European Journal of Mechanics A/Solids 59 (2016) 232–241

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

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

Elasticity analysis of sandwich pipes with functionally graded interlayers

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A R T I C L E I N F O

Article history:
Received 27 November 2015
Received in revised form
14 March 2016
Accepted 20 March 2016
Available online 22 March 2016

Keywords:
Functionally graded material
Elasticity theory
Sandwich pipe

A B S T R A C T

Sandwich pipes that combine structural performance with thermal insulation in their design are viewed as a light-weight alternative to pipe-in-pipe systems, in which the core material is used only for thermal insulation purposes. Incorporating functionally graded interlayers into the sandwich pipe design may help improve adhesion at the interfaces between the core layer and inner and outer pipes which has been identified as one of the major factors affecting sandwich pipe performance. In this paper, sandwich pipes with two thin functionally graded interlayers between the core layer and inner/outer pipes are investigated in the context of elasticity theory. Closed form analytical solutions are derived for stresses and displacements in the pipes subjected to internal and/or external pressure. Comparative analysis of sandwich pipes with and without functionally graded interlayers is performed and beneficial effect of graded interlayers on stresses and displacements in the pipe is established.

1. Introduction

As oil and gas production move to deepwater and ultra deepwater fields new structural configurations are required to meet simultaneous demands for thermal insulation and mechanical integrity to ensure safe and reliable transportation of hydrocarbons. Since single walled pipes are not viable in these conditions due to their limited operational depths and lack of insulation, pipe-in-pipe systems have been developed over the past two decades for fields with flow assurance challenges (Bai and Bai, 2014).

A typical pipe-in-pipe system consists of an inner pipe positioned inside an outer pipe, often with the help of centralisers located at certain intervals along the inner pipe. The annular space between the inner and outer pipe is filled with insulation material to meet specific thermal requirements. The outer pipe is designed to withstand high external pressure dictated by the water depth and installation method. More recently, electrically heated pipe-in-pipe systems have been developed (Denniel et al., 2011; Denniel, 2015) which have the capability to maintain the required temperature of the fluid inside the inner pipe thus offering enhanced flow assurance.

It should be pointed out that, in the pipe-in-pipe concept, the insulation material does not perform any structural function, which is performed entirely by the outer and inner pipes. This means the annular space between the inner pipe and outer pipe is not used to its full structural potential. With increasing water depths and associated increasing demands on structural performance, the pipe wall thickness in pipe-in-pipe systems will have to increase leading to pipe-in-pipe systems becoming exceedingly heavy and uneconomical.

As a lightweight alternative to pipe-in-pipe systems, a concept of sandwich pipe is being developed. A sandwich pipe combines thermal insulation and structural performance in its design and attempts to realise the full structural potential of the annular space between the inner pipe and outer pipe. A sandwich pipe typically consists of two thin-walled pipes an inner pipe and an outer pipe and a core layer that completely fills the annular space between the pipes and is bonded to them. Estefen, Netto and Pasqualino (2005) performed small-scale tests to evaluate the structural performance of sandwich pipes with two different options of core material. The obtained experimental results were used to validate a three-dimensional finite element model that took into account nonlinear geometric and material behaviour. Strength analysis of sandwich pipes under combined external pressure and longitudinal bending showed that sandwich pipe systems with either cement or polypropylene cores are feasible options for ultra deepwater

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http://dx.doi.org/10.1016/j.euromechsol.2016.03.012
0997-7538/

applications.

An analytical approach for estimating the buckling capacity of sandwich pipes with various structural configurations and core materials, subject to external hydrostatic pressure was developed by Arjomandi and Taheri (2010). In addition to the exact solution, they proposed two simplified equations for estimating the buckling capacity of two configurations commonly used in practice. Arjomandi and Taheri (2011a, b) also performed extensive finite element modelling of sandwich pipes. They analysed different bonding scenarios at the interfaces between the core layer and the pipe layers and examined the effect of material and geometrical nonlinearities on the pipe buckling and post-buckling behaviour. On the basis of a large number of finite element models, a set of simplified and practical equations for calculating the external pressure capacity of sandwich pipes was proposed. Behaviour of sandwich pipe systems under pure bending was studied by Arjomandi and Taheri (2012).

Collapse behaviour of sandwich pipes with strain hardening cementitious composite reinforced with polyvinylalcohol (PVA) fibers as a core material was investigated experimentally and numerically by An et al. (2014). A parametric study examined the effects of ovality, thickness and outer/inner radius ratio on the collapse pressure of these sandwich pipes. Post-buckling responses and pressure capacity of sandwich pipes with the solid polypropylene core was investigated by He et al. (2015) using finite element modelling. The degree of the inter-layer adhesion between the core layer and the surrounding pipes was modelled by the contact surfaces adopting different maximum shear strength values to allow the relative displacement between the layers. The effects of inter-layer adhesion interactions, thickness-to-radius ratios, the core thickness, the material parameters, the relative initial ovality directions and the inelastic anisotropy on the collapse pressure of sandwich pipes were examined.

Adhesion between the core layers and the inner and outer pipes has been identified as one of the major factors affecting performance of sandwich pipes. Castello and Estefen (2007) investigated the influence of the inter-layer adhesion between steel and polymer on the ultimate strength of sandwich pipes under external pressure and longitudinal bending using finite element modelling. The effect of the reeling method of installation was also simulated. It was established that the ultimate strength of the sandwich pipe is strongly dependent on the shear stress acting at the interface between the core and the pipes. Arjomandi and Taheri (2011a) investigated elastic buckling capacity of bonded and unbonded sandwich pipes under external hydrostatic pressure and examined the influence of intra-layer adhesion configuration of the pressure capacity of sandwich pipes. Four bonding configurations were considered: core fully bonded to both pipes; core fully bonded to the inner pipe but free to slide against the outer pipe; core fully bonded to the outer pipe but free to slide against the inner pipe; core unbonded to both pipes. They established that if the core layer is free to slide against both the inner and outer pipes, the increase in the core modulus of elasticity would not improve the structural performance of the pipe when subject to external pressure. For other configurations, however, the increase in the cores modulus of elasticity would increase the buckling pressure of the system. One potential solution to the adhesion problem in sandwich pipes is to incorporate the concept of Functionally Graded Material (FGM) into the sandwich pipe design and introduce functionally graded interlayers between the core and the inner and outer pipes. Functionally Graded Materials (FGM) are heterogeneous composite materials with gradient compositional variation of the constituents from one surface of the material to the other which results in continuously varying material properties (Suresh and Mortensen, 1998). Functionally Graded Materials has generated a lot of interest in recent years, see for example reviews by Birman and Byrd (2007), and Jha et al. (2013).

Beneficial effect of functionally graded interlayers on stress and displacement fields has been already established for coating/substrate systems (Kashtalyan and Menshykova, 2009; Sburlati et al., 2015), while using thin functionally graded layer was shown to reduce stresses in hollow pressurized cylinders (Sburlati, 2012) and spherical vessels (Atashipour et al., 2014) as well as around open holes (Sburlati, 2013).

The benefit of FGM elements in sandwich cylindrical shells has been recently studied for vibration and buckling using graded coating (Sofiyev, 2014) or core (Sofiyev and Kuruoglu, 2015a) and also for dynamic instability in sandwich shells with graded interlayers (Sofiyev and Kuruoglu, 2015b).

In this paper, we examine sandwich pipes with functionally graded interlayers between the core layer and the inner/outer pipes and analyse the effect of FGM interlayers on response of sandwich pipes to internal and/or external pressure and their combination. If proven beneficial, FGM interlayers could be potentially developed for specific combinations of pipe and core materials and applied as coatings to the internal surface of the outer pipe and external surface of the inner pipe prior to the annular space being filled with the core material.

2. Analytical modelling

2.1. Problem formulation

Let us consider a sandwich pipe of internal radius a and external radius b, referred to the cylindrical co-ordinate system, with $z-$axis directed along the pipe axis. The pipe, cross-section of which is shown in Fig. 1, consists of five layers: the inner pipe (layer 1) of thickness h_l, the outer pipe (layer 5) of thickness h_l, the core layer (layer 3) of thickness $2h_c$ and two interlayers of the same thickness t, one being the inner interlayer (layer 2) between the inner pipe and the core layer, and another being the outer interlayer (layer 4) between the core layer and the outer pipe. The total thickness of the pipe wall is denoted. $H = 2(h_l + h_c + t)$.

The material of the inner and outer pipes is assumed to be

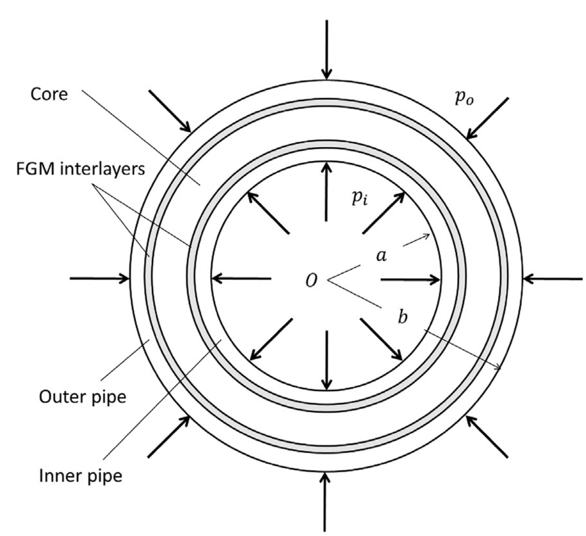

Fig. 1. Sketch of the mathematical problem studied.