in maximum single cable displacement.

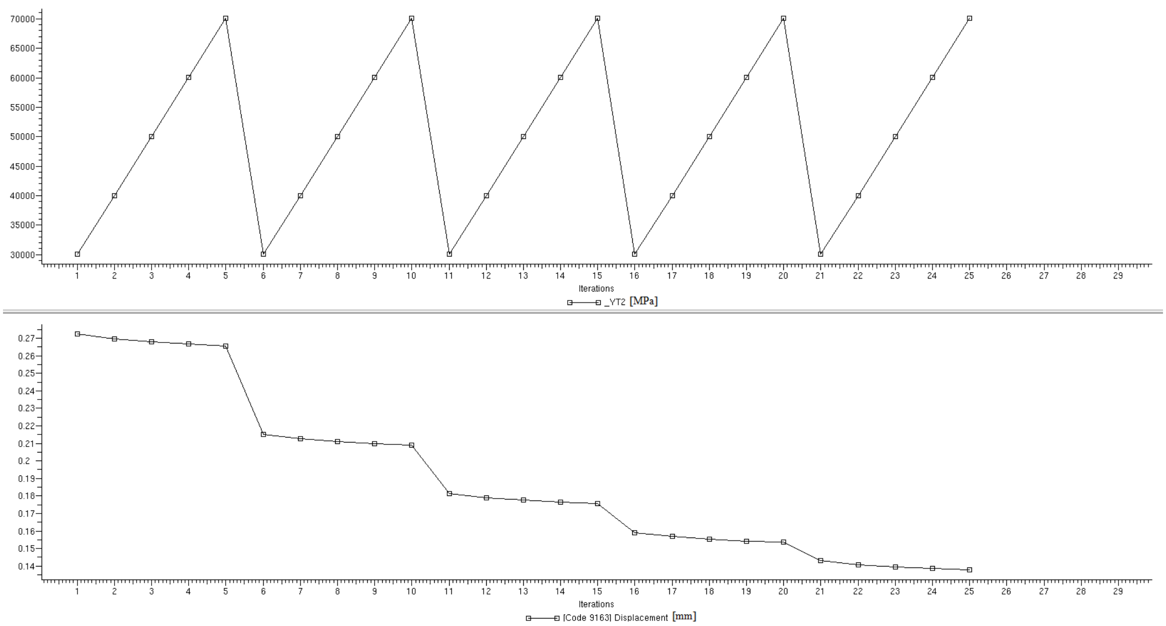

Figure 9: Influence of copper Young's modulus in maximum single cable displacement.

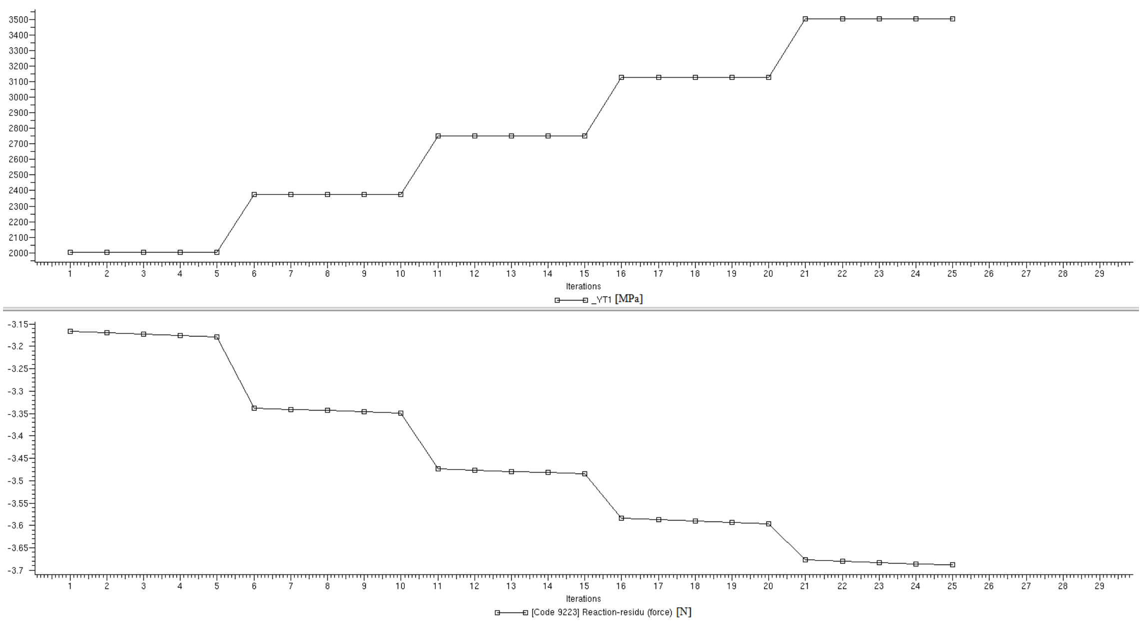

Figure 10: Influence of PVC Young's modulus in maximum single cable residual force.

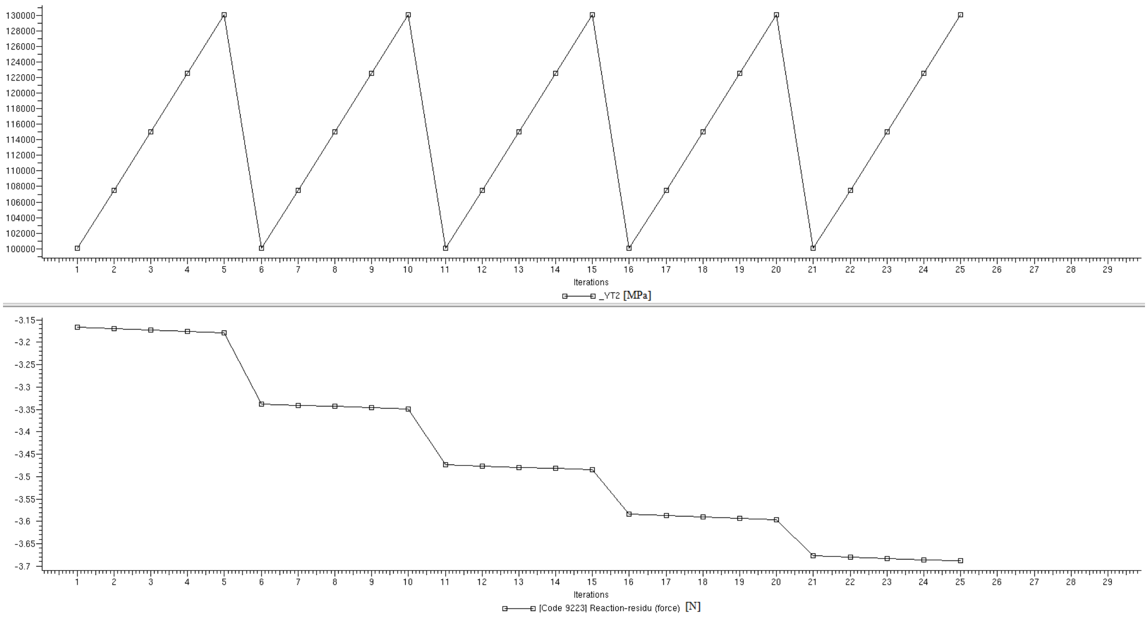

Figure 11: Influence of copper Young's modulus in maximum single cable residual force.