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Friction models for evaluating dynamic stresses in non-bonded flexible risers

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ABSTRACT

This paper addresses friction models used for evaluating dynamic stresses in non-bonded flexible risers. A review of the most commonly used methods to model friction between layers in such structures was performed. Four models for calculating friction under dynamic contact pressure and constant shear interaction stick stiffness conditions were then formulated to enable stress calculation of cross-sections exposed to variable tension and bending loads. The friction models were implemented into a computer code used for numerical studies. A sensitivity study was carried out to determine the optimum shear interaction stick stiffness parameter, K_0, with respect to representing the plane surfaces remain plane assumption. This was followed by an investigation of the performance of the developed models with respect to the tendon axial force next to the outermost fibre position. The proposed friction models were also verified against full scale tests in terms of bending moment-curvature data. As the test data indicated less bending stiffness in the stick domain than that can be obtained by the plane surfaces remain plane assumption, a method to estimate the parameter K_0 was proposed, which accounted for the shear deformation of the plastic layers. The initial strain concept was further applied to deal with the significant hysteresis observed in the test data for low internal pressures pointing the way forward with respect to dealing with this effect in stress analysis. Furthermore, a friction model comparison study was carried out for investigating the static friction effect on the axial force at the outermost fibre position and the bending moment-curvature relationship.

1. Introduction

The flexible riser concept may be applied for flexible pipes, power cables and umbilicals. All consist of several layers involving various materials and components in the composite cross-section, which depend on the specific application. In general, flexible pipes are used to transport oil and gas, whereas umbilicals may serve different purposes such as chemical injection, electrical and hydraulic power transmissions/control and monitoring. The umbilical cross-section may therefore include steel tubes, tensile armors, fluid conduits, electrical cables and fibre optic cables. As the fatigue performance of the

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cross-section components always determines the fatigue life of the whole structure for dynamic applications, it is of great importance to correctly predict the dynamic stresses in each cross-section element.

The most important stress component with respect to fatigue is the helix element's longitudinal stress caused by tension and bending variations. The longitudinal stress includes contribution from axial force and local bending, where friction in many cases governs the axial force variation. Many researchers have emphasized the importance of including all stress contributions in the local stress analysis to obtain correct fatigue life, see Refs. [1–5]. Therefore, accurate modeling of the friction stress behavior becomes important in fatigue design. There are various strategies to deal with friction in such structures. The ideal method would be to model the complex cross-section by full 3D approaches, however resulting in long computing time. Therefore, the global response and local stress analyses are normally separated. The curvature and tension time histories from the global analysis are used as input to generate the helical elements' stress history from local analysis. These local analyses are usually performed at selected locations, i.e., the hang-off, sagging, hogging, and touch down sections of a flexible riser. The local analysis can be achieved by analytical methods or finite element approaches.

Most analytical and 2D finite element approaches are feasible only if the stress state is fully determined by the global quantities at the selected cross-section, e.g., tension and curvature, which requires that 3D effects are negligible. The moment-curvature relation established from the 2D model can also be implemented into 3D-beam element material models to capture the hysteresis effect during global dynamic time domain analysis. Then the stress history can be found from post-processing directly. Otherwise, 3D approaches based on modeling each helix individually over a sufficient model length are needed. This requires a shear interaction formulation describing layer contact in combination with a stick-slip model for friction which is the focus in the present paper. The slip between adjacent layers occurs if the maximum static friction force is exceeded by the shear force induced by bending loads. Typically, the complex cross-section structure behaves like a rigid pipe before slip, whereas after slip, the friction force becomes constant. Some models, e.g., as proposed by Sævik [6], are based on an elastic-plastic friction model where the maximum elastic relative deformation is determined by a fixed stick displacement which means that the shear interaction stick stiffness represented by the parameter, K_0, may be too small to obtain the assumption of plane surfaces remain plane at small contact pressures. Therefore, a constant K_0 approach is applied in the present work.

When it comes to the importance of the friction coefficient, Kavanagh et al. [1] established two non-linear time domain models using respective no friction and full friction, giving a factor 10 difference in fatigue life. In Olsen et al.'s work [7], friction tests for different materials in an umbilical were reported. A reduction from 0.25 to 0.2 in the friction coefficient resulted in a factor 2 larger fatigue life, demonstrating the importance of the friction coefficient.

The friction coefficient in shear interaction models is normally measured by testing, obtained as an average value between the static and dynamic friction coefficients observed during cyclic runs. More importantly, static and dynamic friction coefficients and the corresponding smooth transition between these two friction coefficients were observed by Rabinowicz [8] in some tests. Several works have been reported in the literature, see Refs. [3,9–13], concerning the hysteric bending behavior of helix elements versus full scale tests. Most of the work demonstrated that good correlation in terms of axial stress of helix elements and hysteresis bending moment-curvature relationship. However, none of these works considered the interaction between static and dynamic friction during the alternating slip process. Therefore, it is of interest to develop a static friction model that includes both static and dynamic friction effects and investigate the consequence of such behavior in a complex cross-section.

Dynamic tests for investigation of internal friction were carried out at Marintek in 1991, as reported by Skallerud [14]. In these tests, a pronounced hysteresis was found in the bending moment-curvature relationship even for small internal pressure levels (small true wall tension). One way of explaining this phenomenon is that contact pressures exist between the layers in the initial state due to material shrinking of the outer sheath resulting from the manufacturing process. As of today, standard industry practice is to neglect this contribution. The initial strain concept is therefore proposed as a method for reproducing the results seen in the test measurements, thus pointing a way forward to avoid nonconservative analysis for low tension and pressure cases.

In Gaidai et al.'s work [15], the slip condition was calculated based on the mean static load conditions. However, for the case of significant dynamic tension, Grealish et al. [4] compared the fatigue life predicted from applying constant mean tension against that from applying dynamic tension and significant differences were found. It not only contributed to the alternating axial stress, but also influenced the friction slip conditions, which signified the importance of updating the slip conditions with respect to contact pressure variation.

In some tests, as reported by Skallerud [16], the moment-curvature relationship was observed to be frequency dependent. In Ozaki et al.'s work [17], an anisotropic friction model was formulated where the transition from static to dynamic friction was velocity dependent. However, this model was based on constant contact pressure while the contact pressure between layers is variable in the dynamic flexible pipe application. Therefore, this friction model has been modified in order to allow calculating the friction under variable contact pressure conditions.

As simplifications made in friction models should be minimized to ensure accurate prediction of fatigue life for arbitrary load conditions, the objectives of the present work are summarized as follows:

1. Present the most commonly used methods considering friction effect on the bending behavior of complex cross-sections.