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On collapse of the inner pipe of a pipe-in-pipe system under external pressure

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ABSTRACT

Collapse of the inner pipe of a pipe-in-pipe (PIP) system under external pressure is studied experimentally and numerically herein. Hyperbaric chamber test results of three PIP systems with identical inner pipes and different outer pipes are presented. It is observed that the geometric and material properties of the outer pipe affect the collapse pressure of the inner pipe. Using validated finite element analyses (FEA), a parametric study is conducted and collapse mechanisms of PIPs with various combinations of outer and inner pipes with practical range of diameter-to-thickness ratios (*D*/*t*) between 15 and 40 are discussed. Empirical expressions are proposed for the collapse pressure of the inner pipe (P_{ci}), and its upper and lower bounds. The proposed empirical equation for P_{ci}, is shown to agree well with the experimental results of the tested PIPs. Moreover, two distinctive modes of collapse in the inner pipe are identified and discussed.

1. Introduction

Subsea pipe-in-pipe systems are preferred to conventional single-walled pipelines due to their superior thermal insulation performance. The PIP system consists of a concentric inner pipe (also known as the product pipe) and the outer pipe (sometimes called the carrier pipe) [1,2]. The inner pipe is designed to carry the high temperature and high pressure (HT/HP) of the hydrocarbons inside the pipe. The outer pipe protects the system from external pressure and mechanical damage. The annulus (the space between the tubes) is either empty or filled with non-structural insulation material such as foam or water. Pipe-in-pipe systems are exploited in subsea developments, where the carrier pipe is designed to resist high hydrostatic pressures (water depths up to 3000 m) and the inner pipe is designed to transmit hydrocarbons at temperatures as high as 180 °C and internal pressure up to 10 MPa [3]. The HP/HT flow can cause global upheaval [4,5] or lateral [6–8] buckling of the system.

In a single pipeline under external pressure, a local dent or ovalization in the pipe wall can cause a local collapse. The collapse pressure of a single pipeline (P_{cr}), with perfectly circular cross-section can be approximated by the classical expression for buckling of elastic tubes under uniform external pressure [9]:

$$P_{cr} = \frac{2E}{1-\nu^2}\left(\frac{t}{D}\right)^3 \qquad (1)$$

In offshore applications, the pipelines typically have diameter-to-thickness ratios (*D*/*t*) ranging from 15 to 40. It should be noted that, in thick pipes ($15 < D/t < 20$), the collapse mechanism is inelastic, and thus Eq. (1) may not yield accurate results [10–13]. In single pipelines, once the buckle is triggered in the pipe, the pipe cross-section is rapidly transformed into a dog-bone shape. The buckle then travels along the pipeline as long as the external pressure is high enough to sustain propagation. The lowest pressure required to perpetuate the buckle is termed propagation pressure, P_p, which is only a fraction of the collapse pressure. The collapse and propagation of buckling in single pipelines have been extensively investigated using analytical, experimental, and numerical methods. Most notable are the analytical studies by Mesloh et al. [14] and Palmer and Martin [15], the experimental and numerical investigations by Kyriakides and Babcock [16] and Albermani et al. [17], the study of collapse pressure under confined buckling [18], and investigations of interaction between global buckling and propagation buckling of submarine pipelines [19–22].

Unlike single pipelines, collapse mechanisms of PIPs have only been marginally addressed [23–28]. Moreover, these studies have been purely focused on the buckle propagation pressure (P_{p2}) of the PIP systems. The existing knowledge on buckling of single-walled pipelines under external pressure can be used to predict the collapse pressure of the outer pipe of a PIP system. However, as will be discussed later in this paper, the buckling mechanisms of the inner pipe and its collapse pressure (referred to as P_{ci} in this paper) are different from those of a

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Nomenclature

D_o	outer pipe diameter
D_i	inner pipe diameter
D	nominal outside diameter
t_o	wall thickness of the outer pipe
t_i	wall thickness of the inner pipe
E_o	modulus of elasticity of the outer pipe
E_i	modulus of elasticity of the inner pipe
E'_o	tangent modulus of the outer pipe
E'_i	tangent modulus of the inner pipe
σ_{Yo}	yield stress of the outer pipe
σ_{Yi}	yield stress of the inner pipe
ν	Poisson's ratio
P_{cr}	critical collapse pressure of a single pipe
P_{co}	collapse pressure of the outer pipe
P_{ci}	collapse pressure of the inner pipe
P_{ini}	initial pressure at the onset of contact between outer and inner pipes
P_{p2}	propagation pressure of the PIP system
V_o	initial internal volume of the PIP system
ΔV	volume change of the PIP system
Ω_o	ovalization ratio

single pipeline. To the authors' knowledge there is no existing study on collapse of the inner pipe of a PIP system under external pressure.

The current study aims to provide insight on buckling mechanisms and capacity of a non-pressurised inner pipe within a PIP system, following the collapse of the outer pipe under external pressure. In Section 2 experimental results from hyperbaric chamber tests of three PIPs with different outer pipes and identical inner pipes are presented. In Section 3, a parametric study on the collapse pressure of the inner pipe (P_{ci}) is conducted using validated FE analyses, and an empirical expression for P_{ci} is provided. The buckle mechanisms and accuracy of the proposed empirical equation in comparison with the experimental results are discussed in Section 4. The paper is concluded with brief outline of significant outcomes of the study.

2. Collapse of pipe-in-pipe systems under external pressure: Experimental observations and validation of the finite element analysis

2.1. Mechanical properties of the PIPs

Three sets of concentric aluminium (Al-6060-T5) PIP systems with parameters given in Table 1 were selected for the experimental study. To compare the collapse pressures of the inner pipes (P_{ci}) from the three PIPs, identical inner pipes were adopted. The diameter to thickness ratio of outer and inner pipes (D_o/t_o and D_i/t_i), designated by subscript "*o*" and "*i*" for outer and inner pipe respectively, are between 25 and 40 which is the practical range in offshore pipeline application. The stress-strain history of the aluminium tubes were obtained from tensile tests conducted on coupon samples (transverse strips), cut from the tubes and having the full thickness of the wall tube according to AS1391-2007 (R2017) [29]. The stress-strain curve of the 80 × 2 mm aluminium tube is depicted in Fig. 1a. Since the coupon strips cut from the tube are not flattened, the modulus of elasticity obtained from such tensile test may not always be accurate. Thus, the modulus of elasticity of the samples were obtained from compressive tests of stub columns with length equal to the tube diameter (D), as shown in Fig. 1b. According to AS1391-2007 (R2017)) [29], the length of the stub column should be at least equal to $D/4$. The modulus of elasticity (E) of the samples listed in Table 1 were obtained from two compressive stub tests (Fig. 1b) conducted for each D/t. The material tangent modulus of $E' = 1\%$ was adopted for the inner and outer pipes. Previous studies [17,26,30] have shown that the ring squash test is a reliable method to calculate the yield stress in metallic tubes. Therefore, the ring squash test was utilised herein to obtain the yield stress of the samples. The yield stresses were calculated based on results of two ring squash tests (RST) shown in Fig. 2. The ring squash test (RST) [17,26,30] is conducted on a short segment of the pipe specimen compressed between two rigid indenters of the same diameter as the pipe specimen (Fig. 2). The yield stress, σ_Y, is calculated from

$$\sigma_Y = \frac{F_0 D}{2L_{RST}t^2} \tag{2}$$

where F_0 is the RST load shown in Fig. 2 at which the four plastic hinges are developed in the pipe wall. L_{RST} is the length of the RST sample which is 150 mm [26].

2.2. Hyperbaric chamber tests

The experimental study on collapse of PIPs under external pressure is carried out in a specially designed and fabricated hyperbaric chamber shown in Fig. 3a. The chamber has an inner-diameter of 173 mm and a length of 4 m and is rated for working pressure of 20 MPa (2000 m water depth). Three sets of concentric aluminium (Al-6060-T5) PIP systems with parameters given in Table 1 and length of 1.6 m i.e. $L/D_o > 20$, were end-sealed and pressurized inside the hyperbaric chamber. To end-seal the PIP system, thick aluminium discs were glued to the ends, ensuring that the inner and outer pipes were concentric and that the inner pipe was completely sealed from the outer pipe. To

Table 1

Geometric and material parameters of PIP systems tested in the hyperbaric chamber.

ID		D (mm)	t (mm)	D_o/t_o	D_i/t_i	$\frac{D_o/t_o}{D_i/t_i}$	D_i/D_o	t_i/t_o	E (MPa)	E'/E (%)	σ_{Yo} (MPa)	σ_{Yi}/σ_{Yo}
PIP-1	Outer pipe	60	2.0	30.0	25.0	1.20	0.67	0.80	66,680	1.0	139	1.12
	Inner pipe	40	1.6									
PIP-2	Outer pipe	80	2.0	40.0	25.0	1.60	0.50	0.80	66,680	1.0	169	0.93
	Inner pipe	40	1.6									
PIP-3	Outer pipe	80	3.0	26.7	25.0	1.07	0.50	0.53	66,680	1.0	209	0.75
	Inner pipe	40	1.6									