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The influence of intra-layer adhesion configuration on the pressure capacity and optimized configuration of sandwich pipes

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ABSTRACT

Sandwich pipes (SPs) offer sensible and cost-effective design alternative for extraction of oil and gas in deep and harsh waters. By employing the potential thermal insulation properties offered by the core material used in SPs, and the structural integrity provided by the sandwich mechanics, SPs can be optimally designed to provide safe transportation system for oil and gas under specific loading and environmental conditions.

In this paper, the influence of the structural parameters that would significantly impact the characteristic behavior and pressure capacity of SP systems, having various intra-layer adhesion properties, are investigated. SPs response is simulated by the finite element (FE) numerical method, accounting for the material and geometrical nonlinearities, and considering the intra-layer condition. Finally, the results of more than 12,000 nonlinear FE models are used to develop three simplified practical equations, capable of evaluating the pressure capacity of SPs having various intra-layer mechanisms and material configurations, with an acceptable accuracy.

As one of the main objectives of this study, the influence of the intra-layer adhesion configuration on the optimal design of such pipes at various water depths is also investigated. The optimization procedure previously recommended by the authors is extended to establish the optimal structural configurations.

1. Introduction

Modern harvesting of our world's limited oil and gas resources has been ongoing since the 18th century. Since then, day by day, the increase in world's demands for more energy and raw material resources has accelerated the oil and gas production. As a result, the access to current oil and gas reserves is diminishing; as a result, demands for deep water resources are increasing. On the other hand, the oil and gas production and transportation facilities and techniques used for shallow and accessible reserves are not feasible for deeper reservoirs located in harsh and remote areas. Consequently, engineers are facing new challenges for improving the traditionally used systems and developing new systems. Pipelines is one of the key components of the transportation system; therefore, their configurations and performance must be improved in order to effectively respond to the new requirements. Employing the traditional steel single walled pipes is limited to a specific operational depth. Moreover, the oil product must be kept adequately warm to flow; therefore the oil product should be thermally isolated from the ambient cooler environment.

In order to improve the thermal insulation properties of the traditional single wall steel pipes, the idea of Pipe in Pipe (PIP) design configuration was developed. PIP systems are composed of three concentric cylindrical elements. The internal pipe, also called the product pipe, is in contact with the product and facilitates the oil product flow. The core layer can be selected such that it would act as a proper thermal insulator surrounding the internal pipe. Moreover, the core layer can be a host for structural and health monitoring systems, the cathodic protection systems and/or the heating facilities. The outermost layer of the system, the external pipe (also called the sleeve pipe), separates the core layer and internal pipe from the surrounding environment. Moreover, the secondary containment provided by the external pipe would improve the assurance of the system in case of oil product leaking from the internal pipe.

Because PIP systems can be designed to fit the required thermal insulation properties, these systems have been employed in many practical offshore applications. However, in most of the PIP projects, the potential sandwich structure has been ignored and each component of the system has been individually designed based on its governing loads. However, previous studies reveal that if the whole system is considered as a sandwich structure, a considerably lighter and a more cost-effective pipeline could be designed for a specific loading condition. As a result, the idea of sandwich pipe has been developed. In SP systems a relatively soft core layer is sandwiched by relatively stiff internal and external pipes. The core layer in SP systems provides the required thermal insulation properties as well as the appropriate structural properties to transfer loads between the

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Nomenclature

A_{s1}	cross section area of the external pipe
A_{s2}	cross section area of the internal pipe
A_c	cross section area of the core
$C_{Man\text{-}SP}$	manufacturing cost of the sandwich pipe
$C_{Man\text{-}P1}$	manufacturing cost of the external pipe
$C_{Man\text{-}P2}$	manufacturing cost of the internal pipe
$C_{Man\text{-}C}$	manufacturing cost of the core
EPG	external pipe's steel grade
E_c	core material's elastic modulus
E_p	internal and external pipes' elastic modulus
IPG	internal pipe's steel grade
$P_{cr\text{-}BASP}$	buckling pressure of the system calculated from Eq. (1)
$P_{cr\text{-}AT}$	buckling pressure of the system calculated from Eq. (4)
P_{co}	collapse pressure of the sandwich pipe system
P_{crs}	external pipe buckling pressure
imp	imperfection magnitude
n	buckling mode number
r_1	outer pipe nominal radius
r_1^{max}	external pipe's maximum radius
r_1^{min}	external pipe's minimum radius
r_2	inner pipe nominal radius
r_1^o	outer pipe initial nominal radius
r_2^o	inner pipe initial nominal radius
r_1^{max}	maximum measured external pipe radius
r_1^{min}	minimum measured external pipe radius
t_1	outer pipe wall thickness
t_2	inner pipe wall thickness
t_c	core layer thickness
σ_{y1}	yield stress of the external pipe material
σ_{y2}	yield stress of the internal pipe material
$\sigma_{y\text{-}X60}$	yield stress of X60 grade steel
Δ	ovalization magnitude
Δr	imperfection of the pipe radius as a function of θ
v_c	core material Poisson's ratio
v_p	pipe material Poisson's ratio

internal and external pipes. Therefore, in SP systems the core layer must include both structural and thermal properties.

One of the initial feasibility studies on employing SP systems for offshore deep and ultra deep waters was conducted by Estefen et al. (2005). They conducted small scale laboratory tests as well as the corresponding finite element (FE) numerical analysis to investigate the behavior of SP systems under various loading scenarios. Finally, through the numerical and experimental studies, they concluded that SP systems having polypropylene or cement core layers can be efficient design alternatives for offshore pipelines. However, they have mentioned that the design of such systems must be tailored for the specific demands of each pipeline project due to the large number of design parameters to be specified. In another study, Castello et al. (2009) investigated the influence of the core layer properties on the external pressure capacity of SP systems through the FE numerical approach. Moreover, they compared PIP with SP design alternatives for a hypothetical oil field and also investigated the effect of the relative direction between the inner and outer pipes maximum diameters on the external pressure capacity of the system.

Other research has been conducted with the aim of developing closed form analytical solutions for predicting the external pressure capacity of SP systems. One of the initial studies on developing the characteristic equations of the system was performed by Brush and Almroth (1975). They developed the characteristic equation of a SP system by simplifying the system to a plane-strain 2D problem of a ring on an elastic foundation. Recently, Sato and Patel (2007) and Sato et al. (2008) improved Brush and Almroth's solutions and recommended a simplified equation for calculating the core stiffness parameter. In another study, Arjomandi and Taheri (2010a) studied the stability problem of the buckling of SP systems under hydrostatic external pressure and developed simplified solutions for estimating SPs' buckling capacity. This study considered the influence of the intra-layer adhesion properties between the core layer and the surrounding pipes and developed four sets of equations for evaluating the elastic buckling pressure. Moreover, it proposed simplified equations for SPs having various intra-layer adhesion properties.

In order to analyze the stability of an SP system under uniform hydrostatic external pressure, the system can generally be considered as a long sandwich cylindrical shell structure having an infinite length. A few other research projects have been conducted to study the behavior of such systems. Kardomateas and Simitses (2002, 2005) analytically studied the stability of long sandwich cylindrical shells under uniform external pressure. Ohga et al. (2005) also studied the reduced stiffness buckling of sandwich cylindrical shells under uniform external pressure, both numerically and analytically.

Former studies have shown that the intra-layer adhesion properties would have a significant influence on both the characteristic behavior and the pressure capacity of the system. Investigating the effect of the degree of adhesion between the core layer and either internal or external pipes was the subject of a study conducted by Castello and Estefen (2006, 2008). Moreover, they studied the influence of the applied cyclic loads during the reeling installation method on the collapse pressure of the system. Arjomandi and Taheri (in press) in a series of works, analytically and numerically investigated the influence of various scenarios of bonding between the structural layers on the elastic buckling pressure of the pipe.

Previous investigations have revealed that under a steady state buckle propagation pressure, which might be lower than external buckling pressure, local buckling could be propagated along the pipeline. Several investigations have been conducted to study this phenomenon from different aspects. A series of remarkable works by Kyriakides and his coworkers (Kyriakides, 2002; Kyriakides and Netto, 2002, 2004; Kyriakides and Vogler, 2002) investigated buckle propagation phenomena from experimental, analytical and numerical perspectives.

A former numerical study of the authors (Arjomandi and Taheri, 2010b), investigating the behavior of a set of practical SP cases, revealed that practical SP configurations are highly susceptible to losing their stability through plastic buckling. Comparison between the elastic and plastic buckling pressures of such pipes shows that the difference between these two values can be excessively large, especially in the case of SPs having a relatively stiff core layer. Therefore, it was concluded that employing the equations developed based on the elastic material assumptions would interject a large margin of error into the design procedure.

In another study, Arjomandi and Taheri (2011) conducted a set of comprehensive numerical FE parametric studies to investigate the behavior of SPs under hydrostatic external pressure considering the material and geometrical nonlinearities. They investigated the structural parameters that would have significant influence on the characteristic behavior and also the capacity of the system.