



NUMERICAL AND EXPERIMENTAL ANALYSIS OF RADIAL COMPRESSION IN UMBILICAL CABLES USING THE FINITE ELEMENT METHOD

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Abstract: This study evaluates the performance of a two-dimensional numerical radial compression model applied to umbilical cables, comparing its results with experimental data. These cables are multifunctional structures essential to the oil and gas industry, responsible for interconnecting platforms and subsea systems, enabling control, monitoring, and fluid injection. Their internal configuration may include hydraulic hoses, electrical cables, optical fibers, steel tubes, filler elements, and armor layers. Installation is carried out by Pipe Laying Support Vessels (PLSVs), operating in vertical or horizontal lay modes. During installation, tensioners apply radial compression and axial tension, and, secondarily, cause radial crushing of the armor layers onto the core due to their helical arrangement. The numerical model was developed using the Finite Element Method in HyperWorks, with OptiStruct as the solver, adopting two-dimensional elements under the plane stress assumption. Loading was divided into three stages, simulating internal pressurization, shoe compression, and crushing pressure from axial tension. Layer interactions were assessed with Helica software. The results showed good agreement for residual and compressed diameters, with absolute errors <1.5 mm and relative errors <1% in most measurements. However, larger discrepancies were observed in residual ovalization, particularly for low-magnitude values, where the relative error was amplified. Thus, the use of absolute error is recommended as the criterion for evaluating sensitive quantities, such as ovalization and deformation.

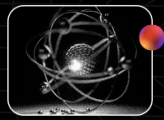
Keywords: *Umbilical cables; Radial compression; Finite Element Method; Numerical modeling and Experimental validation.*

1. Introduction

The objective is to analyze the performance of the numerical radial compression model applied to the umbilical, comparing its results with experimentally obtained data.

Umbilical cables are multifunctional structures of high complexity and versatility, widely employed in the oil and gas industry. They play a critical role in the interconnection between the production platform and the set of subsea valves installed at the wellhead. Their primary function is to enable the control and monitoring of subsea operations, as well as to allow the injection of chemical fluids aimed at optimizing flow. The configuration of the components within an

umbilical cable varies according to its specific function and intended application, and may include hydraulic and injection hoses, electrical cables, optical fibers, and steel tubes. As described by Marzo (2010)[1], the arrangement of these internal elements is designed to ensure flexibility, reduce stresses, and provide mechanical strength. The components can exhibit two main motion patterns: local rotation, which occurs when only a single internal element undergoes rotational movement, and global rotation, characterized by the simultaneous rotational movement of all internal components around a common reference axis, generally coinciding with the umbilical's center.



1.1 Umbilical Components

The hydraulic hose consists of a central tube responsible for maintaining hydraulic fluid containment, an aramid layer designed to withstand internal pressure, and an outer sheath whose function is to protect and bundle the internal elements. According to Alves (2022)[2], the electrical cables used in umbilicals can be classified into two types: signal cables and power cables. Depending on the application, these cables may include armor layers to enhance mechanical strength.

The rods are polymeric filaments used to fill voids in the umbilical's cross section, thereby reducing the likelihood of slippage and crushing between internal components. The armor is composed of wires arranged helically in opposite directions, whose primary function is to protect the umbilical core against axial tensile loads and external pressure, in addition to providing torsional stiffness (SUÑÉ, 2008,[3]). Finally, the inner sheath protects the umbilical core during the manufacturing process, while the outer sheath serves to protect the armor during installation and operation, as illustrated in Figure 1

1.2 Umbilical Installation

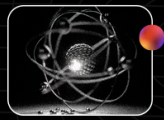
Umbilicals are installed using vessels known as Pipe Laying Support Vessels (PLSVs), which can operate in either vertical or horizontal lay configurations. In vertical lay operations, the tensioners are arranged in an upright position, pulling the umbilical in this direction and guiding

it toward the sea through a sheave located at the top of the tower. In horizontal lay operations, the tensioners are positioned horizontally, directing the umbilical toward a sheave located at the vessel's stern.

According to Mendonça (2016)[4], the tensioners function to control the umbilical's descent speed and to support the weight of the installed section, relying on the friction generated by the contact between the track shoes and the umbilical's outer sheath. The umbilical cross section passing through the tensioners is primarily subjected to two types of loading: radial compression, resulting from contact with the track shoes, and axial tension, caused by the weight of the already deployed line. In addition to these loads, Mendonça (2016)[4] also reports a secondary effect of radial crushing of the armor layers onto the umbilical core, induced by axial tension due to the helical arrangement of these layers.

2. Methodology

Numerical modeling, particularly through the Finite Element Method (FEM), has assumed an increasingly significant role in engineering. According to Alves Filho (2000)[5], FEM, based on the discretization of the continuum, offers broad applicability regardless of geometry or loading conditions, providing approximate solutions that must meet the accuracy criteria established for the problem under analysis. In this context, Guttner (2015)[6] validated a two-dimensional numerical model for the analysis of

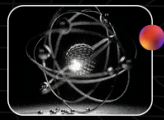


crushing in umbilical cables, based on the methodology developed by Pesce et al. (2015)[7]. This approach incorporates three-dimensional effects into a two-dimensional model by considering the radial loads induced by helical elements as a result of the choking effect. According to the author, this integration enables the consideration of conditions not accounted for in purely two-dimensional analyses, thereby making the numerical representation of the problem more faithful to the actual behavior.

For the development of the two-dimensional numerical model, the HyperWorks software was used for pre- and post-processing (Altair, 2021.[8]), while OptiStruct was employed as the solver due to its efficiency in structural, dynamic, and optimization analyses, including nonlinear and high-complexity problems. The model was constructed under the plane stress assumption, using first-order two-dimensional elements: quadrilateral CQPSTN elements, with four nodes, and triangular CTPSTN elements, with three nodes. Inspired by the experimental radial compression test of the umbilical, the loading was applied sequentially to accurately reproduce the observed conditions. Initially, the umbilical hoses were internally pressurized to 3,000 psi. Subsequently, a compressive force of 39.20 tf/m was applied through two equally spaced shoes, while a third shoe had all its degrees of freedom fully constrained, ensuring that the reaction force matched the experimental load of 39.20 tf/m.

After applying the internal pressure and the shoe compression, the umbilical sample was longitudinally tensioned to 113.74 tf, with a loading rate of 30.59 tf/min. Using the proprietary software Helica, developed by DNV-GL, the interaction between the layers in the umbilical cross section was analyzed. The tensile load was converted into 4.21 MPa of crushing pressure between the intermediate sheath and the internal elements, following a loading rate of 1.30 MPa/min.

The loading procedure was divided into three load cases. In the first, covering 0 to 120 seconds, the internal hose pressure was gradually applied until reaching 3,000 psi, accompanied by an initial compression force of 8.62 tf (22% of the total experimental load) to stabilize the model. The second load case, lasting from 120 to 1120 seconds, began by maintaining the internal pressure at its maximum value and progressively increasing the compression force to 100% of the total load within the first 360 seconds. Between 360 and 600 seconds, the crushing pressure was applied, and together with the other loads, held at maximum for the following 520 seconds to stabilize the model and minimize potential hysteresis effects. The third load case, from 1120 to 1800 seconds, involved the gradual release of loads: initially, the shoe compression force was reduced to 22% of the total load, followed by the removal of the crushing pressure. Finally, the internal hose pressure and the remaining compression were gradually released.



2.1 Processing

The solver is responsible for generating the local stiffness matrices of each element, taking into account its geometry and material properties, and subsequently assembling the global stiffness matrix $[K]$. With this matrix established, and knowing the applied loads represented by the force vector $\{F\}$, it is possible to determine the nodal displacements, described by the vector $\{U\}$, by solving Equation (1). From these nodal displacements, the corresponding strain and stress vectors are then calculated.

$$\{F\} = [K]\{U\} \quad (1)$$

2.2 Post- Processing

In a numerical radial compression model, it is essential that the macroscopic behavior of the umbilical be represented accurately. At the same time, the internal elements, which act as sacrificial components under this type of loading, must be modeled precisely to ensure the reliability of the simulation. To complete the correlation study, it is necessary to calculate the absolute and relative errors between the numerical and experimental results, using Equations (2) and (3), respectively. These calculations make it possible to assess the degree of agreement between the datasets and to determine the representativeness of the numerical results in relation to the experimentally obtained values.

$$E_a = |x_{medido} - x_{verdadeiro}| \quad (2)$$

$$E_r = \frac{|x_{medido} - x_{verdadeiro}|}{x_{verdadeiro}} \quad (3)$$

3. Results

The horizontal and vertical displacements, in millimeters, at the end of the first load case, when the internal pressure in the hoses reaches its maximum value and the compression applied by the shoe corresponds to 22% of the total load, are presented in Figure 2.

Figure 3 illustrates the maximum horizontal and vertical displacements, in millimeters, at the end of the second load case, when all three loadings, internal hose pressure, shoe compression, and crushing pressure on the inner sheath resulting from the axial tension of the sample, reach their maximum values.

Figure 4 presents the residual horizontal and vertical displacements, in millimeters, after the complete removal of all applied loads.

Small asymmetries can be observed in the distributions, even when considering the symmetry of both the umbilical cross section and the applied loading. These asymmetries can be attributed to the high sensitivity of the model, stemming from its pronounced nonlinearity. Factors contributing to these nonlinearities include the use of frictional contact between elements and layers, as well as the adoption of materials with nonlinear stress-strain curves. This asymmetric behavior was also verified in the experimental tests conducted by MFX do Brasil



in 2015[9]. As illustrated in Figure 5, it is possible to identify the compression-induced deformation and the pronounced asymmetry of the cross section, which is more significant than that observed in the numerical results. This difference is explained by the fact that, in the experimental test, the compression reached 80 tf/m, whereas in the numerical model it was limited to 39.20 tf/m.

The vertical and horizontal diameters under compression (DVc and DHc), as well as the residual diameters (DVr and DHr) of the umbilical's outer sheath obtained through the numerical simulations, are presented in

Table 1, alongside the corresponding experimental values. The macroscopic behavior of the cross section is characterized by the dimensions under compression and by the residual deformation of the outer sheath. The results indicate that the numerical model adequately represents the diameters, with a relative error of less than 1.00% in all four measurements. However, in the case of ovalization, although the absolute error remains below 1.50%, the relative error exceeds 50.00%. Despite the high relative error values for ovalization, the low absolute error suggests that the numerical model provides a good overall approximation in relation to the experimental results.

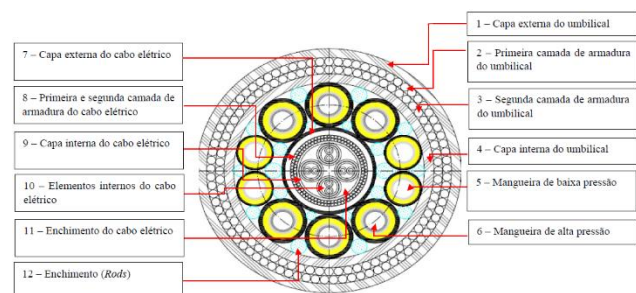
4. Conclusion

The results indicate that the numerical model showed good agreement for the residual and compressed diameters of the umbilical's outer sheath, with absolute errors below 1.5 mm and relative errors under 1% in most measurements. However, significant discrepancies were observed in the residual ovalization values, particularly in low-magnitude quantities, such as the residual ovalizations of the high- and low-pressure hoses. In these cases, the relative errors were amplified, although the absolute errors remained small, highlighting the need for improvements to the model. Accordingly, this study proposes the adoption of absolute error as a more reliable criterion for assessing the correlation of sensitive quantities, such as ovalization and deformation.

Measure ment	Numerical	Experimental	Absolute error	Relative error
DVc	161.61 mm	162.53 mm	0.92 mm	0.57%
DHc	168.49 mm	167.00 mm	1.49 mm	0.89%
OVc	4.17%	2.71%	1.46%	53.87%
DVr	165.45 mm	165.15 mm	0.30 mm	0.18%
DHr	165.66 mm	164.75 mm	0.91 mm	0.55%
OVr	0.13%	0.24%	0.11%	45.83%

Attachments

Figure 1. Umbilical cables.



Source: MFX do Brasil (2018)[10]



Figure 2. Horizontal and vertical displacement, first load case, in millimeters.

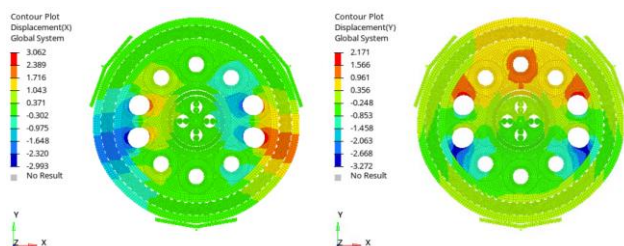


Figure 3. Horizontal and vertical displacement, second load case, in millimeters.

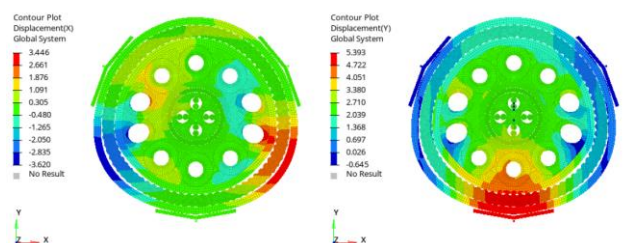


Figure 4. Horizontal and vertical displacement, third load case, in millimeters.

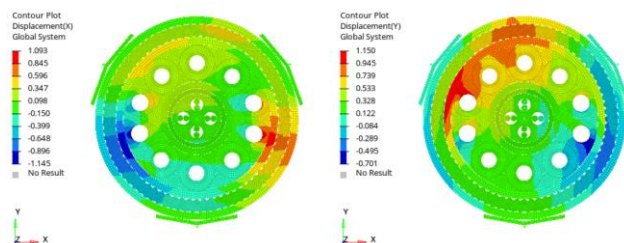


Figure 5. Umbilical cross section compressed in the experimental crushing test at 80 tf/m per shoe.



Source: MFX do Brasil (2015)[9]

Table 1. Comparison between numerical and experimental values of diameters and ovalizations for the umbilical outer sheath, with associated absolute and relative errors.

Measurement	Numerical	Experimental	Absolute error	Relative error
DVc	161.61 mm	162.53 mm	0.92 mm	0.57%
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