Test Procedures for Investigating the Buckle Propagation of Pipe-in-Pipe Systems

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Abstract. This paper investigates the collapse and propagation of buckling along the length of Pipe-in-Pipe system (PIPs). Experimental study has been performed inside a hyperbaric chamber on buckling of aluminum (Al-6060-T5) PIPs with outer and inner pipe diameter to wall-thickness ratios (D/t) of 30 and 25 respectively. A simple testing method known as Ring Squash Test (RST) is proposed for estimating the propagation buckling pressure of PIPs. Full length hyperbaric chamber and RST results are compared against previously reported empirical equations. It has been shown that the proposed RST is a much expedient test to implement in comparison to hyperbaric chamber test and estimates the propagation pressure of PIPs with reasonable accuracy.

Introduction

Pipe-in-Pipe systems (PIPs) are broadly used in offshore industry where the inner pipe is designed to carry hydrocarbons with high-temperature and high-pressure and the outer pipe resists the collapse due to external hydrostatic pressure. The void between the two pipes is either empty or filled with non-structural insulation materials. Integrity of the system due to collapse of outer pipe because of external pressure and its effect on the inner pipe is an important practical issue. In deep waters the high hydrostatic pressure can initiate the collapse of the pipeline which can rapidly grow along the structure if the pressure is maintained at the propagation pressure P_p. The propagation pressure of single pipelines has been investigated thoroughly using experimental [1-3] and numerical [4, 5] methods; however, only limited research has been conducted on propagation buckling pressure of PIPs. Two empirical equations (Eqs.1&2) are reported for the propagation pressure of the PIPs (P_{p2}). Eq.1 is based on extensive experimental study By Kyriakides [6] and Eq.2 is founded on finite element simulations performed by Gong et al [7].

$$\frac{P_{p2}}{P_p} = 1 + 1.095\left(\frac{\sigma_{Yi}}{\sigma_{Yo}}\right)^{0.4}\left(\frac{D_i}{D_o}\right)\left(\frac{t_i}{t_o}\right)^2 . \tag{1}$$

$$\frac{P_{p2}}{P_p} = 1 + 0.970\left(\frac{\sigma_{Yi}}{\sigma_{Yo}}\right)^{0.8}\left(\frac{D_i}{D_o}\right)^{0.3}\left(\frac{t_i}{t_o}\right)^2 . \tag{2}$$

In Eqs. 1 and 2, σ_Y is the yield stress, D is the pipe diameter, t is the pipe-wall thickness and subscripts o and i correspond to the outer pipe and inner pipe respectively.

In this work, an experimental investigation is conducted in the hyperbaric chamber using 1.6m aluminum PIPs with parameters shown in Table 1. The modulus of elasticity E and strain-hardening modulus $E^{/}$ where calculated from coupon tests; however, the yield stress is calculated from the ring squash test as will be discussed later.

Hyperbaric Chamber Tests

The experimental protocol is comprised of end-sealing concentric PIPs with length 1.6m and pressurizing the PIPs inside the 25MPa hyperbaric chamber as shown in Fig.1. A volume-controlled pressurization with a high pressure pump is used and the pressure is increased until collapse of the system due to external pressure is occurred under quasi-static steady-state conditions. Two valves are connected to each end of the outer pipe and inner pipe. One valve is used for bleeding the pipe while filling it with water. The second valve is used to vent the outer and inner pipes, as well as to collect water from the inner pipe and the gap between the outer and inner pipes during the buckle propagation. The change in volume of outer and inner pipes (ΔV) during the test is calculated by measuring the weight of water exiting from the inner pipe and the cavity between the pipes separately.

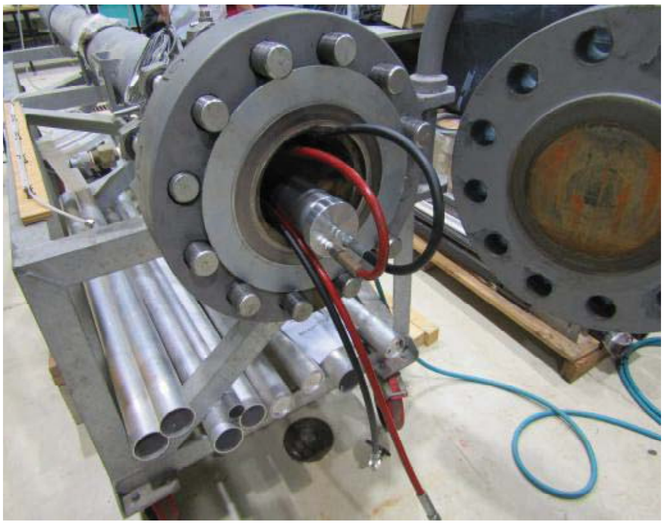


Figure1: The hyperbaric chamber used in the test

Fig.2 shows buckle propagation response of a single pipe (outer pipe). The pressure inside the chamber is plotted against the normalized change in volume of the pipe. The chamber is gradually pressurized until the initiation pressure P_I is reached at which a section of the pipe collapses resulting in drastic drop in chamber's pressure. The pressure is then maintained at the propagation pressure P_p with the dog-bone buckle shape (shown in Fig.1) longitudinally propagating along the length of the pipe.

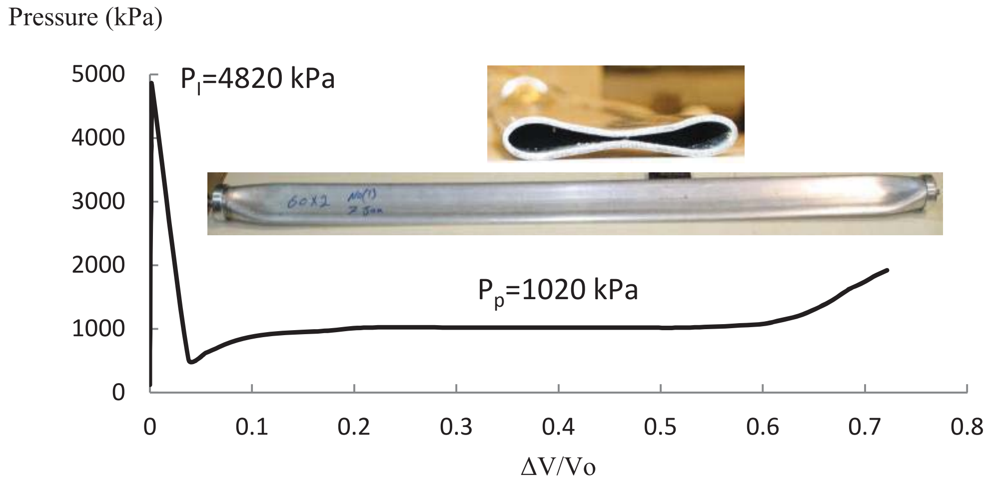


Figure 2: Buckle propagation response of 60×2 mm single pipe in the hyperbaric chamber

The buckle propagation response of the PIPs is shown in Fig.3. The change in pressure of the system is plotted against the normalized change in volume of the inner pipe and outer pipe (the gap between the two pipes). Dog-bone buckle shape similar to that observed in the single pipe was observed in the PIPs chamber tests. The buckle is initiated first (P_{I2}) on the outer pipe, then the energy is released through ovalisation of the outer pipe, until the outer pipe touches the inner pipe. Since the wall-thickness of the outer pipe is greater than that of the inner pipe, the collapse spreads from the outer pipe over the inner pipe and propagates along the length of the PIPs, as predicted in the FE study by Gong et al. [7].

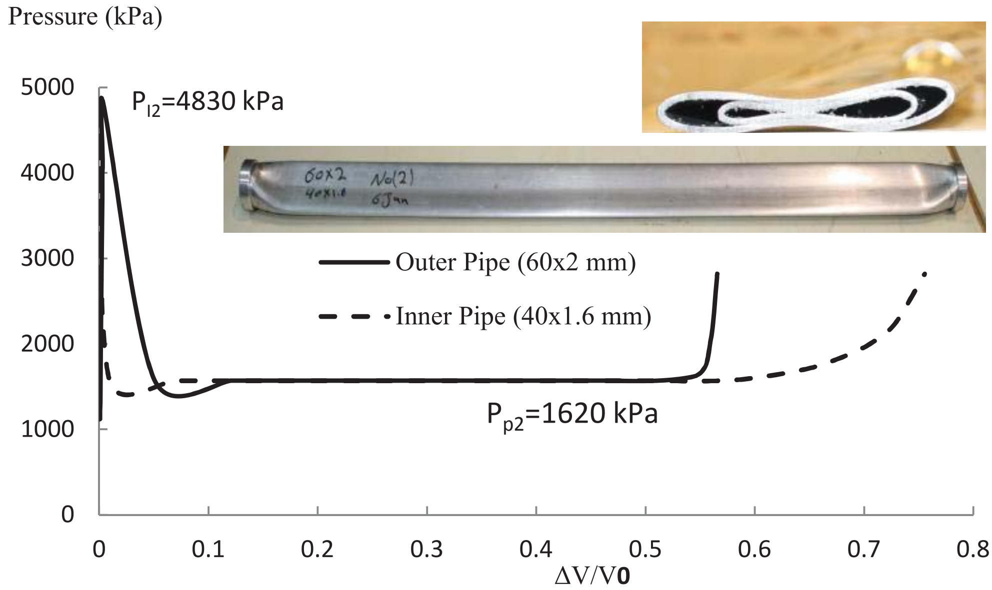


Figure 3: Buckle propagation response of the PIP system in the hyperbaric chamber

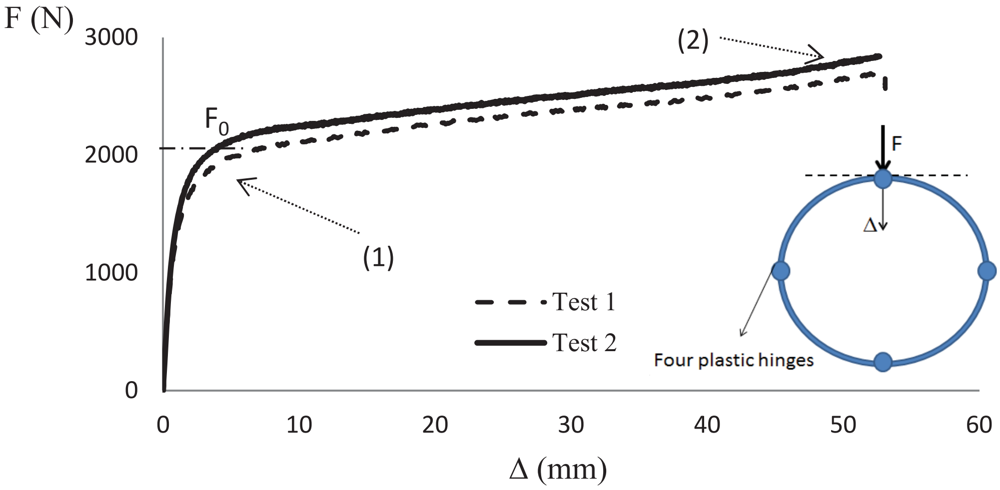
The buckle initiation pressure of the PIPs (P_{I2}) is only affected by mechanical and geometric properties of the outer pipe and is close to P_I of the single pipe shown in Fig.2; however, the propagation pressure of the PIPs (P_{p2}) is significantly higher than P_P of the single pipe.

Ring Squash Tests

Previous studies [1, 8] have shown that the ring squash test (RST) is a satisfactory approach that gives a lower bound estimate of the buckle propagation pressure in single pipelines. The RST is conducted on a ring cut from the pipe specimen in such a way as to produce the actual dog-bone shape of the deformed pipe observed in the hyperbaric chamber. Fig. 4b shows RST set-up for the single pipe (60×2mm). In this test a short segment of the pipe with a length l=150mm (around 2.5D) is squashed (Fig.4b) between two rigid cylinders of the same diameter and length as the pipe being tested in a compression-testing machine. The force (F) required to compress the ring is plotted against the deformation of the pipe right under the load (Δ) in Fig.4a. The total energy dissipated in the RST process can be evaluated by calculating the area under the force-displacement curve in Fig.4a. The pressure (P_{RST}) associated with the energy required for plastic deformation of the ring can be calculated from the following equation:

$$P_{RST} = \frac{U}{l \cdot \Delta A} \quad (3)$$

where ΔA is the difference in area between the original circular shape and the final dog-bone configuration.



(a)

(b) (c)

Figure 4: (a) Ring squash test results, single pipe (60×2 mm), (b) Collapse state 1 and (c) Collapse state 2.

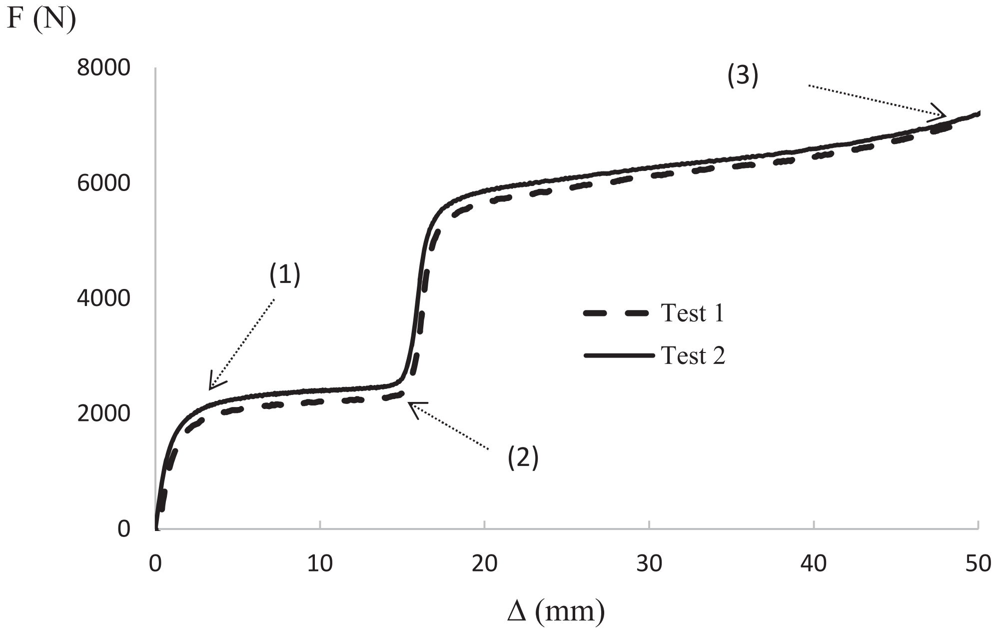
In this work, the RST has been modified to determine the propagation pressure of the PIPs as shown in Fig. 5. Short segments of the outer and inner pipes with lengths of 2.5D_o (l=150mm) are cut from the PIP specimen. The pipes are held concentric during the test by using foam with no structural resistance in the space between the two pipes. The RST results of the PIPs are shown in Fig. 5. The collapse states 1 and 2 correspond to the onset of development of plastic hinges in the outer pipe and inner pipe respectively. At the ultimate collapse state shown in Fig. 5d, four plastic hinges are developed in each of the outer and inner pipes.

Eq. 3 can be used to determine the RST pressure of the pipe-in-pipe system (P_{RST2}). While calculating the propagation pressure of PIPs in Eq.3, ΔA corresponds to the summation of changes in areas of the outer and inner pipes. Based on the average of the results from the two tests shown in Figs 4a and 5a, the propagation pressure of the single pipe and PIPs are calculated as P_{RST}=603 kPa and P_{RST2}=801 kPa respectively.

It should be noted that the ring squash test can be used to determine yield stress σ_Y of the pipe [1, 8] from Eq. 4:

$$\sigma_Y = \frac{F_0 r}{l t^2} \tag{4}$$

where, F_0 is the load level at which four plastic hinges are developed in the pipe-wall (see Fig. 4a).



(a)

(b) (c) (d)

Figure 5: (a) PIPs Ring squash test results (outer pipe 60×2 mm and inner pipe 40×1.6 mm) (b) Collapse state 1, (c) Collapse state 2 and (d) Collapse state 3

Summary

Hyperbaric chamber tests were conducted on pipes with parameters shown in Table 1 and propagation pressures P_p=1020 and P_{p2}=1620 were found for the single pipe and PIPs respectively. Dog-bone deformed buckle shapes were observed in both single and two-pipe systems in the chamber tests. A simple test based on ring collapse mechanism was proposed for PIPs. Using energy balance method, the RST propagation pressures were evaluated. The ratios of the propagation pressure of the PIPs to that of the single outer pipe (P_{p2}/P_p) from hyperbaric chamber tests and RST are shown in Table 1. As expected from previous studies on single pipes, the RST gives a lower bound of propagation pressure of PIPs. Current experimental results are compared against empirical equations (Eq.1 and Eq.2). The effective yield stress calculated from Eq.4 implicitly accounts for the strain hardening response of the material and is thus used in Eqs. 1 and 2 of Table 1. Empirical results agree well with current hyperbaric chamber and RST results.

Table 1. PIPs parameters and propagation pressure results

D_o (mm)	t_o (mm)	D_i (mm)	t_i (mm)	E (MPa)	$E^/$/E (%)	σ_{Yo} (MPa)	σ_{Yi} (MPa)	P_{p2}/P_p Chamber	RST	Eq.1	Eq.2
60	2	40	1.6	69,000	0.97	139	130	1.59	1.33	1.45	1.52

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