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An experimental study on the key fretting variables for flexible marine risers

S.M. O'Halloran [a], A.M. Harte [b], P.H. Shipway [c,1], S.B. Leen [a,*,1]

[a] Mechanical Engineering, National University of Ireland, Galway, Newcastle Rd., Galway H91 HX31, Ireland
[b] Civil Engineering, National University of Ireland, Galway, Newcastle Rd., Galway H91 HX31, Ireland
[c] Faculty of Engineering, The University of Nottingham, Nottingham NG7 2RD, UK

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ABSTRACT

This paper presents an experimental investigation into the effects of contact conformity, contact pressure and displacement amplitude on gross-slip fretting behaviour for grease-lubricated cylinder-on-flat contacts in the context of flexible marine riser pressure armour wire, and compares behaviour with that observed in unlubricated conditions. Characterisation of friction and wear is critical to fretting fatigue life prediction in flexible risers since friction directly controls trailing-edge fretting stresses and hence fatigue crack initiation, on the one hand, and on the other hand, directly affects wear via relative tangential slip (displacement). Wear can have a beneficial or detrimental effect on fatigue crack initiation and propagation, depending on relative slip and slip regime. For the grease-lubricated conditions, the behaviour is determined by whether grease can be retained in the contact (as opposed to being extruded out). Retention (or replenishment) of grease in the contact results in low rates of wear and low coefficients of friction; these conditions are favoured by fretting displacements above a critical value, by low contact conformity, and by low applied loads.

1. Introduction

Fretting is defined as surface damage that occurs between contacting bodies under normal load combined with micro-scale relative oscillatory motion. Vingsbo and Söderberg [1] mapped the dependency of fretting damage on slip amplitude and normal load and demonstrated that fretting fatigue (cracking) is the dominant damage mechanism in the partial slip regime but, as slip amplitude increases, fretting wear becomes the dominant mechanism in the gross slip regime. This leads to an increase in component life due to the redistribution of stresses as wear takes place [2], and as embryonic cracks are worn away before propagation [3]. In fretting, the retention or ejection of debris developed in the contact area also influences the magnitude and mechanism of wear damage [4].

Fretting wear is a complex damage process; Dobromirski proposed that there are up to 50 variables that affect fretting behaviour [5]. The fretting process includes multiple physical phenomena such as asperity contact, causing plastic deformation and damage, oxidation of wear surface material and debris behaviour (covering its retention in the contact and/or removal from the contact). Most experimental studies on fretting are based on simplified contact geometries, such as cylinder-on-flat, crossed cylinders or flat-on-flat [6]. It has been demonstrated [7–9] that the specific wear rate is dependent on the radius of curvature for cylinder-on-flat and ball-on-flat for unlubricated fretting. It is difficult to model the full complexity of fretting using computer models; however, a number of authors [10–13] have developed finite element fretting wear models to predict the geometrical development of a contact in fretting, normally assuming that the specific wear rate itself is a constant.

There are many methods for reducing friction (thus, commonly resulting in a reduction or elimination of fretting damage and wear) while still allowing relative displacement between contacting surfaces; these include lubrication, surface texturing or thin film coating. Different forms of lubrication are used to reduce fretting damage, such as solid (powder graphite, polymeric film), liquid (oil) or semi-solid (grease) lubricants. However, where the contact slip amplitude is small, the desired lubricant penetration into the fretting contact can be limited. McColl et al. [14,15] investigated the effect of lubricant viscosity and slip amplitude. It was demonstrated that for grease-lubricated contacts, the fretting regimes depend on pressure and the penetration of the lubricant into the contact zone, and hence, on the formation of a lubricant tribo-film. Zhou et al. [16,17] showed that, in lubricated fretting, the higher the viscosity of the lubricant, the slower the transition towards a low tribofilm-lubrication interface. It was also shown that the coefficient of friction depends on slip amplitude for grease-lubricated fretting: lower

* Corresponding author.
E-mail address: sean.leen@nuigalway.ie (S.B. Leen).
[1] Prof. Sean Leen and Prof. Philip Shipway: Joint senior authors.

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friction values were observed for tests carried out with larger slip amplitudes. Recently, Haviez [18] quantified the tribological response of grease-lubricated fretting contacts using a friction energy wear approach for partial slip, gross slip and near reciprocal sliding cases. It was shown that for grease-lubricated fretting, wear volume is mainly controlled by metal-on-metal contact and can be rationalised using a modified effective friction work approach. Fretting damage mechanisms and rates are dependent on oxygen penetration into the contact area [16,19]. Wright [19] found that the concentration of oxygen in air is about six times that in an oil-based lubricant and that the rate of oxygen diffusion within lubricant is approximately proportional to the inverse of its viscosity, indicating that lubricants significantly limit oxygen ingress into the contact. Neyman and Sikora [20] have shown that for fretting contacts with higher viscosity lubricants, higher wear rates are observed; this was attributed to the exclusion of oxygen from the contact, restricting the production of beneficial oxidised wear particles, (which reduce the wear rate since wear particles are less abrasive than steel-on-steel fretting). Similarly, grease lubrication has been shown to restrict oxygen from the contact area, thus preventing oxide-based debris from developing [14, 21]. Moreover, the presence of lubricant at the fretting contact also hinders the escape of debris from the contact [20].

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. 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). Due to the geometrical and loading conditions of the nub and groove feature of the pressure armour layer, it can be susceptible to fretting damage (see Fig. 2). For the inter-locking pressure armour steel wires, micro-articulation of nub and groove mechanical contacts plays a key role in achieving the flexible structural properties of the riser, while also allowing for extraction of hydrocarbons from deep water (high pressure environments). Normal forces due to internal fluid and external hydrostatic pressure and an additional outer pressure due to the tension of the helically wound tensile armour wires keep the nub and groove of the pressure armour in contact. Micro-scale relative displacement can occur due to global riser bending moments, for example, caused by sea-state loading and vessel motions.

The pressure armour wire represents a critical aspect of riser design [22–24]. The problem of fretting fatigue in flexible marine risers has received relatively little attention. Researchers have presented analytical solutions to calculate stresses, contact pressures and slip between layers

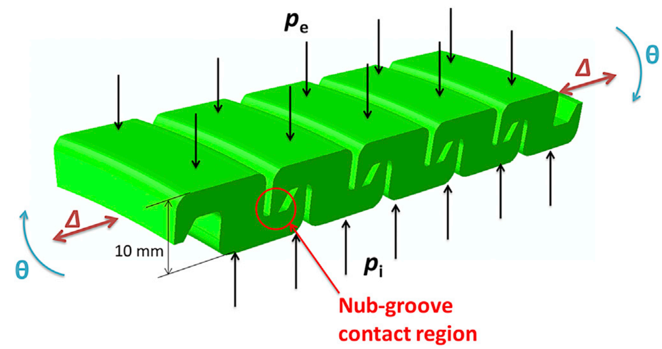

Fig. 2. Schematic of pressure armour layer geometry and loading conditions.

for flexible pipes [25–27]. More recently, Perera [28] presented an experimental investigation for grease-lubricated fretting of the pressure armour layer of unbonded flexible pipes, concluding that the issue requires further investigation. Previous work by the current authors [29, 30] has focused on finite element modelling of the nub-groove fretting wear contact using adaptive meshing techniques and multi-axial fatigue life predictions. Increased coefficient of friction was predicted to have a detrimental effect on fretting fatigue life to crack initiation [29]. In gross-slip conditions, increased wear was shown to have a beneficial effect on predicted crack initiation life due to redistribution of stresses [30]. Little or no experimental research has been presented on fretting fatigue in flexible marine risers; therefore, this paper investigates the effects of key fretting variables for fretting of flexible risers under dry and lubricated conditions.

In practice, a lithium (Li) -based grease is used in the laying process of the helically wound wire around the riser; this grease can remain in the nub-groove region during the service life of the riser. Thus, an experimental investigation has been conducted here to (i) characterise the dry fretting wear behaviour, and (ii) investigate the effect of a Li-based grease lubricant on the fretting wear behaviour, of representative pressure armour layer material. This experimental methodology considers both dry and grease-lubricated contacts for two different cylinder-on-flat contact conformities under various normal loads, combined with different tangential displacements, which are representative of the nub-groove fretting contact of flexible marine riser pressure armour wire [29–31] (Fig. 2).

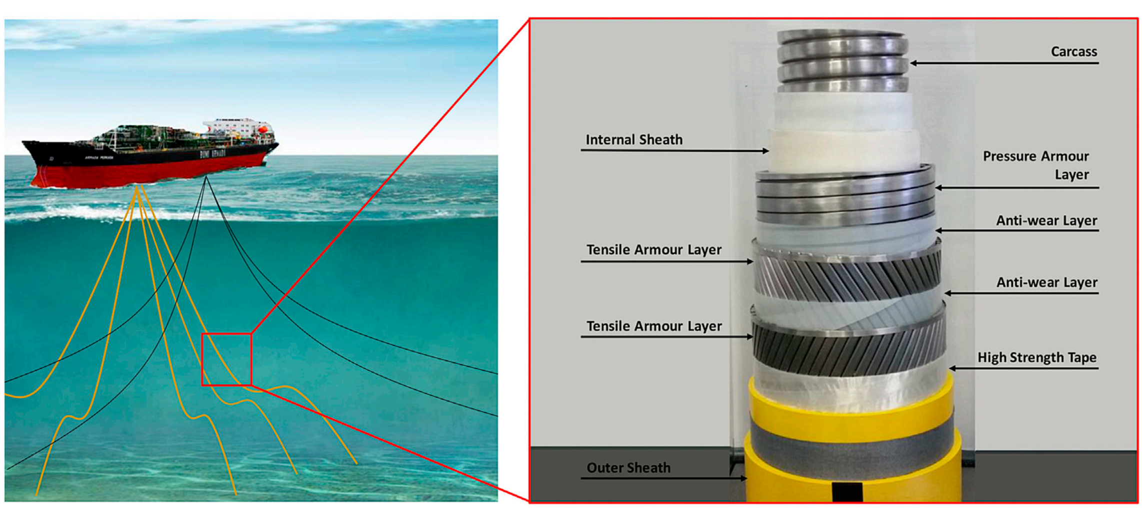

Fig. 1. Schematic of global flexible riser and photograph of cross-section of flexible marine riser.