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UMBILICAL CABLES INSTALLATION – A CRUSH MODEL

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Abstract. *Umbilical cables are fundamental structures to petroleum industry. They are formed by different layers, each one designed for a specific purpose, functional or structural. One of the most important structural component of umbilical cables are the high collapse resistance (HCR) hoses, which are projected to aid to resist external radial loads, like hydrostatic pressure and the crush load during the umbilical cable installation. In this work special attention is taken to prevent failure by the crush load during the umbilical cable installation. Both analytical and numerical models are presented to estimate the umbilical cross section radial stiffness to resist to the forces applied by pads, as well as, the compression generated on the HCR hoses by the armour wires submitted to axial loading.*

Keywords: *HCR hoses , umbilical installation, crush load*

1. INTRODUCTION

In this paper a finite element (FE) model is proposed to describe the umbilical cables cross section mechanical behavior during installation, with especial attention to HCR hoses. The compression load provided by the caterpillar pads are taken into account to estimation of compression of the inner parts of the umbilical as well as the compression caused by the armour wires when they are submitted to axial loads. To improve the understanding of the variables that are important for the crush model, a simplified analytical model is also proposed and used to compare with FE results. A commercial Finite Element package, ANSYS, is used to model a specific structure; nevertheless the contact definition and some simplification hypotheses can be extended to adapt to other umbilical configurations. Analytical models are easier to be formulated, with fewer approximations, for flexible pipes than for umbilicals because the pipes are formed by a set of concentric layers. On the other hand, umbilicals may have complex and usually non symmetric structures. Technical papers modeling umbilical installation process, specifically for umbilical with thermoplastic high collapse resistance HCR hoses are uncommon, but see Santos *et al*. (2015) for a good technical paper in this area.

As the HCR hose is constructed from a helical conformed plate and has a complex profile, Tang *et al.* (2012) used an equivalence method to simplify the geometry and then apply the finite element method. Sousa *et al*. (2001) proposed a numerical study to analyze the flexible pipes stress distribution during the installation using the analogy of orthotropic shell to get more a compact model. Martins *et al.* (2003) used the theory of elasticity to get a mathematical formulation of the crush load for flexible pipes. A detailed finite element formulation was proposed by Saevik *et al*. (2005) to analyze umbilicals subjected to crush load. The model was used to develop the software Uflex and has a friendly interface and it has been used for umbilical steel tubes modeling. Batrony *et al.* (2012) used the Uflex2D and related a good agreement between the experimental and numerical results for umbilicals with different structures.

In this work it is used a plane stress hypothesis to implement the 2D FE umbilical HCR hose cross section model. In fact because its helical construction, which each “ring” is loosely attached axially with its neighbors “rings”, so it is not expected that a HCR hose develops a plane strain condition, unless if it is sufficiently stretched in such a way that each “ring” get in touch with its neighbors “rings”. As HCR hoses is used to provide radial stiffness and the armour wires are used to provide the umbilical axial stiffness, it is reasonable suppose that the HCR hoses experiences very low axial loads, inducing a cross section constrain state closer to plane stress condition.

For this present study, the main dimensions and the shape of the HCR hose are presented in Fig.1 and Table 1. The material properties used along the paper are shown at Table 2.

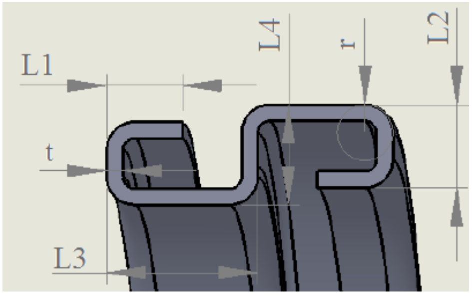


Figure 1. HCR hose cross section principal dimensions.

Table 1. HCR hose cross section dimensions

Dimensions	(mm)
L_1	1.1
L_2	0.8
L_3	2.2
L_4	1.6
t	0.3
r	0.1

Table 2. Hose's mechanical properties

Mechanical Property	Polymer	Carcass
Young's Modulus (GPa)	$E_p = 1.2$	$E_c = 193$
Poisson's Ratio	$\upsilon_p = 0.48$	$\upsilon_c = 0.3$

At next section an analytical model is presented not only to grow up the understanding of the load sharing between the several cross section umbilical components submitted to pad loads, but also to estimate an equivalent Young's Modulus and ring thickness for simplifying the HCR hoses F.E. geometric model.

2. ANALYTICAL MODEL

A proposed analytical model, based in mechanics of solids, which takes into account the pad radial compression load is presented next.

2.1 PAD RADIAL COMPRESSION LOAD

The analytical model is based in mechanics of solids. A hose section is treated as a concentric ring and the arrangement of the total hoses are carried out as springs in parallel configuration.

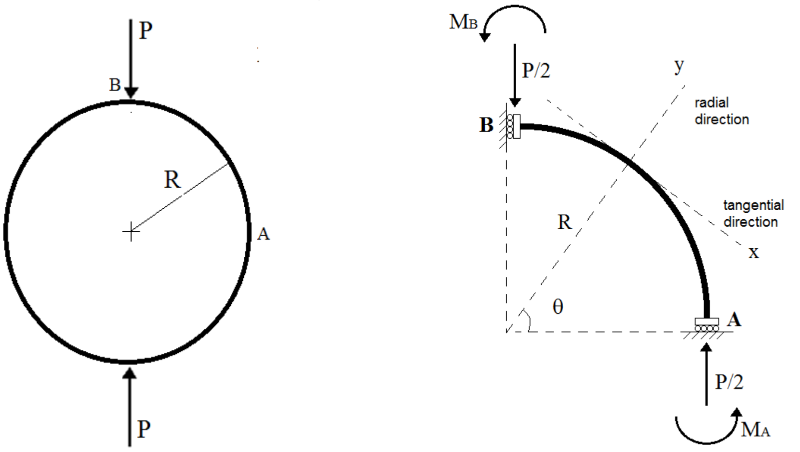


Figure 2. Two points compression ring model: (a) the entire ring and (b) a quarter ring using symmetries.

Three hypothesis are proposed to extend the two points compression ring model, shown at Fig.2, for a ring compressed radially to apply it to carcass: (i) the radial displacement applied by the pads is equal to the hose ovalization; (ii) the shoes are rigid; (iii) the contacts between the concentric rings is considered without separation.

For a radially compressed ring, as Fig. 2, using the Castigliano's Theorem and the boundary conditions imposed by symmetry, assuming that the energy derivative by the moment at the point *A* is zero and the energy derivative by P/2 force at the *B* is equal to the radial displacement at *B*, w(π/2), Timoshenko and Gere (2009), it is possible to estimate the radial displacement in each point as

$$w = \frac{PR^3}{4EI}\left(\cos(\theta) + \theta\sin(\theta) - \frac{4}{\pi}\right) \tag{1}$$

where *P* is the applied force, *R* is the medium radii, *E* is the Young's Modulus and *I* is the second moment of inertia of area. Another useful relation, which can be obtained directly by simple manipulation of Eq. 1, is the total vertical diameter decrease d_v

$$d_v = -\frac{PR^3}{EI}\left(\frac{\pi}{4} - \frac{2}{\pi}\right) \tag{2}$$

With this equation, the compressed ring can be expressed as a spring, which follows the Hook's Law, with stiffness *k*, Timoshenko (1941)

$$k = \frac{EI}{R^3}\frac{1}{\left(\frac{\pi}{4} - \frac{2}{\pi}\right)} \tag{3}$$

Once the radial displacement *w* was obtained, considering a thin ring, the normal stress generated by the curvature variation can be expressed, Timoshenko and Gere (2009)

$$\sigma_x = E\varepsilon_x = -E\left|\frac{1}{R^2}\left(w + \frac{d^2w}{d\theta^2}\right)\right|y \tag{4}$$

Where σ_x and ε_x are, respectively, the normal stress and strain in tangential direction. To represent the real structure, it is necessary to quantify the load share between the HCR hose and the other layers. For a high collapse resistance HCR thermoplastic hose there are four different layers of materials: the carcass - to resist for the external radial load; a nylon layer extruded onto the external surface of the carcass - which works as a barrier to avoid fluids leakage; the aramid layers - to resist internal pressure and a final extruded layer of polyethylene - to protect against abrasion damage. For simplification, the aramid layers effect will be neglected, once its function is to resist internal pressure, and all the polymer layers will be modeled with polyethylene properties. Although an umbilical is installed with pressurized hoses to avoid excessive deformation, ISO 13628-5 (2009), to simplify the model it will be considered that the hoses are depressurized withdrawing the influence of aramid layer. Hence, the complete hose can be understood for instance as two spring in parallel (carcass + polymer).

The carcass profile looks like an "S" in horizontal position, as shown at Fig. 1. To guarantee an efficient transformation of the carcass in a homogeneous ring, the distance from centroid position to the inner radius of the carcass and the carcass bend stiffness (in relation to the to the set centroid, not in relation to the carcass centroid) must keep the same after transformation. So, a new (equivalent) Young's Modulus and the ring thickness, let's say E_c^* and t^*, should be calculated. As a first approximation, the equivalent thickness t^* can be estimated as equal to the carcass height (L_4) and then the equivalent Young's Modulus can be easily computed, according to the condition of keeping the same bend stiffness, solving the following equation

$$E_c^*\left\{\frac{L_4^3}{12} + L_4\left[\frac{E_c^*L_4\left(\frac{L_4}{2}\right) + E_pt_p\left(L_4 + \frac{t_p}{2}\right)}{E_c^*L_4 + E_pt_p} - \frac{L_4}{2}\right]^2\right\} = E_ci_c \tag{5}$$

Where E_p and t_p are the polymer Young's modulus and thickness (t_p = 5.5mm), respectively, E_c is the carcass Young's modulus and i_c means the stiffness per unit of length ($i_c = L_4/12$). For the dimensions used in this paper (see Table 1), E_c^* = 172.4 GPa. This approximation results in error of 1.68% about the distance from centroid to the ring internal radius and 1.42% about the bend stiffness. The material properties used are shown at Table 2.

Sousa *et al*. (2001) did an equivalence keeping the same bend stiffness in relation to the carcass centroid to calculate an equivalent thickness for flexible pipe applications. Thus, the radial stiffness of each hose can be calculated as

$$k_h = \frac{(EI)_{eq}}{R_m^3}\frac{1}{\left(\frac{\pi}{4}-\frac{2}{\pi}\right)} \tag{6}$$

where

$$R_m = \frac{E_c^* A_c R_c + E_p A_p R_p}{E_c^* A_c + E_p A_p} \qquad (EI)_{eq} = E_c^* I_c + E_p I_p \tag{7}$$

where $R_c = 7.2$ mm and $R_p = 10.7$ mm are the medium radius of the carcass and the polymer, A_c, A_p and I_c, I_p are theirs area and second moment of area. See Vignoli *et al*. (2014) for their expressions.

Considering the crush arrangement showed in Fig. 4.a, a simplified approximation of the parcel of force applied by each pad can be done considering that only the hoses below a pad feel this load, and as the pad touch the umbilical in two different points with equal forces. For instance, consider for F_P applied by one pad. It is supposed that this force is divided in two equal parts between the contact points and later it is shared again between the two hoses below these points, which results in a parcel of the force $0.5F_P$ for the central hose and $0.25F_P$ for the others two lateral hoses. This simplified hypothesis revealed a good agreement with the FE results, which will be shown at next section.

To share the load between the parts of the HCR hose (polymer and carcass) it is necessary to guarantee that the displacement in any cross section must be continuous to satisfy the geometrical compatibility. Note that the stresses can present discontinuities on its distribution. For a HCR thermoplastic hose, the aramid contribution is too small and can be neglected. Considering that each hose can be separated in just two layers, the carcass and a polymeric layer, it is possible to model this set of layers as two springs in parallel arrangement. The radial displacement of a hose arrangement w_h can be estimated adapting equation (1) as

$$w_h = \frac{P_h R_m^3}{4(EI)_{eq}}\left(\cos(\theta)+\theta\sin(\theta)-\frac{4}{\pi}\right) \tag{8}$$

Where P_h is the force applied on the hose. Once the radial displacement is obtained, considering a thin ring, the normal stress generated by the curvature variation can be estimated adapting equation (4) as

$$\sigma_x^{bend} = -E_c^*\left|\frac{1}{R_m^2}\left(w_h + \frac{d^2 w_h}{d\theta^2}\right)\right| y \tag{9}$$

The shear stresses caused by the transverse forces are neglected. Note that x and y are represented in Fig.2 and means, respectively, tangential and the radial directions of the coordinate system.

Using a direct formula application, the von Mises equivalent stress is, as in Crandall *et al.*(1973)

$$\sigma_{vM} = \left|\sigma_x^{bend}\right| \tag{10}$$

The approach showed above is important not only for estimate analytically the critical effect of the crush but also as input for the equivalent Young modulus in FE analysis, therefore it is important to use the correction factor E_c / E_c^* to adjust the final results.

3. NUMERICAL MODEL

The FE mode was created using commercial ANSYS package. Considering this is the starting paper of this research line, a simple umbilical structure was chosen. This structure is composed by 10 HCR hoses, numbered from 1 to 10 at Fig. 4 and its cross-section a 1/10th symmetry. The materials were considered linear elastic and the properties were shown at Table 2, except the effective Young's modulus of the carcass, E_c^*, which was discussed at section 2.

A finite element formulation was proposed by Saevik *et al*. (2005) to analyze umbilicals subjected to crush load. That model was developed for umbilical steel tube, where plane strain condition could be considered. For this paper model, the HCR hose cannot be modeled using a plane strain hypothesis due to its helical and not continuous geometry. Indeed, in the 2D model it is used plane stress assumption, as used by Vignoli (2014) in a previous study. Also, the following simplifications were adopted at numerical model: the hose carcass was modeled as a ring, keeping the inner and outer diameter, as explained in details at section 2; an equivalent Young Modulus of carcass was proposed at section 2; all polymeric layers were modeled using Polyethylene properties; and the armour wires and the external sheath were not explicitly modeled but its contribution to crush load was considered as commented at next item.

3.1 ARMOUR WIRES RADIAL COMPRESSION LOAD

Another important load during the installation is the armour wires radial compression, which happens of a direct consequence of armour wires stretch during axial loading. This phenomenon is extensively studied in the literature, for instance by Custodio and Vaz (2002) and Witz and Tan (1992), using differential geometry for modelling helical layers and solving a system of equations to satisfy the boundary conditions of applied load and geometrical compatibility. Custodio and Vaz (2002) commented that the typical radial stiffness of an umbilical core (hoses + inner bundle) ranges from 10^8 to 10^9 Pa/m, which was measured experimentally. The umbilical cross section used in this paper has a radial stiffness equal to $3.5 \cdot 10^9$ Pa/m, compatible with Custodio and Vaz (2002), as a first approximation.

Armour wires radial compression and pad force are clearly dependents of the cable weight per unit of length and the water deep. To estimate, in a simple way, this dependence, let's consider for a given axial force applied on the umbilical cable F_a (determined by parameters commented above), the pad force can be determined as Malcorps and Henry (2008)

$$f_p = \frac{F_a}{N_f N_p L_p \mu} \tag{11}$$

where f_p is the force per unit of length in each pad, N_t is the number of tensioners, N_p and L_p are, respectively, the number and the length of pads and μ is the frictional coefficient.

For this given force, the axial umbilical cable strain ε can be obtained as describe in details by Custodio and Vaz (2002). According to their results, up to 300kN the following approximately linear curve can be used

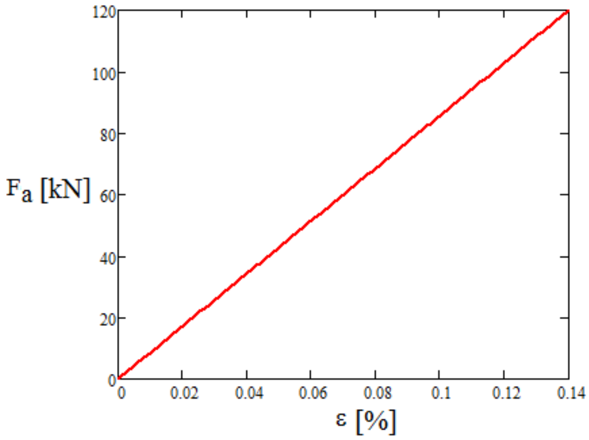


Figure 3. Relation of the applied axial load with the longitudinal strain - adapted from Custodio and Vaz, (2002).

Note that Fig. 3 represents the longitudinal strain along the umbilical cable axis, and not the longitudinal strain of each armour wire. Once this strain is obtained, the armour wires radial pressure can be estimate as Bahtui *et al.* (2009)

$$p = nEA\varepsilon \frac{\sin^2 \alpha}{2\pi R_m^2 \cos\alpha} \tag{12}$$

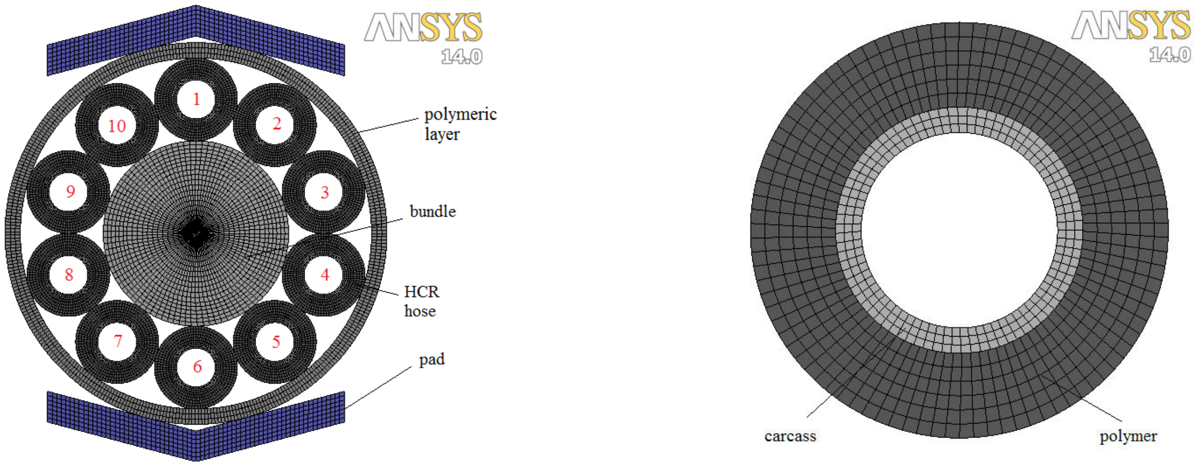
Where p is the resultant pressure, n is the number of armour wires, E and A are Young modulus and the area of the armour wire, α is the lay angle and R_m is the medium radius of the armour wires layer. Obviously the number of contact pairs grows up abruptly if the armour wires are represented in the FE model. Note that even for 3D geometries the armour wires are usually omitted Sato *et al*. (2013).

3.2 GEOMETRY AND MESHING

All the inner contacts was modeled as "No separation", a linear formulation which allows contact surfaces to slide frictionless but does not allow gaps between them, as in Lee (2012). This simplification seems to be a good and efficient one for a first approach. On the other hand, as usual in Brazilian projects, the contact between pads and umbilical was set with frictional coefficient μ = 0.09, Malcorps and Henry (2008).

The mesh used at the FE model is presented at Fig.4. A total of 37941 nodes and 11054 elements were generated. The elements used were PLANE183 and the pair CONTA172 and TARGE169.

PLANE183 is a higher order element with quadratic displacement behavior, which one can have 6 or 8 nodes, depending if the element is quadrilateral or triangular and it was chosen to get a better description of the stress distribution. CONTA172 and TARGE169 are pair of elements. For each CONTA172 element there is a TARGE169 at the other face in contact, which is used for bi-dimensional with midside nodes ANSYS (2009).



(a) (b)

Figure 4. (a) Umbilical cross section with mesh used; (b) detailed HCR hose mesh.

Two different FE simulations were carried out: first only the pad load is considered to evaluate the proposed analytical model and second one considers both loads, the pad and the compression load caused by the armour wires. To improve convergence aspects, each load was separated into 10 sub steps and for each one the stiffness matrix is uploading by an iterative solver considering contact nonlinearities when necessary.

To compare the results, that will be presented in next section one path was created along the inner diameter of the hose located immediately below the pad, which is the critical position. The complete geometry was used instead the one quarter symmetry of the cross section because this way the hoses can be rotate to evaluate where is the critical position. The hoses are positioned in a helix pattern because the fabrication process and all the possible positions must be evaluated. The hose bundle was rotate by steps of 6º up to 36º, to access all different arrangements.

4. DISCUSSION

The pad load for both analytical and FE models, and the FE model for both pad and compression load caused by the armour wires are analyzed. The results are presented considering just one half symmetry of the hose. An arbitrary pad force was set in 100 N/mm. To include the compressive armour wires effect a pressure of 1 MPa was arbitrary adopted to the FE model. The results of the three different models are plotted at Fig. 5. For this figure, and for now on, $\theta = 0º$ is the point of contact between the HCR hose and the inner bundle and just the hose marked as 1 at Fig.4.a will be analyzed because it represents the critical position (the critical hose position was obtained after analyze all the possible positions). For the results presented in this section, the index ′′*′′ indicates the use of the correction factor cited in section 2.

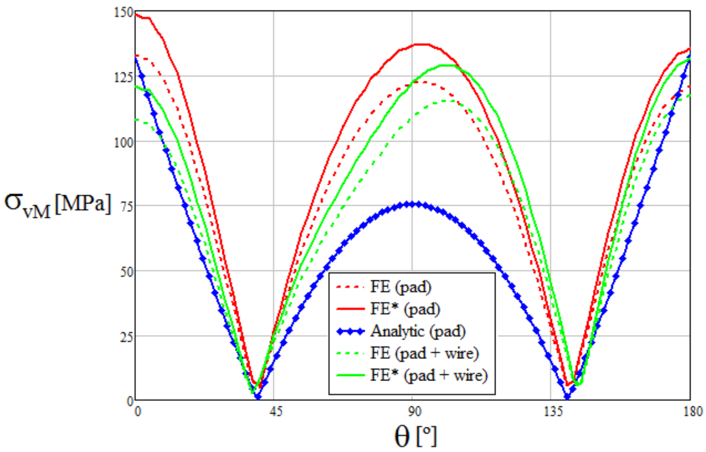


Figure 5. von Mises equivalent stress for different models.

Comparing the red and blue lines, it is possible to realize that the proposed analytic model provides satisfactory agreement with the equivalent FE one when the maximum von Mises stress is analyzed. When the shape of the stress distribution is compared, the analytic approach does not represent faithfully the results from numerical simulation. One reason for this discrepancy can be the utilization of concentrated force model, which not really happens in real structures. An improved description regarding the contact effect is given as suggestion for a further work. The maximum stress value, which is usually the most important estimation during design, can be considered accurate enough at angles 0º and 180º.

Another not intuitive result from Fig. 5 is that for the same pad force, when the pressure is applied, what means consider the armour wire compression effect, the von Mises stress can even decrease. A consequence of this fact that consider just the pad effect result in conservative estimations and can be used as simplified model during design stage. It is must be clear that this last affirmation is not a generalization; it is a conclusion for the present case. As the curve shape changes, the critical point also do not keep the same, in other words, considering just the pad load, the critical point is when θ = 0º, and for the complete case (pat + armour wires), the critical point is θ = 180º.

Considering the procedure described in section 3.1, two different axial forces are considered: 80 kN and 100 kN. The results of the FE simulation for the complete case, considering the pad and armour wires loads, are plotted at Fig. 6.

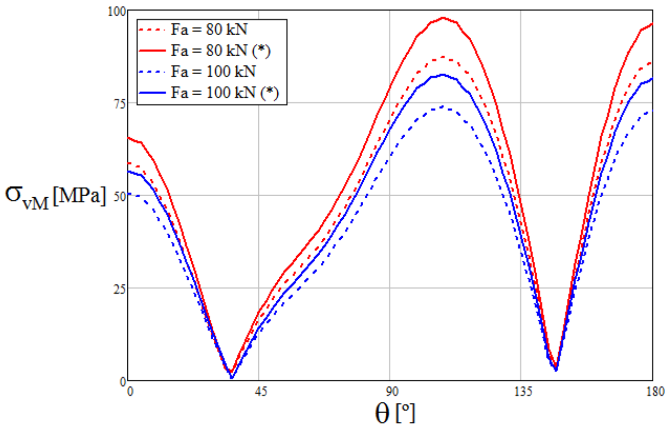


Figure 6. FE results for different axial forces.

It becomes clear that the critical point for these cases is θ = 180º. An important conclusion of these results is that the maximum stress can increase when the axial force decrease. One explanation for this unexpected effect can be expressed as: as the axial load increase the armour wires stiffs, becoming more rigid, interfering at both load path and load magnitude that reaches the hoses from the pads.

5. CONCLUSIONS

A simple FE model was proposed to describe the umbilical cables cross section mechanical behavior during installation, with especial attention to HCR hoses. For the FE model both pad and armour wires compressive loads were applied. The proposed analytical model only recognize the pad load, but was also useful to estimate the equivalent Young's Modulus, rather than a most traditional approach of creating an equivalent thickness to carcass, used to simplify the FE models geometry. The advantage of the proposed model is its relatively low computational cost, once the umbilical cable cross section could be modeled as a bi-dimensional geometry giving special attention to the HCR hoses modeled as being submitted to plane stress condition.

6. ACKNOWLEDGEMENTS

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