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Slip and stress of tensile armors in unbonded flexible pipes close to end fitting considering an exponentially decaying curvature distribution

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ABSTRACT

An analytical model is given to investigate the end-fitting effect on slip and stress of tensile armors in unbonded flexible pipes under tension, torsion and varying bending in the absence of friction. An exponentially decaying curvature distribution is assumed to represent controlled curvature over the end region. The deviation from the initial helical angle is taken to describe the armor wire path as the pipe is stretched, twisted and bent, which is determined by minimization of the strain energy functional using the Euler equation. The obtained simultaneous differential equations are numerically solved by transforming them into a boundary value problem. An analytical solution is found by neglecting the twisting rotation of the wire cross-section. The developed model is validated with a finite element simulation and geodesic based analytical expressions for constant curvature and with a current numerical model for varying curvature. Reasonable correlations are observed between the model predictions and the results from other methods. The validated model is then applied to typical flexible pipe designs to find the level and location of the greatest increases in stress. The results show that the end restraint could cause a significant stress increase in the armor wire at the end fitting vicinity and the critical location is close to the extreme fiber position on the compressive side of the pipe for typical cases. The effect of end restraint on layer bending stiffness is also evaluated.

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1. Introduction

Unbonded flexible pipes have been largely used as the offshore industry advances into deeper waters and harsher environments where a high level of bending deformation is expected. End fitting (see Fig. 1) is an essential component of flexible pipes, at which all the strength members in the pipe's construction are terminated, so that axial loads and bending moments can be transmitted into the end connector without adversely affecting the fluid-containing layers [1]. In dynamic applications, large bending effects take place near the end fitting owing to the joining of rigid and flexible system elements. Therefore, stress concentrations and higher fatigue will result.

While flexible pipe behavior distant from any restraint has been extensively analyzed [2,6–9,11,12,14,16,19,20,26–28], there has been relatively little work concentrating on the mechanical behavior of flexible pipes close to end fittings. Most of

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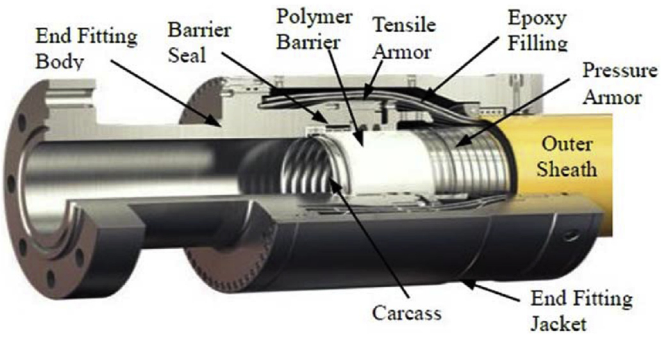

Fig. 1. Example of a flexible-pipe end fitting [13].

the models, analytical or numerical, assume constant bend curvature over a sufficiently long domain, which means the clamping end conditions and curvature distribution cannot be taken into account. Together with the greater likelihood of failure in this region, it calls for a detailed study of this topic.

Dong et al. [10] reviewed the main works regarding the analysis of structures incorporating helical layers with end restraints. The models listed are mostly developed for the analysis of spiral strands or cables. Recently Zhu and Tan [29] conducted an investigation on the stress evaluation of tensile armor wires in a bent pipe due to end termination. The results show that the end-fitting effect plays an important role on the wire stress calculation. Among those dealing with the flexible pipe behavior considering the termination effect, the approaches proposed by Sævik [22–24] and Martindale [18] are attractive. Sævik [22–24] developed a curved beam element for finite element (FE) modelling of one single tensile armor tendon, and an arbitrary curvature distribution along the pipe can be considered. The model presented by Martindale [18] uses small changes in helical angle along the wire to describe tensile armor configuration as the pipe is stretched and bent. The path adopted by the wire is found by minimizing total strain energy to find slip characteristics and stress concentrations. An exponentially decaying distribution is assumed to capture the curvature attenuation experienced by the pipe as the curvature profile may vary quite sharply in the region of an end fitting. However, friction is not considered in this model, and radial contraction of the wire associated with traction and ovalization of the supporting surface due to bending are also missed. The solution to the case in which the pipe is under tension only was extended by Dong et al. [10] to account for the axial strain effect (ASE) and the twisting rotation of the wire cross-section. Twisting rotation was found to decrease the lateral bending stress and the inclusion of the axial strain effect introduced another bending stress component which is linearly proportional to the pipe strain.

In this paper, combined loading including tension, torsion and varying bending is considered, in which case greater lateral slip and severer stress concentrations will be involved. Martindale's model [18] is extended by incorporating wire contraction, axial strain effect and wire cross-section twist.

2. Analytical model

The phenomenon of tensile armor slip governs a flexible pipe's response to bending. Pre-defined slip paths, either the strained helix or a geodesic curve, are used in previous analytical solutions. However, in the vicinity of the end fitting, the geodesic is not compatible with the restraint, despite the absence of friction. There is also no guarantee at all that the wire is restrained to adopt the strained helix path. The aim here is to find the new limiting curve that indicates the ideal location towards which the wire will attempt to move. Once this location is found, slip and stress of the armor can be evaluated. The new configuration of the wire is described by the deviation through a small angle from the initial helical angle, and can be determined by the minimization of armor strain energy due to axial strain, bending and torsion, with appropriate boundary conditions.

2.1. Assumptions and definitions

The main assumptions used throughout the analysis are the same as those adopted by Dong et al. [10], but the one that assumes the helix radius remains unchanged is removed. One additional assumption is made here that the bend curvature experienced by longitudinal lines on the cylindrical surface is the same as that of the pipe center-line. The error induced by this assumption is very small (see the Appendix), as the pipe radius is typically much smaller than the bend radius.

Fig. 2 shows the geometry for a helix of length L and helical angle α_0 wound on a cylindrical surface subjected to tension and torsion. When bending is included, a small element is considered, as shown in Fig. 3. As the pipe is loaded, the helical angle of the armor wire must change slightly, with a small angle α deviated from the initial helical angle. Lateral displacement occurs and is the integral of α:

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