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A strain energy-based equivalent layer method for the prediction of critical collapse pressure of flexible risers

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ABSTRACT

Flexible risers are being required to be installed in a water depth of over 3000 m for fewer remaining easy-to-access oil fields nowadays. Their innermost carcass layers are designed for external pressure resistance since the hydrostatic pressure at such a water depth may cause the collapse failure of flexible risers. Determining a critical collapse pressure for the carcass is of great importance to the whole structural safety of flexible risers. However, the complexity of the carcass profile always makes FE analysis computational intensive. To overcome that problem, the treatment of the interlocked carcass as an equivalent layer is adopted by researchers to accelerate the anti-collapse analyses. This paper presents an equivalent layer method to enable that treatment, which obtains the equivalent properties for the layer through strain energy and membrane stiffness equivalences. The strain energy of the carcass was obtained through FE models and then used in a derived equation set to calculate the geometric and material properties for the equivalent layer. After all the equivalent properties have been determined, the FE model of the equivalent layer was developed to predict the critical pressure of the carcass. The result of prediction was compared with that of the full 3D carcass model as well as the equivalent models that built based on other existing equivalent methods, which showed that the proposed equivalent layer method performs better on predicting the critical pressure of the carcass.

1. Introduction

The ongoing ultra-deep water (UDW) exploitation requires riser systems that are able to be used beyond 3000 m water depth (Luppi et al., 2014; Vidigal da Silva and Damiens, 2016). As one key technology in subsea production systems, unbonded flexible riser has been a good choice for such exploitation due to its flexibility and corrosion resistance (Edmans, 2014; NOV, 2015; Technip, 2014). This pipelike structure comprises multiple layers with different structural and operational functions. A typical internal configuration of a flexible riser is shown in Fig. 1. The innermost carcass layer is designed for external pressure resistance while the pressure armour layer is for internal pressure resistance. These two metallic layers are separated by an impermeable polymeric inner liner and nested inside one or more pairs of tensile armours. Those layers along with other functional polymeric layers are encased in an external plastic sheath, being isolated from the external environment (Cooke and Kenny, 2014).

As operators contemplate the subsea development to a water depth beyond 3000 m, the flexible riser products are required to have adequate anti-collapse capacity to withstand a very high external pressure (Wolodko and DeGeer, 2006). The more flexible the pipe is, the less its collapse resistance becomes. The critical pressure (maximum external pressure before collapse) of flexible risers does not only depend on the pipe material properties but also on pipe geometrical properties (Suleiman, 2002). Experimental tests could be an reliable approach to determine the critical pressure but such kind of the hydrostatic tests usually costly. As for numerical analyses performed on full 3D FE models, they are quite computational intensive because of the complex interlocking cross-section and the inner contacts of the carcass. Alternatively, the treatment of the carcass as a homogenous layer with equivalent thickness is adopted by researchers to simplified the anti-collapse analysis of flexible risers. This equivalent layer model could not only boost the computational efficiency in numerical analyses but also allow the development of analytical models based on ring buckling theory (Timoshenko and Gere, 1963).

Up to now, several equivalent layer methods have been proposed to calculate the thickness for that equivalent homogeneous layer. Those methods are proposed based by imposing equity between the carcass and the equivalent layer for some properties, such as cross-sectional area, bending stiffness per length or area (Zhang et al., 2003; De Sousa et al., 2001; Martins et al., 2003; Gay Neto et al., 2009; Loureiro and Pasqualino, 2012; Tang et al., 2016). Area equivalent method is carried

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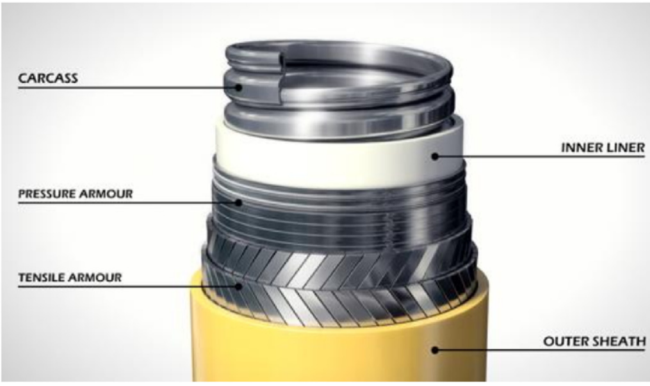

Fig. 1. Typical design of a flexible riser (NOV, 2014).

out based on the equivalence of cross-sectional areas (Zhang et al., 2003). As the cross-sectional area is the only parameter considered in this method, the actual material distribution in the carcass profile is not accounted and hence the accuracy of the prediction may not be guaranteed (Cuamatzi-Melendez et al., 2017). Considering that collapse of ring-like structures is a bending-dominated problem, two methods based on the equivalence of structural bending stiffness were presented. One equivalent method obtained the thickness through sectional bending stiffness equivalence (De Sousa et al., 2001) while the other built the equivalence through bending stiffness per length (Martins et al., 2003). However, those bending stiffness equivalent methods are unable to consider the self-contact issue of the carcass, leading to an overestimation of the actual structural bending stiffness. Recently, a method based on strain energy equivalence is proposed (Tang et al., 2016). The strain energy of the carcass was obtained through the finite element model. In this carcass model, the Dirichlet-type boundary condition was applied to ensure that only hoop strain was generated along the circumferential direction. Such a strong boundary conditions enhanced the structural stiffness of the carcass, lowering its absorbed strain energy. As a result, the thickness of the equivalent layer was underestimated.

In general, most equivalent layer methods fail to capture the actual structural stiffness of the carcass due to the neglect of contact issues of the carcass. Moreover, since those methods are only focused on determining the equivalent layer thickness, other potential equivalent properties might be missing. To solve above-mentioned problems, an equivalent method is proposed in this paper that trying to construct a layer with equivalent geometric and material properties. Those properties were determined through both strain energy and membrane stiffness equivalences. The reason of adopting the strain energy equivalence is because that no available approach can be used to calculate the actual bending stiffness of the carcass. As the strain energy absorption is directly influenced by the structural stiffness, it was chosen as a representative parameter to reflect the actual bending stiffness of the carcass. Numerical models were constructed to obtain that strain energy of the carcass in this paper. After the equivalent properties of the layer were determined, the equivalent model was built and then used to predict the critical pressure of the carcass. The prediction result was compared with that of the full 3D carcass model to verify the reliability of the proposed method. This paper is organized as follows: following the introduction, Section 2 presents the establishment of the strain energy based equivalent method. Section 3 provides a feasible FE simulation for offering strain energy to the proposed equivalent method, which were verified by the test data given in the work of Tang et al. (2016). In Section 4, the equivalent models are constructed based on the proposed method and examined by related case study. The final Section 5 concludes the work.

2. Equivalent layer method based on strain energy equivalence

When the treatment of the carcass as a homogeneous layer is adopted, the equivalent properties of the layer should be determined in order to perform a similar collapse behaviour. Many researchers impose equity between those two tubular structures for their bending stiffness since the bending stiffness is a dominant factor of the critical pressure of pipe (Timoshenko and Gere, 1963)

$$p_{\mathrm{e,cr}} = \frac{3EI}{R^3} \tag{1}$$

where $p_{\mathrm{e,cr}}$ is the elastic critical pressure, EI is the bending stiffness of the pipe cross-section, R is the mean radius of the pipe. The bending stiffness of the equivalent layer is determined as follow (Fergestad et al., 2017)

$$EI_{\mathrm{eq}} = Kn\frac{EI_{2'}}{L_{\mathrm{p}}} \tag{2}$$

where n is the number of tendons in the carcass layer, L_{p} is the pitch and $I_{2'}$ is the smallest inertia moment, K is a factor that depends on the laying angle of the carcass tendons and the moment of inertia in the section.However, the actual bending stiffness of the carcass is influenced by its inner-contact and therefore much smaller than the calculated result according to its geometric configuration. In order to solve this problem, the absorbed strain energy of the carcass is chosen to reflect its actual structural stiffness when subjecting to radial compression loads. This loading case is referred to the experimental set-up of carcass radial compression tests presented in the work of Tang et al. (2016), which is shown in Fig. 2.

The strain energy of the carcass in such a loading case needs to be extracted from corresponding numerical models, which will be elaborated in the following section. For an equivalent ring model with radial compression force P, the loading force $F=P/2$ (at the cross section A) on its one quarter model can be resolved into component forces F_{r} and F_θ on any cross section, as shown in Fig. 3.

Therefore, its strain energy is made up of three parts

$$\begin{aligned} &\text{a) Due to axial force } F_\theta \quad U_1 = \int \frac{F_\theta^2 R(1-\nu^2)}{2AE}\mathrm{d}\theta \\ &\text{b) Due to axial force } F_r \quad U_2 = \int \frac{CF_r^2 R}{2AG}\mathrm{d}\theta \\ &\text{c) Due to bending moment } M \quad U_3 = \int \frac{M^2R(1-\nu^2)}{2EI}\mathrm{d}\theta \end{aligned} \tag{3}$$

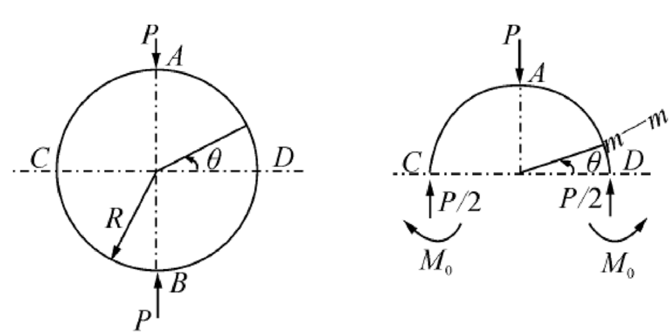

Fig. 2. Schematic diagram of a ring compressed in the radial direction (Tang et al., 2016).