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Experimental and numerical study of structural behavior of a flexible riser model

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ABSTRACT

Experimental tests and detailed finite element analyses were carried out on a model of flexible riser to evaluate the capability of the finite element method to predict its nonlinear structural response. The riser consists of four layers, which include two cylindrical polycarbonate tubes and two steel helical layers. One helical layer represents the carcass layer in a flexible riser whilst the other represents the riser tendon armour layer. First, bending load experiments on the model are described which provide some insight regarding the fundamental behavior of flexible pipe structures. This is followed by the description of the FE models in which all layer components are individually modelled and a surface-to-surface frictional contact model is used to simulate their interaction. Finally, the FE numerical results were compared with the test data to outline the capacity of the numerical method to predict the response of flexible riser structures.

Nomenclature

E	Module of elasticity
I	Area moment inertia
L	Length of beam
M	Bending moment
P	Bending load
R_i	Inner radius
R_O	Outer radius
t	Thickness
x	Horizontal direction at bending
k	Bending curvature
y	Vertical direction at bending
ϵ	Strain
σ	Stress
σ_y	Yield stress

1. Introduction

In recent decades, as global oil demand has been rising, oil exploration and production have been progressing into deeper water. As a result, industrial competition for designing efficient and reliable facilities to reach the hydro-carbonates in ultra-deep waters, in areas such as Gulf of Mexico, southern shores of Caspian Sea, Norwegian Sea and Greenland waters, has become inevitable. This competition has led to the rapid development of flexible risers capable of functioning in a harsh environment in deeper waters often exceeding 3 km below sea level. These risers are now becoming the main means for transporting oil and gas between the seabed and surface in ultra-deep waters. They consist of several polymer and steel layers that can move internally relative to each other. This gives them low bending stiffness and makes them highly valuable tools for subsea oil and gas companies. Their ability of withstanding large displacements and rotations makes them ideal for floating platforms.

The complex structural behavior of flexible risers is not sufficiently understood for many design and development purposes. Whilst, on the one hand, flexible risers must be reliable enough to safeguard the environment, on the other hand, they must make the exploitation of the subsea hydrocarbons economically feasible. This requires a great understanding of the structural behavior of flexible risers under various conditions. In many problem of very significant industrial interest, sufficient accuracy in analysing flexible risers can only be obtained by the use of models that properly take into account contact and frictions between layers and the relation of those frictions to internal and external pressure, bending and torsion of individual tendons, large displacements and rotations. Despite the fact that many attempts have been made to develop

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highly reliable and economical flexible risers, they are not meeting their recommended service life. This is because the basic technology, is relatively new (compared to steel pipes) and has not evolved enough to support more challenging applications for deeper waters and harsher environment [1].

The oil and gas industry relies on computational mechanics software to analyse and design flexible pipes. One of the most widely used approaches is the Finite Element Method (FEM), which is capable of handling geometrically complicated domains, a variety of boundary conditions, nonlinearities, and coupled phenomena that are common in flexible risers. Several commercial and in-house codes are now available for analysing flexible pipes, such as Abaqus, Adina, Algora, Ansa, Ansys, Ls Dyna, Lusas, and Nastran. Merino et al. [2] used a commercial finite element (FE) package and an analytical method for studying the torsional behavior of a 1.2 m flexible pipe. In their FE model, the carcass and pressure armour layers are modelled as equivalent cylindrical layers with orthotropic properties while tendons are modelled as three-dimensional Euler-Bernoulli beams, with a penalty method for contact constraint enforcement. The pipe was subjected to torsion combined with tension. Some differences were reported between the FE and analytical models. However, because in their FE model frictional contact between layers was included, the FE predictions were in better agreement with the experimental measures. De Sousa et al. [3] used an FE model to simulate the structural behavior of a flexible riser under different types of mechanical loads. In this model, all layers of the flexible riser and the interactions between them were included to address geometric, material and contact nonlinearities. A “sandwich” of concentric thin-walled shells was used to represent the inner carcass, the pressure armour and all polymeric layers while the wires of the tensile armours were modelled as space frame elements. Interactions between all layers are taken into account by using surface-to-surface contact elements. The model was used to predict the response of a 2.9 m flexible riser to the loads imposed by a hydraulic collar and reasonably good agreement was found between numerical results and experimental measurements.

The computational requirements of the FE analysis of flexible risers limit their applicability to just a few meters in length at most. To reduce the computational cost of large flexible pipe one can develop constitutive laws based on large-scale beam models, which link generalised stresses and strains and capture the hysteresis loops occurring for flexible pipes subjected to cyclic loading. Due to the close analogy between the aforementioned hysteretic response and the elasto-plastic behavior of metal beams, this hysteretic response can be modelled as a rate-independent elasto-plastic relationship between generalised strains and stresses as shown by Tan et al. [4]. Following this approach, Sævik [5,6] presents an FE model for predicting stresses due to axisymmetric loads in flexible pipes. The interlayer stick-slip behavior due to friction is taken into account by formulating a constitutive relation based on a plastic beam model, with nonlinear stiffness derived from an analytical formulation in terms of the moment resultants and the wire slips. A similar approach is used by Alfano et al. [7], building on the analogy between frictional slipping between different layers of a flexible riser and frictional slipping between micro-planes of a continuum medium in non-associative elasto-plasticity.

One major challenge in using a constitutive law based on the elasto-plasticity analogy is the determination of the input parameters of such constitutive laws. One way to determine these parameters and avoid very expensive experimental testing is to run a large number of detailed non-linear FE analyses with a small-scale model, and use the results to estimate the parameters which define the behaviors of the large-scale model. In this way, the small-scale FE model is effectively used as a virtual experimental rig to determine the model parameters at the large scale, but this is still an onerous task [8,9].

An alternative type of approach, which does not require a predefined large-scale constitutive model and the determination of its input parameters, is a fully-nested multi-scale procedure, currently in widespread use for the modelling of composite materials [10]. With this method, at each integration point (i.e. cross section) of the large-scale beam model, the stress resultants corresponding to assigned generalised strains are determined through the solution of the small-scale FE problem. This requires recasting the computational homogenisation problem in a more general theory which can link different structural models at different scales. This method can be used for structural analysis of flexible risers if the model used at the small scale has a sufficiently low computational cost [11,12]. For example, as shown by Rahmati et al. [13], by exploiting cyclic symmetry and applying periodic boundary conditions, only a very short segment of a flexible pipe can be used for a detailed FE analysis at the small scale, which significantly reduces the computational cost.

Whether an FE code is directly used for analysing flexible risers or it is used as a part of a constitutive or computational homogenization, it is essential to determine the degree to which that FE codes can represent the physical reality of the riser, by comparing its numerical predictions with experimental measurements. However, a major challenge is that very few experimental data is available in the public domain. Leroy et al. [14] present the results of a bending experimental test on an 8 m flexible riser. One end of a flexible pipe was anchored while the other end was moved cyclically, using a crane, which enforced a pipe curvature of up to 1 m^{-1}. Strain gauges were applied along one helical wire and around the circumference of two pipe cross-sections. Sævik [5] performed a bending test on a 14.5 m flexible pipe. Strain sensors were installed on both sides of several helical wires in the pipe. The testing procedure involved imposing internal pressure of 340 bar, followed by axial tension of 750 kN, followed by imposed cyclic curvature. Witz [15] compared experimental studies with analytical predictions of the response under flexural, axial and torsional loading, based on different models. Although reasonable agreement is found in the case of axial and torsional loading, agreement for the case of flexural loading was not reasonable. An experimental study on a simplified prototype of a flexible pipe with only four layers under bending moment is partially described in [16]. A simplified model is chosen to better understand the nonlinear effects due to frictional contact between the layers on the bending behavior of flexible riser.

Building on the preliminary work in [16], in this paper a more accurate FE model and its use for non-linear numerical analysis of the experiments in [16] are presented. A comparison between numerical and experimental data is discussed in detail to examine the capability of the developed FE model to predict the structural response of the riser with adequate enough accuracy for industrial applications.

2. Experiment

In this section, the results of experimental testing carried out on a scaled down model of a flexible riser pipe are presented. Here, first the effects of static load on the deformation and strain changes of a single helical tendon layer were also studied. Then, the model is subjected to a three point bending load in order to study its bending-curvature behavior experimentally.

2.1. The bending test

A model of flexible pipe was tested by applying variable bending loads to check the nonlinear behavior of the specimen under bending. The prototype consists of one carcass, one helical tendon layer, and two tubes as outer sheath and anti-wear layers. A