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A three-dimensional analytical solution for sandwich pipe systems under linearly varying external pressures

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A B S T R A C T

A three-dimensional analytical model is presented to calculate the stress and deformation of a sandwich pipe (SP) system subjected to linearly varying external pressures. Based on a stress function method, an analytical solution for a thick-walled pipe was researched, and then an analytical solution for a SP system was obtained according to the boundary and continuity conditions of stress and displacement. Furthermore, the analytical solution of a SP system was verified by comparing with finite element method (FEM). The results indicate that the stresses from present method (PM) are in a good agreement with that from FEM. Finally, our researches provide a benchmark for approximate or numerical solutions, and are beneficial to evaluate the safety and integrality of SP systems.

1. Introduction

As a crucial common facility for the offshore oil and gas transportation, the deep-water submarine pipeline has been investigated systematically (Hong et al., 2015; He et al., 2015; Xia et al., 2001, 2002; An et al., 2012). Collapse is one of the most important problem for the pipelines (He et al., 2014; An et al., 2014). To insure the safety in deep-water oil and gas exploitation, the concept of sandwich pipe (SP) has been proposed as a new transportation pipeline. The SPs are a composite structure consisting of two thin-walled steel pipes and a polymeric or cement-based core (Estefen et al., 2005). The inner and outer pipes mainly offer the structure support and the core layer is bonded to the inner and outer pipes to provide both structure functionality and thermal insulation. Compared with a single-wall pipe, the SP systems have lighter submerged weight and more efficient insulation property. The SP systems are more suitable to resist the harsh environmental conditions and present a better comprehensive performance (Estefen et al., 2005; Zou and Taheri, 2006).

As a particular composite structure, the SP systems were numerically and experimentally investigated to obtain data about mechanical behavior. Estefen et al. (2005) develop a finite element model to evaluate the structural performance of SP with two different core material under combined external pressure and longitudinal bending. Castello and Estefen (2007a) analyzed numerically the effect of the inter-layer adhesion between steel and polymer on the ultimate strength under external pressure and longitudinal bending, and found that the inter-layer adhesion has a large influence on ultimate strength. At the same year, Castello et al. (2007b) took the Epoxy syntactic foam and polyimide foam as the annular materials, which resulted in excellent relations between thermal insulation and mechanical strength. In addition, compared pipe-in-pipe system, the design reduced the submerged weights. In another study, Castello et al. (2009) investigated the geometric shape (ovality) on the collapse. Arjomandi and Taheri (2010) analyzed the bucking capacity of SP with different structural configurations and core materials subjected to external hydrostatic pressure, and the effect of adhesion between the core layer and inner or outer layer. Arjomandi and Taheri (2011a) further studied the influence of intra-layer adhesion properties and the design parameters such as the thickness to radius ratios of steel pipes, core thickness, stiffness and steel grades on the pressure capacity of SP by using finite element model. Arjomandi and Taheri (2011b, 2011c) further studied a wide range of structural parameters the plastic buckling pressure, and proposed an analytical simplified equations according the finite element analysis results. An et al. (2014) discussed experimentally and numerically the collapse behavior of SP filled with strain hardening cementitious composites under external hydrostatic pressure. He et al. (2015) analyzed 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 by using FEM.

An army of individuals focus on the elastic or plastic collapse of SP system subjected to uniform external pressure based on the finite element approach. However, few characters pay close

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Nomenclature

r_0	internal radius of inner pipe
r_1	external radius of inner pipe (internal radius of core layer)
r_2	internal radius of outer layer (external radius of core layer)
r_3	external radius of outer pipe
D_i	internal diameter of inner pipe $D_i = 2r_0$
E_c	Young's modulus of core material
E_p	Young's modulus of inner and outer pipes, respectively
G_c	shear modulus of core material
G_p	shear modulus of inner and outer pipes, respectively
h	height of the sandwich pipe
k_{p_i}	increment of p_i from the top to the bottom along the vertical direction
k_{p_o}	increment of p_o from the top to the bottom along the vertical direction
k_{s_1}	increment of s_1 from the top to the bottom along the vertical direction
k_{s_2}	increment of s_2 from the top to the bottom along the vertical direction
k_i	increment of p_1 from the top to the bottom along the vertical direction
k_o	increment of p_2 from the top to the bottom along the vertical direction
p_1	internal pressure of single layer pipe
p_2	external pressure of single layer pipe
p_i	internal pressure of sandwich pipe
p_o	external pressure of sandwich pipe
q	initial axial stress of single layer and sandwich pipe
r_i, r_o	internal and external radii of single layer pipe, respectively
s_1	interaction force between inner pipe and core layer at the top of the model
s_2	interaction force between outer pipe and core layer at the top of the model
t_c	thickness of core layer $t_c = r_2 - r_1$
t_i, t_o	thickness of inner and outer pipe $t_i = t_o = r_1 - r_0 = r_3 - r_2$
u_r^i, u_r^o	radial displacement of inner and outer pipes, respectively
u_r^c	radial displacement of core layer
w^i, w^o	axial displacement of inner and outer pipes, respectively
w^c	axial displacement of core layer
σ_r^i, σ_θ^i, σ_z^i	radial stress, hoop stress, and axial stress of inner pipes, respectively
σ_r^c, σ_θ^c, σ_z^c	radial stress, hoop stress, and axial stress of core layer, respectively
σ_r^o, σ_θ^o, σ_z^o	radial stress, hoop stress, and axial stress of outer pipes, respectively
μ^c	Poisson's ratio of core layer
μ^p	Poisson's ratio of inner and outer pipes, respectively

attention to the stresses distribution of SP system subjected to linearly varying external pressure. Linearly varying external pressure can change the stresses distribution, accelerate fatigue and shorten the service life of submarine pipeline. In this paper, we report on the stress and deformation analyses of SP system under linear varying loading. An analytical model based on stress function theory is presented. Moreover, a comparison of the results of analytical calculations to that of FEM is carried out. This paper is crucial and beneficial for the safety evaluation of SP.

2. Geometric model and basic hypotheses of the problem

Sandwich pipe is a kind of three-layered pipes with different materials as shown in Fig. 1. The inner and outer are steel tubes with a high Young's modulus. The core layer is cement or polymeric material (such as epoxy foam and polyimide foam) with a low Young's modulus. In this paper, we adopted cement as the core cement. As a new transportation pipeline in deep-water oil and gas exploitation, the inner and outer pipes in SP system are considered to resist the mainly external and internal load and the core layer is expected to be bonded to outer and inner pipe to provide both thermal insulation and structure support. The adhesion between layers will not fail in the entire process. To simplify the calculations, we assume that pipes and core are considered working together to resist external pressure without corrosion, worn and weld defects.

In addition, we make the following assumptions:

(1) The inner, outer pipe and core layer are perfect cylinders and share the same axis;
(2) The external load acting on the SP is a linear load, while the internal and axial loads are ignored;
(3) The core layer is bonded to both inner and outer pipes without cracks.

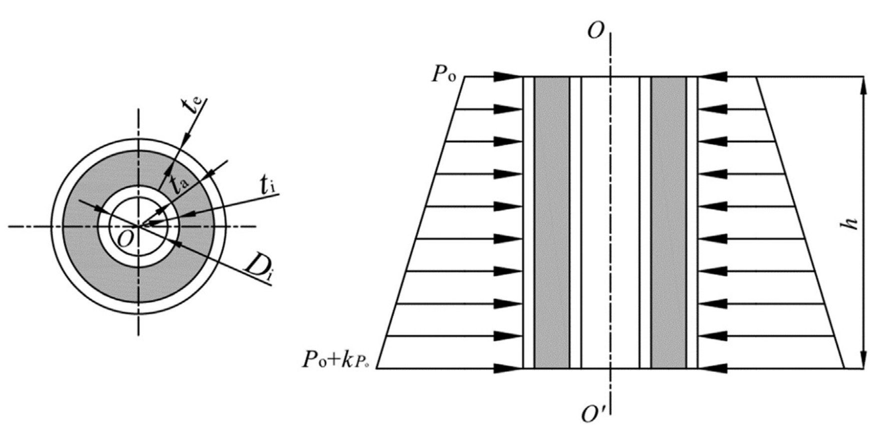

Fig. 1. Sandwich pipe model and external pressure.