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Hybrid composite tensile armour wires in flexible risers: A multi-scale model

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ABSTRACT

Traditional carbon-steel armour wires pose limitations (*e.g.* long spans, weight reduction, corrosion and fatigue) for flexible risers to operate in demanding and deeper water environments. In this context, an alternative to carbon-steel tensile armour wires is proposed recently by the authors (Gautam *et al.*, 2016), comprising of hexagonally packed polymer composite rods with uni-directional fibres and an over-braided (*i.e.* bi-axial braid with high performance fibres) sleeve. These hybrid composite wires offer opportunities to tailor their mechanical properties by varying the geometrical (*e.g.* rod diameter, packing) and processing parameters (*e.g.* material selection, braid pattern) involved. In order to understand the mechanical behaviour of these hybrid composite armour wires, this paper presents a multi-scale model developed by using a combined analytical-computational approach. The multi-scale model is developed to predict the torsional and flexural behaviour of the hybrid composite wires; and the role of over-braid structural parameters, pre-tension and internal friction are investigated. The behaviour of the multiscale model is found to be in good agreement with the experimentally observed behaviour. After validating the multi-scale model with the experimental data available for specific configurations, parametric studies are conducted on the torsional and flexural behaviour of the hybrid composite wires to study the role of internal friction between un-bonded components and the braid tow tension in the over-braided sleeves.

1. Introduction

There is a growing need for innovation in the design and manufacture of flexible risers as the Oil & Gas industry continues its efforts in exploring deeper offshore reservoirs. Flexible risers carry fluids from the facilities at the sea bed to floating units. A typical un-bonded flexible riser comprises of multiple un-bonded layered assembly, consisting of helically wound metallic wires (rectangular cross-section) as pressure and tensile armours that are interlayered with polymeric sheaths, which help the riser to be highly compliant— especially in flexural mode. Although flexible risers are highly deformable and compliant in flexural mode, yet they provide a strong and stiff response to internal/external pressure, tension and torsion [2]. Among different layers in a traditional un-bonded flexible riser, the tensile armour is an integral part consisting of metallic (typically carbon-steel) wires with a rectangular cross-section, which resists tensile, flexural and torsional loads [3–5].

Major failures in flexible risers are often driven by the damage and failure of tensile armours [6], which include crack nucleation, tensile fatigue, radial buckling, and lateral buckling. Moreover, carbon-steel, which is the most widely used material for tensile armour wires, is more prone to environmental degradation (*e.g.* corrosion, hydrogen sulphide induced stress cracking [3]), and thus the type of carbon-steel to be used depends upon the service environment and conditions. Recent works [8–11] have shown great potential for carbon fibre thermoplastic and thermoset matrix composites (similar dimensions to metallic wires) in replacing metallic tensile and hoop armours. These composites show higher tensile strength and fatigue, excellent corrosion resistance, and enable significant overall weight reduction of flexible riser systems. However, these composite wires develop high strains when wound in the riser, limiting the usable thickness and resistance to brittle damage/fracture.

Due to the limitations of carbon-steel material and the recently introduced carbon composite tensile armour wires, a novel hybrid composite armour wire (as shown in Fig. 1) is proposed by Gautam *et al.* [1]. These hybrid composite armour wires consist of carbon and vinyl ester pultruded rods, stacked in form of hexagonal closed

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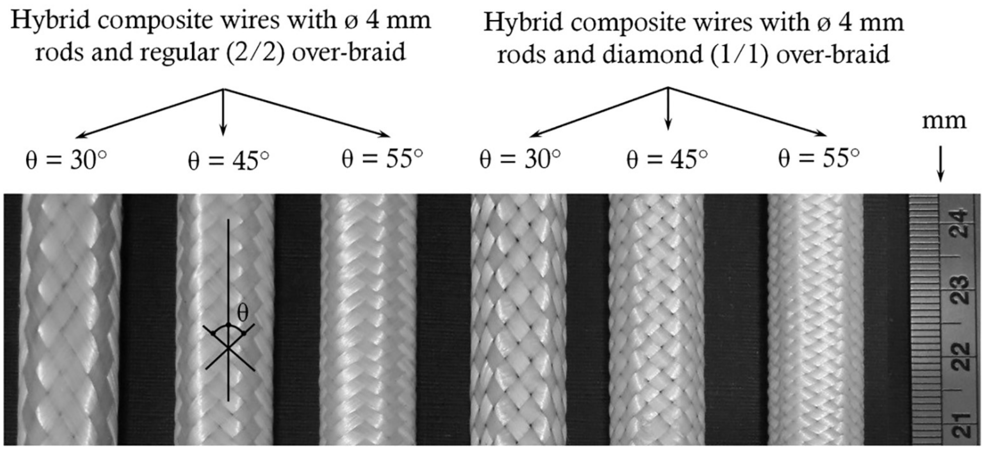

Fig. 1. Hybrid wire armour wires with different over-braided sleeve configurations.

packing, completely un-bonded to each other, but held together by an over-braided ultra-high molecular weight polyethylene (UHMW-PE) fibres—commercially known as Dyneema. The combination of braiding and pultrusion process together can help in continuous production of tensile armour wires. The hybrid composite armour wires aim not only to provide lower torsional and flexural rigidities but also to ensure high tensile stiffness and strength. The structure is analogous to the structure of flexible riser itself, comprising of multiple un-bonded components.

This paper, with emphasis on computational modelling, is an extension to the experimental work conducted by the authors in Gautam *et al.* [1]. A multi-scale model is developed by using a combined analytical-computational approach for the hybrid composite armour wires to study the torsional and flexural behaviour as a function of over-braid parameters, internal friction, and braid tow pre-tension. The over-braided sleeve is modelled as a homogenised orthotropic shell; and the composites rods are modelled as homogenised orthotropic solids. These homogenised elastic properties are then used to develop a multi-scale model for the hybrid composite wires. The internal friction between composite rods as well as the rods and the shell (*i.e.* homogenised over-braid sleeve) are also incorporated in the model. Moreover, braid tow pre-tension is accounted for in the form of an equivalent hoop pressure and then exerted on the composite rods. The combined analytical-computational approach proposed reduces computational effort as micro- and *meso*-scale computational models are avoided. The experimental response is used to validate the model and then further employed for parametric analyses.

2. Materials and manufacturing

The procedure followed for the manufacturing and testing of the hybrid composite armour wires is reported by the authors in Gautam *et al.* [1]. The manufacturing process of the hybrid composite wires involved over-braiding of hexagonally packed pultruded rods, where each rod had a diameter of 4 mm. This form of packing provides the highest packing efficiency, and densest packing for straight cylinders when their axes are parallel [12]. This form of packing also extends the interaction of energy between the rods [13] and geometrically all the pairs of neighbouring axes are located at a constant distance from each other. Prior to the braiding process, the packed rods were taped at the ends and no adhesive is used to bond the rods together. For over-braiding the hexagonally packed rods, regular (2/2) and diamond (1/1) braid topologies are used, and three different braid angles (30°, 45° and 55°) are employed. The hexagonal packed rods are over-braided using 24 and 48 carrier braiding machines. All 24 carriers on a 24 carrier machine are used to produce a regular (2/2) braid topology, and only 24 carriers on a 48 carrier machine are employed to obtain a diamond (1/1) braid topology. These two configurations are considered to study the effect of braid topology on the flexural and torsional behaviour of the hybrid composite wires.

The braid structural parameters are given in Table 1. These parameters are measured physically and through image analysis. The crimp phenomenon in a braid refers to the waviness or undulation of a tow as a result of interlacement between tows. Braid crimp can be quantified (see Eq. (1)) as the ratio of the difference between the length of the crimped tow (L_c) and the length of the non-crimped tow (L_{nc}) to that of the length of the crimped tow (L_c). The braid crimp percentage (C) for all the braided configurations is calculated using Eq. (1). The crimp factor (α) derived from the crimp ratio (A) (see Eqs. (2) and (3)) can be used to calculate the crimp angle (β), as in Eq. (4), that the tows make upon crossing over and under the other tows during braiding. The following equations are taken from ISO 7211–3 [14].

$$C = \left(\frac{L_c - L_{nc}}{L_{nc}}\right) \times 100 \tag{1}$$

$$A = L_c/L \tag{2}$$

$$\alpha = \sqrt{A - 1} \tag{3}$$

$$\beta = \tan^{-1}\alpha \tag{4}$$

When the braid angle is increased from 30° to 45°, it can be observed from Table 1 that the braid crimp increased by 12% for the diamond braid and 38% for the regular braid. When the braid angle is increased from 45° to 55°, the braid crimp increased by 79% for the diamond braid and 52% for the regular braid. This increase in braid crimp with an increase in braid angle is thought to have caused by the increase in braid density, which increases as more tows are deposited per unit length [7]. The effect of braid topology on braid crimp is found to be significant for 30° and 55° braid angles, where a decrease of 18% in braid crimp for 30° braid angle and a further decrease of 14% for 55° braid angle is observed when the topology is varied from diamond to regular. However, for 45° braid, a small decrease in braid crimp, only about 0.8%, is observed as the topology is varied from diamond to regular. For the diamond and regular braids produced using the same number of tows, the same length of tow in a regular braid experiences a lower crimp as compared to that of the diamond braid due to its higher float length.