Applied Ocean Research 55 (2016) 181–189

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Axisymmetric viscoelastic response of flexible pipes in time domain

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ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form
17 November 2015
Accepted 15 December 2015
Available online 8 January 2016

Keywords:
Flexible pipes
Axisymmetric analysis
Viscoelastic behavior
Helical wires

ABSTRACT

The challenges for determining the mechanical behavior of flexible pipes mainly arise from highly non-linear geometrical and material properties and complex contact interaction conditions between and within layers components. This paper develops an innovative model to investigate the linear viscoelastic behavior of flexible pipes under axisymmetric loads in time domain. The model is derived from an equivalent linear elastic axisymmetric model by invoking the elastic-viscoelastic correspondence principle. Analytical formulations that describe the behavior of the metallic helical layers based on a combination of differential geometry concepts and Clebsch–Kirchhoff equilibrium equations for initially curved slender elastic rods are presented. The elastic response of the homogenous polymeric cylindrical layers is also presented. The assemblage of both types of governing algebraic equations that approximate analytical solutions for force and moment distributions, deformations in each layer, as well as contact pressure between near layers, taking time-dependent characteristics of polymeric layers into account are provided and it is clear that the relationship between axial force and elongation is non-linear and encompasses a hysteretic response. Besides, the creep behavior in axial direction can also be found. Some insights into the differences in the behavior for several loading conditions are discussed by considering variable frequencies.

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1. Introduction

Non-bonded flexible pipes, which have been widely used in offshore industry for oil and gas extraction from subsea reservoirs to floating production platforms for more than 35 years, are designed as composite structures comprised by a number of layers with different properties to withstand large tensile loads, torsional and bending moments as well as external and internal pressures and installation radial crushing loads in accordance with API 17J [1] established criteria. The mechanical behavior assessment of flexible pipes subjected to axisymmetric loads, i.e. axial tension, torsional moment, internal and external pressures, is of paramount importance because of the increasingly adverse operation conditions involving new developments with large diameter pipes in deep water applications. The main challenges and difficulties to predict the mechanical properties of flexible pipes originate from the complex profiles configurations in carcass and pressure armour layers, material non-linearity introduced by polymeric layers and the contact interactions between neighbor layers and within elements from the same layer under loading, as shown in Fig. 1.

Over the past thirty years, a considerable amount of models dealing with the mechanical behavior of flexible pipes have been published, where axisymmetric elastic analysis has been thoroughly investigated. The first reported work about the internal mechanical behavior of flexible pipes was presented by Féret and Bournazel [2]. They derived simplified formulations to evaluate stresses in flexible pipes under axisymmetric loads. However, little attention was paid in their work for the interaction mechanism between adjacent layers. Witz and Tan [3] presented an analytical model for predicting the axial-torsional structural behavior of flexible pipes. They divided the flexile pipe into a set of individual elements and employed Clebsch–Kirchhoff's non-linear differential governing equation, presented in Love [4], to describe the behavior of the helical layers. Witz [5] conducted a detailed case study in structural analysis of a non-bonded flexible pipe cross-section, and presented and compared analytical results provided by ten different institutions with available experimental data. Custódio and Vaz [6] presented formulations and solutions for the local axisymmetric analysis of umbilical cables and non-bonded flexible pipes considering material and geometrical non-linearities. Sævik and Bruaseth [7] and Sævik [8] developed models for predicting stresses from axisymmetric loads in flexible pipes and umbilicals based on non-linear finite element methodology. Yue et al. [9] proposed an analytical model to predict the tension behavior of flexible pipes employed in shallow waters. In their model, the effect of radial deformation was carefully assessed and the pressure armour layer was assumed only subjected to pressure. Ramos et al. [10] presented main results of experimental tests involving both internal pressure and tensile loadings on a 63.5 mm (2.5 in.) flexible pipe. Ramos and Kawano [11] provided additional contributions to the

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0141-1187/$ – see front matter © 2015 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2015.12.003

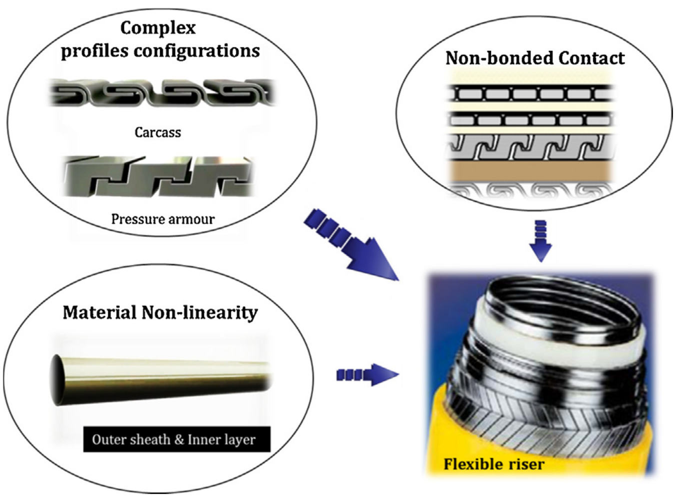

Fig. 1. Challenges on studying mechanical behavior of flexible pipes.

structural response of flexible pipes subjected to axisymmetric loads taking into account the internal and external pressures.

It should be noted that in previous studies no attention has been paid on the viscoelastic response of the polymeric layers, whose properties have always been considered to behave as solid elastic. As the flexible riser length increases in deeper waters, it is justifiable to investigate the viscoelastic behavior, which may generate a non-negligible impact on capturing the flexible pipe axial stiffness and structural damping in global analysis as discussed by Silveira et al. [12]. In addition, viscoelastic analysis has not yet been widely employed for predicting the mechanical behavior of flexible risers, only Guedes [13] discussed the effect of the polymer matrix viscoelastic behavior in thick multilayered composite pipes and Medina [14] started to study the viscoelastic behavior of flexible pipes.

Therefore, this paper aims to establish a formulation to analyze the viscoelastic mechanical behavior of flexible pipes under axisymmetric loads. The solution to such arduous problem in linear viscoelasticity is obtained by means of the correspondence theorem, which enables the result to be generated from a corresponding problem in linear elasticity. Laplace transform is applied to describe the response for viscoelastic cylinder from an elastic cylinder as assumed initially. In this model, time-dependent properties of polymers are taken into account to depict the flexible pipe viscoelastic response. The radial deformation in each layer is also considered, as well as the interlayer contact pressure. Given the geometric contact condition, force equilibrium and the interaction of viscoelastic and elastic materials, some detailed insights into the axisymmetric viscoelastic response of flexible pipes, the time-dependent characteristics and especially the relationship between axial force and elongation can be achieved.

2. Mathematical model

Flexible pipes consist of cylindrical and helical layers, therefore it is convenient to perform the mechanical analysis by combining formulations for describing the mechanical behavior of each type of component. Contact and boundary conditions are also necessary. However, the geometric non-linearity is not considered. The analytical model is based on a number of assumptions regarding the applied loads, geometry and material used in the pipe assembly, which are:

(i) The materials used in flexible risers are homogeneous and isotropic;
(ii) The material constitutive response for the polymeric layers is linear viscoelastic;
(iii) The structure can be described by an axisymmetric geometry and the deformations are small;
(iv) The position of the central axis of the riser remains constant, independently of the load;
(v) Forces and moments on each layer are axisymmetric and evenly distributed;
(vi) Friction forces are not taken into consideration.

2.1. Cylindrical elements

The polymeric cylindrical inner liner in flexible pipes is mainly used as a barrier to contain produced gas and liquid within the riser bore, preventing hydrocarbons' permeation. Meanwhile, external sheaths protect the steel layers from sea water and corrosion. Besides, antiwear layers (API 17J) constituted by thin tapes are also employed between adjacent metallic layers to reduce friction and associated wear and abrasion in dynamic applications, resulting in substantial increase in service life of flexible pipe. Consider a polymeric cylinder with length L, inner and outer radii r_1 and r_2, respectively, subjected to axial force F, torsional moment M, internal and external pressures P_1 and P_2 as shown in Fig. 2, where the

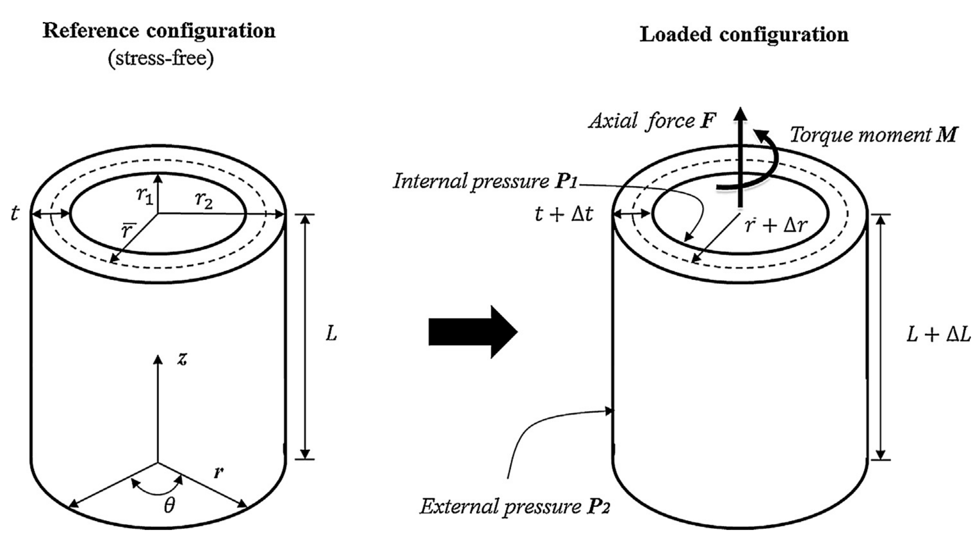

Fig. 2. Cylinder subjected to axisymmetric loads.

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