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Theoretical and numerical analysis of bending behavior of unbonded flexible risers

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ABSTRACT

This paper presents theoretical and numerical study on bending properties of unbonded flexible risers. To capture nonlinearities in layer's sliding, the stress component due to slip-stick behavior is considered and energy conservation principle considering sliding-caused heat consumption is employed in the analytical model. Besides, a finite element model estimating mechanics of unbonded flexible risers' bending is proposed. In the finite element model, couplings between bending moment–curvature and axial stress as well as contact interaction among layers and tendons have been considered. The theoretical and numerical results were validated against the corresponding experimental data in literature and mutually compared in analyzing nonlinear bending behavior of flexible risers. Moreover, the impacts of axisymmetric loads on riser's bending behavior have been further investigated.

1. Introduction

As exploitation of oil and gas resources advances into deeper water and harsher environment, flexible risers are widely employed to transport oil and gas from the underwater wellheads to the offshore rigs. The main advantage of the flexible risers is that they are compliant and highly deformable

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in terms of bending, while maintaining sufficient tensile stiffness to withstand large loads induced by self-weight, currents, waves, vortex-induced vibrations, and the motion of the floating vessels. Regarding the complexity and the importance of the bending responses of unbonded flexible risers, numerous studies have been conducted in this field over last decades.

As for experimental work, a case study for the structural analysis of a 2.5-inch flexible riser was of crucial importance [1]. In this case, the bending stiffness was tested under various internal pressures. Witz [1] described mechanics of the layers in the riser in detail and proposed a "blind" test to several institutions by asking them to estimate the stiffness with their models. These institutions covered the broad spectrum of flexible pipe manufacturers, oil companies, engineering consultancies and academic institutions, such as Maritime Seanor, Statoil, NHT and so on. Analytical results were provided by these different institutions for a coflexip flexible riser design. These results are compared with available experimental data. Despite the complexity of the flexible riser cross-section, the various methods used by the institutions broadly agree with the experimental data provided that layer interaction was taken into account in the various models.

Since experiments are normally expensive and time consuming, a large amount of the analytical and numerical studies are being carried out. Witz and Tan [2] proposed a general analytical model to predict the bending behavior of multiple-layer flexible structures, such as flexible risers, umbilicals, and marine cables. Based on equilibrium equations, they analyzed the sliding of helical tendons once a critical curvature has been exceeded. They noted that the slip mechanism leads to a hysteretic bending moment–curvature relationship for generic flexible structures. However, no detailed function for sliding progression was provided in their studies. Kebadze and Kraincanic [3,4] conducted studies on this topic in which slip initiation and progression are considered. A straightforward analytical model was developed based on the Coulomb friction model and the principle of virtual work. Their model accounts for the nonlinearity caused by the sliding of individual helical tendons between the surrounding layers. A significant impact of the interlayer contact pressure on the moment–curvature relationship was illustrated in their case study. Starting from this point, Dong [5] analyzed bending stiffness of flexible risers considering the impact of local bending and twisting of the tendons. Dong et al. [5] studied the influence of local bending and twisting of helical tendons on the bending behavior for the entire riser was evaluated. Dong et al. [5] showed that the local bending and twisting of the tendons significantly influences bending stiffness of the flexible riser under full-sliding state.

Mechanical behavior of unbonded flexible risers is highly nonlinear because of friction. This has motivated a significant amount of research into the development of refined finite-element models. In particular, Zhang and Tuohy [6] studied the application of finite element models to the structural analysis of unbonded flexible risers using commercial finite element software package. These authors used elements with equivalent materials and geometric properties to model the contacts between layers. They suggested that the friction between contact surfaces should be taken into account and that 3D solid elements should be used in the finite element model. Bahtui [7,8] studied the response of a five-layer flexible riser under axisymmetric loads with a detailed 3D finite element model using ABAQUS package. In this model, the 3D solid elements are used to mesh the sheath, antiwear and helical armor layers, and the shell elements are used for the carcass layer. A very good agreement was found between the proposed model results and the analytical results [9–11]. Saevik and Bruaseth [12] presented a finite element model for predicting the structural behavior of umbilical cables by combining curved-beam kinematics, thin-shell theory, and the principle of virtual displacement. The model took into account a number of nonlinear features such as material nonlinearity, gaps between individual bodies, and hoop responses caused by contact effects. Later, Saevik and Gjosteen [13] introduced bending analysis into this model. Witz [1] concluded that correct consideration of the interaction between layers was the key factor for accurately predicting the bending structural behavior.

Regarding the complexity and the importance of the bending responses of unbonded flexible risers, this paper presents both theoretical and numerical methods for bending properties estimation. Energy conservation principle considering the sliding-caused heat consumption is employed in the analytical model. Meanwhile, a finite element model which considers the coupling between the bending moment–curvature and the axial stress, as well as the contact interaction among layers and tendons is proposed. The theoretical and numerical results are validated against the corresponding experimental