Collapse Mechanisms of Pipe-in-pipe Systems under External Pressure during Operation

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ABSTRACT

This study investigates collapse mechanisms of the inner pipe of a pipe-in-pipe (PIP) system under external hydrostatic pressure. It is observed that the geometric and material properties of the outer pipe affect the collapse pressure of the inner pipe ($P_{ci}$). A finite element analysis (FEA) is presented and is validated against the experimental results. Using the validated FEA, a parametric study is conducted. An empirical expression is proposed for $P_{ci}$. Then the collapse mechanisms of the inner pipe during the operation, by incorporating various fractions of the burst pressure in the inner pipe, are studied using the FEA and are compared to the response of PIP with no internal pressure. It was shown that the collapse pressure of the inner pipe when the outer pipe caused a local contact pressure is not significantly affected by the internal pressure.

KEY WORDS: Offshore pipelines; pipe-in-pipe systems; external pressure; shell buckling; collapse; cylindrical tube.

INTRODUCTION

Collapse behaviour of offshore pipelines under external pressure is a primary concern for ultimate limit state design structural integrity. The pipe-in-pipe system, consisting of a concentric insulated inner pipe and outer pipe, has wide applications in offshore pipelines. Under the external hydrostatic pressure, the contact between the inner pipe and the outer pipe may occur. In a PIP system, the outer pipe can collapse when the external hydrostatic pressure becomes very large. Once the outer pipe collapses under external pressure, the inner pipe can support the collapsed outer pipe. However, at a pressure level higher than the propagation pressure of PIP system, the inner pipe collapses at level ($P_{ci}$). Therefore, collapse under external pressure plays a major role in the design of pipelines required to be installed and to operate in deep waters.

For offshore applications, the pipelines typically have diameter-to-thickness ratios ($D/t$) ranging from 15 to 40. The major parameters that affect the collapse pressure ($P_{cr}$) of pipes are the pipe geometry represented by the value of $D/t$, the elasticity modulus and yield stress of the material and geometric imperfections, particularly initial ovality (Yeh and Kyriakides, 1986; Yeh and Kyriakides, 1988; Dyau and Kyriakides, 1993; Park and Kyriakides, 1996). For different combinations of these parameters, the pipe collapse can occur in the elastic or plastic regime of the material (Gong et al. 2013). According to the mechanics of buckling and collapse of long pipes under external pressure, the buckling of thinner pipes is determined by the elastic behavior of the pipe material, and thicker pipes used in deeper water buckle and collapse in the plastic range. The collapse pressure of a thin-walled pipe with linearly elastic material can be derived from the classical method with the following formula (Timoshenko and Gere, 1961)

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

However, the aforementioned classical formula cannot fully reflect the material and geometrical nonlinearities. For pipes which buckle elastically, Timoshenko’s design formula can be used to predict the collapse pressure, but for thick-walled pipes, the main failure modes are plastic buckle and collapse, therefore an updated simplified formula is necessary for the latter case. Fraldi (Fraldi and Guarracino, 2011; Fraldi et al. 2011) refined the Timoshenko method in a series of papers, oriented towards better assessment of collapse pressure of offshore pipelines. The proposed method accounts for the magnitude and shape of the imperfection and for the non-linear elastic–plastic stress–strain relationship through the tangent modulus.

In (Yeh and Kyriakides, 1986), the collapse of long thick-walled single pipes under external pressure is studied both experimentally and analytically. A 2D theoretical model developed to include initial geometric imperfections of the pipe cross section such as initial ovality and wall thickness variation. Subsequently, the effect of interaction between geometric nonlinearities and material nonlinearities due to plasticity has been studied and proposed that the initial ovality can drastically reduce the collapse pressure of the pipe and can be the initiators of buckle propagation (Dyau and Kyriakides, 1993; Park and