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Modelling of fretting in the pressure armour layer of flexible marine risers

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ABSTRACT

This paper presents a computational methodology for frictional contact mechanics of the pressure armour layer in flexible risers. This will allow, for the first time, quantification of key fretting variables, such as contact pressure, relative slip and sub-surface stresses in this complex geometry, under representative loading conditions. Fatigue lives are calculated using the 3-dimensional critical plane Smith–Watson–Topper multiaxial fatigue parameter. It is shown that COF has a significant effect on predicted trailing-edge tensile stresses in the pressure armour layer and, hence on fretting crack initiation in risers. It is also shown that operating pressure and bending-induced axial displacement significantly affect predicted crack initiation. These results will facilitate representative fretting wear and fretting fatigue testing of pressure armour layer material.

1. Introduction

Flexible marine risers are a key component in the delivery of offshore hydrocarbons from the seabed to sea level, typically to a floating structure, such as a platform or vessel. In recent decades, flexible marine risers have transformed the oil and gas industry, allowing for hydrocarbon extraction at deeper depths and higher pressures in comparison to the traditional rigid structures. The structural integrity of flexible risers is paramount to personal and environmental safety. The economic implications of riser failure are significant. Flexible risers rely on a complex, composite cross-sectional architecture of helically-wound, interlocking steel wires and polymer layers to give a unique combination of high bending flexibility, axial and torsional stiffness and internal pressure resistance, as well as internal and external corrosion resistance (see Fig. 1) [1]. The research presented focuses on the helically wound, interlocked metallic wires, the pressure armour layer; the primary function of this layer is to contain internal pressure and resist hoop stress. For the inter-locking steel wires, micro-articulation of nub and groove mechanical contacts plays a key role in achieving this complex combination of exceptional mechanical and structural properties. Normal forces keep the nub and groove of the pressure armour in contact. The inner normal force is due to internal pressure in the flexible riser and the outer normal force is due to the tension of the tensile armour wire of the flexible riser (see Fig. 2). Failure of these sub-layers due to fatigue is one of the main concerns during the service lifetime of the flexible riser.

Fretting is a wear damage mechanism that occurs in the contact region between two materials under combined normal load and micro-scale cyclical relative tangential motion. The effects of fretting wear and fretting fatigue are a potential problem that is difficult to analyse and solve, so it is not presently considered during design of flexible risers. The American Petroleum Industry (API) design codes recommend a safety factor of 10 for fatigue design of pressure armour layers [2], to account for the uncertainties associated with fretting, for example. Fretting has a large potential to nucleate fatigue cracks in the pressure armour layer.

Fretting damage can be associated with three slip regimes [3], depending on the slip amplitude: (i) gross slip, (ii) partial slip and (iii) mixed slip regime. Because of this, the contact mechanics of two bodies in contact under combined normal and tangential loading is important for fretting behaviour. Hertz was the first to solve the problem of contact between two elastic half-spaces, in terms of semi-ellipsoidal geometries with an elliptical contact area e.g. [4]. Cattaneo [5] and Mindlin [6] independently combined solutions for normal and tangential loading of Hertzian contact to develop a solution for the partial slip case. Generalised analytical solutions have been presented based on elasticity theory to calculate substrate stresses for bodies in contact [7,8].

In marine risers, fretting action along the contact surfaces is produced by shearing loads due to bending. This gives rise to a

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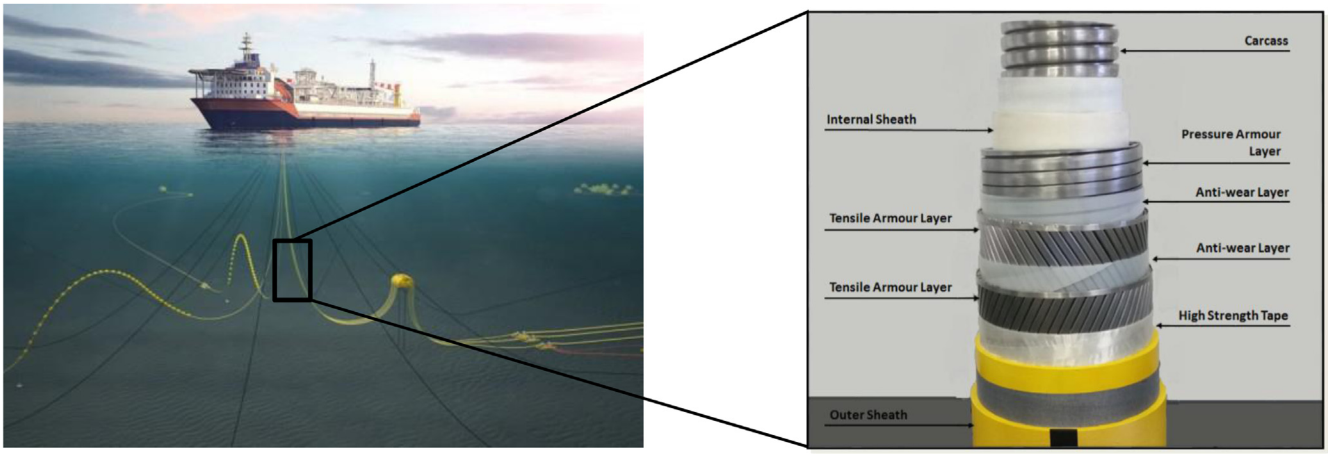

Fig. 1. Schematic of loading on the pressure armour layer of a flexible marine riser; cross section of a flexible marine riser (Wood Group Kenny).

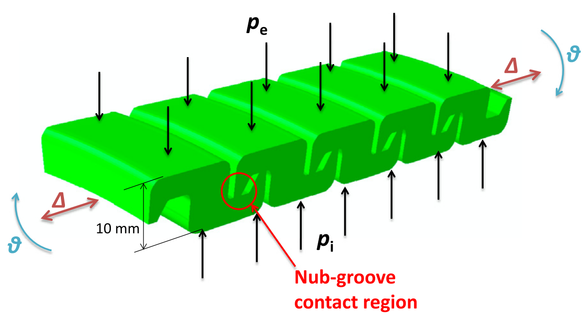

Fig. 2. Loading conditions on the pressure armour layer; Δ – relative slip between wires; p_e – external pressure on the layer; p_i – internal pressure on the layer; θ - bending induced rotation of the layer.

micro-scale frictional contact phenomenon leading to micro-scale surface damage, typically, a combination of wear and fatigue micro-crack nucleation, ultimately leading to loss of function and fatigue cracking and failure. The predominance of wear or fatigue crack nucleation is dependent on a large number of mechanical and physical variables; therefore the development of a combined modelling and experimental capability is critical for a service life prediction (design) methodology. Fretting behaviour in the pressure armour layer of flexible marine risers has been recently identified as a critical aspect of riser design which requires further research [9]. Løtveit and Bjaerum [10] identified fretting of the pressure armour wire as a potential failure mode for flexible marine risers. Significant advances have been made in fretting fatigue of spline couplings, used in aerospace engineering [11,12], gas turbine dovetail joints [13], steel wire ropes [14] and other industrial applications. The problem of fretting fatigue in flexible marine risers has received relatively little attention. Féret and Bournazel [15] presented a theoretical approach to calculate stresses, contact pressures and slip between tensile armour layers of flexible pipes under axisymmetric loading. Burke and Witz [16] presented an excellent review of the problem at an industrial conference. More recently, Perera et al. [17] presented an experimental investigation for fretting of the pressure armour layer of unbonded flexible pipes.

It is generally accepted that the main variables that affect fretting are contact pressure, slip amplitude and coefficient of friction (COF) and these are investigated here. The aim of the present work is to determine accurate substrate stresses for the nub and groove contacts in the pressure armour layer for a range of riser loading conditions and nub-groove contact COF. This will facilitate representative fretting wear and fretting fatigue testing of pressure armour layer material. Fatigue life predictions are made for the pressure armour layer using a 3-dimensional critical plane Smith–Watson–Topper [18] multiaxial approach. This approach has been shown to give good predicted life results in comparison to experimental test results for multiaxial in-phase and out-of-phase fatigue lives for combined cyclic axial and torsional loading displaying tensile cracking [19]. The critical plane SWT parameter has been used in many fatigue life prediction applications [20–25].

2. Analytical model

When two elastic bodies come into contact under normal loading, elastic deformation takes place. This results in a contact area in the 3-dimensional case and a contact width in the 2-dimensional case. Here, a generalised analytical solution is presented for substrate stresses in contact cases where the contact pressure is known.

The classical assumptions of Hertz are adopted in order to calculate the pressure distribution for both the sliding and partial sliding contact problem [4]:

- Surfaces are continuous and non-conforming;
- The strains are small;
- The bodies are infinite elastic half-spaces i.e. the dimension of the contact is small in comparison to the dimensions of each body and the radii of the curvature of the surfaces.

2.1. Distributed normal and tangential loading

In general, contact stresses are transmitted through normal pressure and shear loading. The sub-surface stress components at a point (x, z) are given by integrating the normal pressure distribution $(p(s))$ and shear traction distribution $(q(s))$ over the loaded region (see Fig. 3).

Substrate stresses are obtained through the application of elasticity theory for concentrated normal and tangential loads and integration over the contact region for specified distributions of normal and shear traction. The two-dimensional Cartesian stress components are thus given by [4]:

$$\sigma_{xx} = -\frac{2z}{\pi}\int_{-b}^{a}\frac{p(s)(x-s)^2 ds}{\left\{(x-s)^2+z^2\right\}^2} - \frac{2}{\pi}\int_{-b}^{a}\frac{q(s)(x-s)^3 ds}{\left\{(x-s)^2+z^2\right\}^2} \quad (1)$$

$$\sigma_{zz} = -\frac{2z^3}{\pi}\int_{-b}^{a}\frac{p(s) ds}{\left\{(x-s)^2+z^2\right\}^2} - \frac{2z^2}{\pi}\int_{-b}^{a}\frac{q(s)(x-s) ds}{\left\{(x-s)^2+z^2\right\}^2} \quad (2)$$

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