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Analytical prediction of umbilical behavior under combined tension and internal pressure

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ABSTRACT

Subsea umbilical is being used increasingly in harsh environments which require its mechanical behavior subjected to the axial symmetrical loads to be described. To predict the mechanical behavior of umbilical with multiple layers, a theoretical model is presented in this paper. The feature of the umbilical cross section in the model is a large-diameter central pipe. The contact problem between two adjacent layers contains deformation compatibility of the contact surface. The principle of virtual work is applied in the theoretical model to formulate the governing nonlinear equations and the contact conditions are introduced into the principle of virtual work. A 3D finite element model using ABAQUS is developed to represent the load condition of umbilical under tension and internal pressure. The mechanical behavior correlation between the ABAQUS and theoretical models validates the applicability of the theoretical model. In addition, the theoretical model is used for the assessment of other important parameters, such as the effects of internal pressure, lay angle and diameter-to-thickness ratio on mechanical behavior of umbilical, which are helpful for the design process of umbilical.

1. Introduction

Subsea umbilical provides a communication and control link between the subsea system and surface vessel in subsea oil and gas exploitation field developments. It normally consists of various functional lines for hydraulic, electrical power and signal transmission such as hydraulic tubes, electric cables, optical fibers, etc. Each field development demands an unique umbilical design. In offshore application, the umbilical is always subjected to axi-symmetric loads such as tension, torsion and internal pressure, etc., no matter under the installation or operation conditions. The prediction of the mechanical behavior of the umbilical in deep water under the axi-symmetric loads with an acceptable accuracy is very important for the installation and operation design.

Several assumptions were made in the theoretical methods developed up to date for predicting the behavior of umbilical under axis-symmetric loads. In the initial model developed by Hruska (1951, 1953, 1952), the wires in the model were assumed to be subjected to pure tensile forces (no moments). Later, a model of multi-strand wire ropes was developed for obtaining wire stress, and the interlayer pressure under tension and torsion. In an 7×1 single strand model (Machida and Durelli, 1973) accounted for the moments in helices and gave explicit expressions of axial force, bending and twisting moments for the helical wires. Knapp (1979,'1975) used the well-known energy method to derive a new stiffness matrix and considered the compressibility and material nonlinearity of the core element in helical armored cable under coupled tension and torsion.(Costello and Phillips (1976)) treated the cables as groups of separate curved rods based on Love's theory(Love, 1944) and gave a rigorous derivation. Fere and Bournazel (1987) gave simple formulas to calculate the stress and the contact pressure between layers due to axiaxisymmetric load. Witz and Tan (1992) considered the umbilical or flexible pipe as two basic components: cylindrical elements and helical elements. The continuity of interface pressure and helical radius was considered to assemble all equilibrium equations. Kumar and Botsis (2001) made an attempt to experimentally test the validity of the deformation derivation results earlier obtained for multilayered wire rope strands with metallic core. Sævik and Li (2013) investigated the validity range of formulation of theoretical models for torsion and curvature due to both axisymmetric loads and bending.

Numerical method can avoid the restrictions of theoretical method such as uniform distribution of contact pressure between layers and ignoring the friction. Custódio and Vaz (2002) presented a finite element formulation and applied the principle of virtual work, as well as solving the Jacobi matrix by Newton's method for the umbilical model. The model takes into account a number of features, such as material nonlinearity, gap formation and interface contact. A three-dimensional finite element

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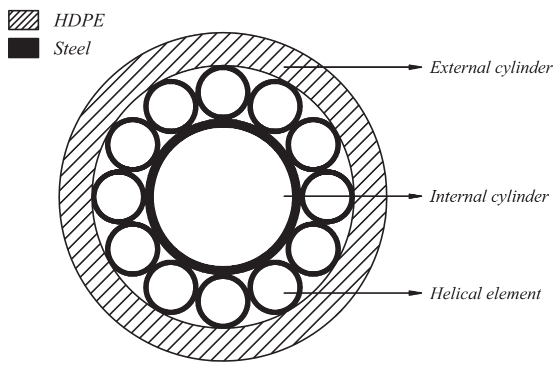

Fig. 1. Umbilical cross section.

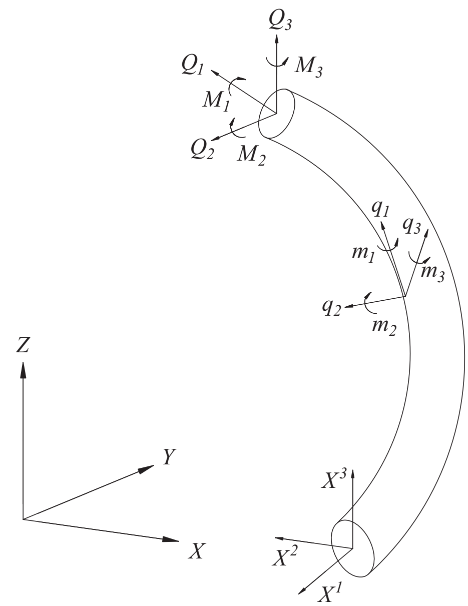

Fig. 2. Local coordinates of a helical element.

formulation for predicting the behavior of complex umbilical cross-section exposed to combined load including bending was developed by Sævik and Gjøsteen (2012). Dixon and Zhao (2008) proposed a three-dimension solid model to capture local stress and contact between internal components for fatigue analysis. Probyn et al. (2007) developed a three-dimension finite element analysis model in ABAQUS to obtain the mechanical behavior of umbilical structures. The cylindrical elements and helical elements are modeled by C3D8R and S4R respectively. Lately, Le Corre and Probyn (2009) used S4R and B31 instead of C3D8R and S4R to save the calculation resources for complex sections of umbilical. Bahtui et al. (2009) presented an analytical formulation and a very detailed finite element analysis for the behavior of multilayer unbonded flexible risers. Additionally, three different analytical approaches were combined in one unified formulation, which included the slip effects as well as layer separation and bird-caging phenomena. Ren et al. (2014) considered the actual complicated cross-sections of carcass and pressure armor, contact and friction between layers in the model to predict the behavior of unbonded flexible risers under axisymmetric load.

Each field development demands an unique umbilical design. In this paper, a unique umbilical with a large-diameter central pipe shown in Fig. 1 will be simulated with a theoretical model with multiple layers under axisymmetric loads to investigate the mechanical behavior of the umbilical. The umbilical are divided into cylindrical and helical components. All the researches up to date, the method for considering the contact conditions between two adjacent layers used to connect two individual components has some limitations. In this paper, the principle of virtual work is applied in the theoretical model to formulate the governing nonlinear equations and the contact conditions are introduced into the principle of virtual work. Moreover, the curvature increments in helical elements are developed from the vector basis of the reference state with consideration of the change in arch length. Meanwhile a three-dimensional model is developed with ABAQUS under the same load conditions and the analysis is performed with the dynamic explicit solver. The comparison on mechanical behavior between the two models is presented. Parametric studies are also applied to study the influence of several important factors on the mechanical behavior of umbilical and some significant conclusions have been obtained.

2. Theoretical model

Umbilical consists of two basic parts: a cylindrical element and a helical element. The inner cylindrical elements are wound by helical elements. The composite structure provides high axial stiffness associated with low bending stiffness. The materials of umbilical are assumed to be in linear elastic range with small deformation. In this work, the cylindrical elements and helical elements are considered individually. Then the two individual parts are assembled by contact conditions with virtual work.

2.1. Helical element

The helical structure is the main structure feature of umbilical, and it has a great influence on mechanical behavior. The helical rod is illustrated in Fig. 2. The equations of equilibrium of a curved rod were derived by Love (1944):

$$\frac{dQ_1}{dX^1} - \kappa_3 Q_2 + \kappa_2 Q_3 + q_1 = 0 \tag{1}$$

$$\frac{dQ_2}{dX^1} + \kappa_3 Q_1 - \kappa_1 Q_3 + q_2 = 0 \tag{2}$$

$$\frac{dQ_3}{dX^1} - \kappa_2 Q_1 + \kappa_1 Q_2 + q_3 = 0 \tag{3}$$

$$\frac{dM_1}{dX^1} - \kappa_3 M_2 + \kappa_2 M_3 + m_1 = 0 \tag{4}$$

$$\frac{dM_2}{dX^1} + \kappa_3 M_1 - \kappa_1 M_3 - Q_3 + m_2 = 0 \tag{5}$$

$$\frac{dM_3}{dX^1} - \kappa_2 M_1 + \kappa_1 M_2 + Q_2 + m_3 = 0 \tag{6}$$

where Q_I is the force stress resultants acting along the local coordinate axes, M_I is the moment stress resultants acting along the local coordinate axes, q_I is the distributed load acting along the local coordinate axes, m_I is the distributed moment acting along the local coordinate axes, κ_I is the curvature along the local coordinate axes. X^I is the local curvilinear coordinates.

The pitch length of a helical element is high in comparison with the diameter of the cross section. It is reasonable to assume that geometric deformation of a helical element can be described by its centerline. The initial bending curvatures and twist were derived by the Serret–Frenet formulas in unloaded configuration, as follows:

$$\kappa_1 = \frac{\sin\,\alpha\,\cos\,\alpha}{R} \tag{7}$$