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Collapse analyses of sandwich pipes under external pressure considering inter-layer adhesion behaviour

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ABSTRACT

Sandwich pipes composed of two relatively thin concentric steel pipes and a thick and flexible core in the annulus, are viewed as a significant potential for deepwater and ultra-deepwater applications in oil and gas transportation because they can simultaneously meet mechanical and thermal requirements. This paper presents a collapse capacity prediction of sandwich pipes with various inter-layer adhesion behaviour under external pressure. The solid polypropylene with favourable thermal insulation capacity and high compressive strength is used as the core layer material. The stress-strain curves of the polypropylene material are measured through the uniaxial tension and compression tests. The tests of simple shear specimen and sandwich pipe section specimen are conducted to evaluate the stick-slip levels of epoxy resin and 3M-DP8005 adhesives in two surface conditions of steel pipe, respectively. Then, the dedicated finite element model is developed and an extensive parametric study is conducted to explore the influences of geometric configuration, initial imperfection, material property, and inter-layer adhesion behaviour on the pressure capacity and deformability of sandwich pipes. It is observed that the inter-layer adhesion behaviour has a strong influence on the collapse capacity of sandwich pipes.

1. Introduction

In recent years, the exploration and exploitation of offshore oil-gas resources have moved into deepwater and ultra-deepwater areas to meet the ever increasing demands to hydrocarbons. The conventional single-walled steel pipes usually demand thicker wall to withstand the external hydrostatic pressure at such high depths, which are extremely expensive and difficult to install due to the excessive buoyancy weight. Moreover, the favourable thermal insulation capacity of the pipeline in deepwater low temperature and high pressure ambient environment is required to ensure the flow of the products during the long distance transport. As a result, offshore pipe bundles such as pipe-in-pipe (PIP) and sandwich pipe (SP) have been developed to overcome the shortcomings of the single-walled steel pipe and achieve the flow assurance in deepwater environments.

Pipe-in-pipe systems, consisting of a concentric insulated inner pipe (sometime called product pipe) and a protective outer pipe (sometimes called carrier pipe), are extensively used in offshore pipeline applications in which the thermal insulation of

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Nomenclature

D_1	outer diameter of external pipe
D_2	outer diameter of inner pipe
D_{max}, D_{min}	maximum and minimum outer diameter of steel pipe
E	Young's modulus of steel pipe
E'	strain hardening modulus of steel pipe
E_p	Young's modulus of polypropylene material
n	material strain hardening parameter of the Ramberg-Osgood model
P	external pressure
P_c	collapse pressure
R	mean outer radius of steel pipe
$R(\theta)$	outer radius of steel pipe at angle θ
t	mean wall thickness of steel pipe
$t(\theta)$	wall thickness of steel pipe at angle θ
t_{max}, t_{min}	maximum and minimum wall thickness of steel pipe
t_1	wall thickness of outer pipe
t_2	wall thickness of inner pipe
t_a	thickness of core layer
D_1/t_1	diameter-to-thickness ratio of outer pipe
D_2/t_2	diameter-to-thickness ratio of inner pipe
w_0	initial radial displacement
$\varDelta$	ovality
Δ_0	initial geometric imperfection amplitude, $\Delta_0 = (D_{max} - D_{min})/(D_{max} + D_{min})$
Ξ_0	initial wall thickness eccentricity, $\varXi_0 = (t_{max} - t_{min})/(t_{max} + t_{min})$
ξ_0	distance between the centres of inner and outer circular surfaces
θ	angular coordinate
ν	Poisson's ratio
ε	strain
σ	stress
$\sigma_{0.5}$	API yield stress (stress at a strain of 0.5%)
σ_y	effective yield stress of the Ramberg-Osgood model

the pipeline is necessary to prevent the heat loss from producing paraffin or hydrate and resulting in the blockage of the line. In general, the annular space between two pipes, called the core layer, can be filled with various non-structural insulation materials. The core layer can not only act as a thermal insulation system for the inner pipe, but also be a host for the structural health monitoring systems, cathodic protection systems, and active heating systems. However, for the deepwater applications of PIP systems, the outer pipe must be designed to solely resist the collapse induced by high external pressure, while the design of inner pipe should be able to independently withstand the required high temperature and high pressure of the carrying hydrocarbons inside. Since inner and outer pipes cannot jointly carry the loads, two steel pipes still have to be designed as thicker wall.

Sandwich pipes, composed of two relatively thin concentric steel pipes and a thick and flexible core between two steel pipes, are viewed as a modification of PIP systems in design that combines the inner and outer steel pipes and the core layer into an integrated structure by inter-layer adhesions, as shown in Fig. 1. Thus, the entire sandwich structure is designed to carry the applied loads. In the structural system, the outer pipe is bonded to the core layer to allow the load transfer between the components, and simultaneously separates the ambient environment from the carrying products and plays a secondary protective role in case of oil-gas leaking from the inner pipe. In general, the materials with superior thermal insulation property always possess inferior structural load-carrying capacity. Thus, the choice of an appropriate core layer material should sufficiently consider cost, strength and thermal insulation, which is of prime importance for the design of sandwich structures. To improve the mechanical performance of the structural system and ensure oil-gas product flow the inner pipe is also bonded to the core layer. Although the fabrication of sandwich pipes is comparatively sophisticated, the life cycle costs are evidently advantageous compared to a directly-heated pipeline or massive injection of chemicals.

In deep waters, high external hydrostatic pressure is prone to result in local collapse and consequent buckle propagation of offshore pipelines, which is a dominant governing factor on the design of the pipe structures. Thus, having a good understanding of the structural behaviour of sandwich pipes is a prerequisite for deepwater applications, which may not only promote the reasonable design of composite structure of sandwich pipes, but also improve the practical fabrication and installation techniques. A great number of findings have been achieved in recent years to identify the structural behaviour of