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Numerical simulation of the buckle propagation problem in deepwater pipelines

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ABSTRACT

Buckle propagation of local collapse appeared in the damaged pipes is one of the failure modes that are of particular interest for deepwater application. The local collapse can propagate along the pipeline for long distances in both directions when the external pressure magnitude is up to the propagation pressure. In this paper, the numerical simulation on buckle propagation of sandwich pipes (SP) under hydrostatic pressure was conducted based on commercial finite element code ABAQUS. The performance of SP filled with different core materials on the propagation pressure were analyzed in 1500 meters. Based on the simulation results, a conclusion was summarized for buckle propagation pressure of the damaged SP, which can be used as a guidance for the choice of core materials.
Keywords: Sandwich pipes; Finite element method; Buckle propagation; Propagation pressure; Core material

1. INTRODUCTION

In recent years, the increasing demand for oil and natural gas resources has prompted the industry to extend exploration and production to deepwater or ultra-deepwater regions. Pipelines play a very important role in these challenging activities, and are the most efficient and economical means of gathering and transporting oil and natural gas from subsea wells to offshore or coastal storage facilities. To achieve flow assurance in extreme deepwater environment, sandwich pipes (SP),

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combining high structural resistance with thermal insulation capability, have attracted considerable research interest over the last few years.

Propagating collapse and its catastrophic effects were first brought tolight around 1975 by researchers in the offshore pipeline industry. Instability is one of the major factors that limit the extent to which these structures can be loaded or deformed. The most familiar example of structural buckling in tubular structures is the propagating buckle (Kyriakides et al.,2006).

Propagating buckle can be initiated from a locally weakened section of the pipe for instance due to a dent induced by impact by a foreign object, due to a local buckle resulting from excessive bending during installation or due to a wall thickness reduction caused by wear or corrosion. Buckles that initiated can propagate at high velocities and have the potential of quickly destroying the whole line. Occurrence of buckle propagation makes the upper and lower pipe walls come into contact (Talebpour et al.,2006).

The lowest pressure at which such a buckle propagates is the propagation pressure (P_P), a characteristic pressure of the pipe (Kyriakides and Babcock, 1981; Dyau and Kyriakides, 1993b). The propagation pressure is typically only 15-20% of the collapse pressure (P_{CO}) and primarily depends on geometric characteristics and material properties of the pipes. Naturally, buckle and collapse due to external pressure play an important role in the design of such tubular structures. As a result, the design of deepwater pipeline with external pressure loading requires that the collapse and propagation pressures be accurately known.

Based on thin shell theory and small strain approximations, allowing for large deformation, Jensen et al. (1988) first carried out finite element modeling of the buckle propagation of a long circular cylindrical shell subjected to external pressure, and compared the predictions of the propagation pressure using the J_2 flow theory and the J_2deformation theory, respectively. In association with experimental observations and results, Dyau and Kyriakides (1993) applied the Sander's non-linear shell kinematics with small strains and large displacements, and elastic–plastic material behavior through the J_2 flow theory with isotropic strain hardening to establish a three-dimensional finite element model of a long cylindrical shell under external pressure, and studied the parametric dependence of propagation pressure and illustrated the effect of axial tension on the propagation pressure. Subsequently, Kyriakides and Netto (2000) explored the dynamics of propagating buckles in offshore pipelines, and revealed the buckle propagation velocity and the flip–flop mode of buckle propagation in more detail. Pasqualino and Estefen (2001) developed a theoretical explicit formulation for numerical simulation of the buckle propagation in deepwater pipelines, and adopted the finite difference method in combination with the dynamic relaxation technique to solve the equilibrium equations. Xue and Hoo Fatt (2001 and 2005) using the software ABAQUS carried out the steady-state buckle propagation analysis in a corroded pipeline subjected to external pressure. Lately, Albermani et al.

(2011) and Khalilpasha et al. (2013) using ring squash tests and hyperbaric chamber tests investigated the buckle propagation scenarios in subsea pipelines, and illustrated the extent of longitudinal plastic stretching and circumferential plastic bending during buckle propagation.

Furthermore, Karampour et al.(2013) investigated and compared the lateral and upheaval buckling responses of a subsea pipeline, and pointed out that the excessive bending stress induced may trigger the catastrophic propagation buckling failure. Then, Karampour and Albermani (2014) investigated the coupling interaction between propagation buckling and pure bending of pipes through experiments and numerical simulations, the findings showed that the buckle interaction would strongly influence the structural responses of subsea pipelines in deep waters. Based on the extensive numerical simulations and experimental results, Gong et al. (2012) proposed a more reasonable empirical formula of the buckle propagation pressure for offshore pipelines. In addition, Omrani et al. (2013) carried out a numerical study of the dynamic buckle propagation in offshore pipelines under external pressure, and obtained a relation for the buckle propagation velocity as a function of the pressure and diameter to thickness ratio. Moreover, the buckle propagation phenomenon in pipe-in-pipe systems under external pressure was studied in combination with hyperbaric chamber test, uniform ring collapse model, and numerical simulation by Kyriakides et al. (2002,2004 and 2008), which put forth an empirical formula of the buckle propagation pressure for two-pipe systems through the fit of limited test data. Lourenco et al. (2008) applied a non-linear three-dimensional finite element model to conduct an extensive parametric dependence analysis of the quasi-static buckle propagation in SP, and further investigated the actual contribution of the core material to the propagation pressure. Castello et al. (2011) investigated the buckle propagation pressure and the cross-over pressure (P_x, the minimum pressure required to cross the buckle arrestor) of SP filled with polypropylene using both experimental and numerical modeling approaches.

In this paper, a three-dimensional finite element model for the sandwich pipe using the software ABAQUS is developed to model the buckle propagation phenomenon. Subsequently, other SP models with various core materials are developed and buckle propagation pressure for each model is obtained. From these results, the feasibility of these polymer-based core materials are compared and discussed.

2. FINITE ELEMNENT MODELING OF SANDWICH PIPES BUCKLE PROPAGATION

2.1 Finite Element Model

A FORTRAN program is developed to generate the INP file of ABAQUS which conclude the pipe model with initial imperfection. The quasi-static steady-state buckle propagation scenarios in the SP under external pressure is simulated numerically in the framework of ABAQUS.

The characteristics of the developed finite element models are as follows:

a) The SP is discretized into 5 elements through the thickness, 8 elements around the quarter circumference, and 40 elements along the length with three-dimensional, 27-node, quadratic brick elements (C3D27).
b) The geometric properties of SP are assigned as follows:

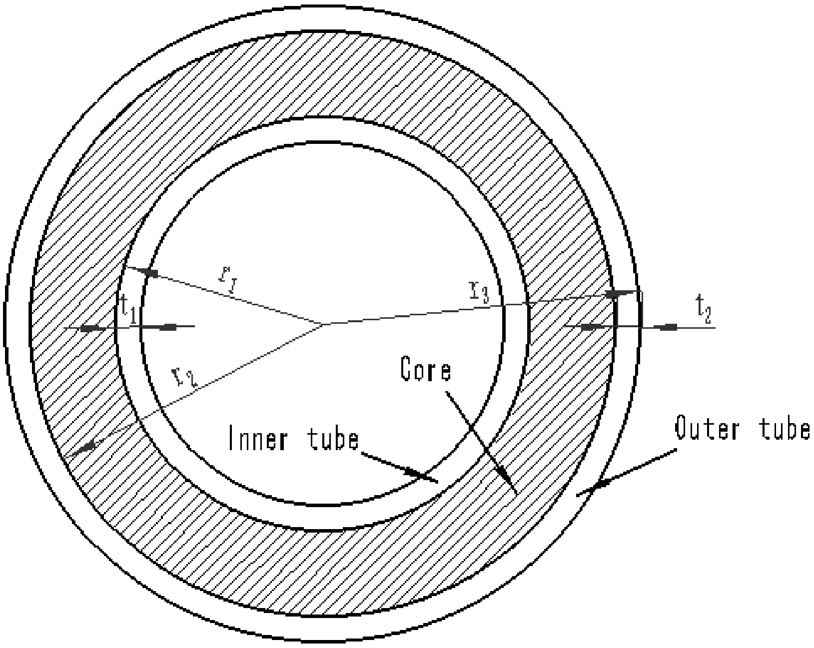

Fig. 1 The geometry of studied sandwich pipe

Table 1 The geometry of studied sandwich pipe

D_n(in)	R_i(mm)	R_e(mm)	t(mm)
8	96.85	109.55	12.7
Annular	109.55	147.65	38.1
12	147.65	161.95	14.3

c) The length of each model is 3500mm (11 times of its diameter). According to the previous studies, for modeling of steady state buckle propagation, the minimum model length must be 10 times of its diameter (Assanelli, 2000).
d) For elimination of bifurcation points, a small imperfection is imposed on the analyzed SP. A buckle propagation is initiated from a local imperfection in the form of ovality in the neighborhood of the symmetry plane Z=0, defined by:

$$W_0(\theta) = -\Delta_0\left(\frac{D}{2}\right)\exp\left[-\beta\left(\frac{x}{D}\right)^2\right]\cos 2\theta \qquad (1)$$

Where $W_0(\theta)$ is the radial displacement, D is the tube diameter, θ is the polar angular coordinate and x is the axial coordinate. The amplitude Δ_0 is chosen to fit the needs of the case to be analyzed and the constant β decides the extent of the imperfection. Fig. 2 shows the applied imperfection on the pipe.

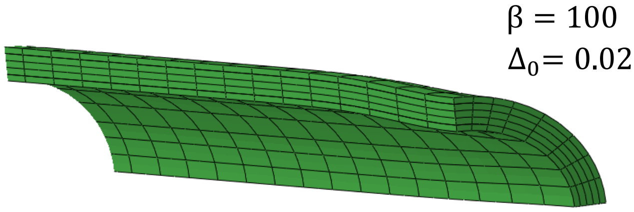

Fig. 2 The applied imperfection on the sandwich pipes

e) The symmetrical boundary conditions are applied at planes x-y and x-z, i.e., in plane x-y, z-direction displacement of the nodes is only constrained, and in plane x-z, y-direction displacement of the nodes is only constrained.

f) In the axial direction, the model is discredited with elements of approximately 0.27D long. In the circumferential direction, the 90° sector is discretized with 8 elements with the following angular spans (starting from the X-Z planeside): 5°-5°-5°-10°-10°-5°-5°-5°. Five elements are used through the thickness. Fig. 3 shows the developed finite element model of the studied pipe.

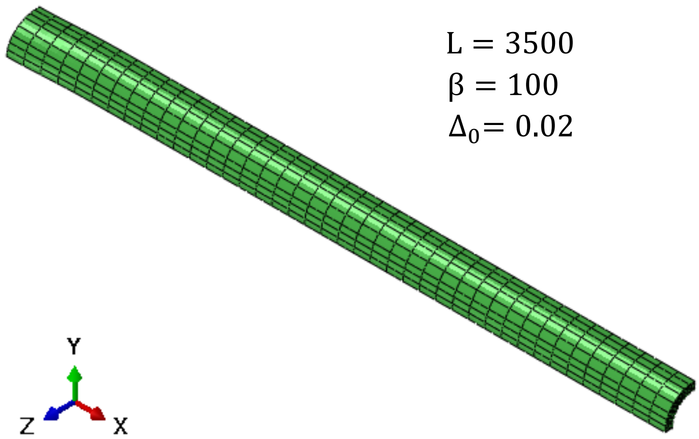

Fig. 3 The finite element model of the studied sandwich pipes

g) The contact element is simulated by using the surface-based contact modeling. This model prevents the nodes that define the inner surface of the tube, from penetrating the planes of symmetry, which are made to be rigid (R3D4).

h) The boundary nodes at Z=L are constrained in the radial and circumferential directions and are free to move in the Z direction. Symmetry conditions are imposed at the nodes at X=0, Y=0 and Z=0.

2.2 Mechanical properties

a) The outer and inner tube worked under 1500 meters water depth are made from X52 and X65 (Venu Rao et al.,2013). The material properties of outer and inner tube are shown in Table 2.

Table 2 The material properties of outer and inner tube

	Material	Yield strength (MPa)	Elastic modulus (GPa)	Poisson's ratio
Outer pipe	X52	386	207	0.3
Inner pipe	X65	448	207	0.3

b) The properties of suitable polymeric core materials for sandwich pipe are shown in Table 3 (Chen An et al., 2013).

Table 3 Properties of suitable polymeric core materials for SP

Material	Density (Kg/m^3)	Yield strength (MPa)	Yield strain (%)	Elastic modulus (MPa)	Thermal conductivity (W/mK)	Tmax* (℃)
SPP	900	23	8.0	1000	0.20	145
PEEK	646	68	4.0	2331	0.18	328
PC	679	44	5.0	1599	0.22	188
ESF	720	22	8.5	1580	0.12	177
HDPF	500	26	9.0	521	0.066	300

*: Maximum service temperature.

2.3 Numerical simulation results

A sequence of deformed configurations of the SP which is calculated by numerically simulating is shown in Fig.4. The initial configuration of the structure is identified by the numbered I. The configuration II represents a pipe of local collapse at the region of imperfections. When the opposite walls of the inner tube come into contact in configuration III, the collapse is arrested locally and the buckle starts to propagate along the downstream pipe. The configuration IV illustrates the profile of buckle propagation of such a pipe, and the area of the pipe wall in contact is seen to have increased. Eventually, as the buckle propagation travels to both ends of the pipe and has to be terminated, the pipe is completely flattened in configuration V.

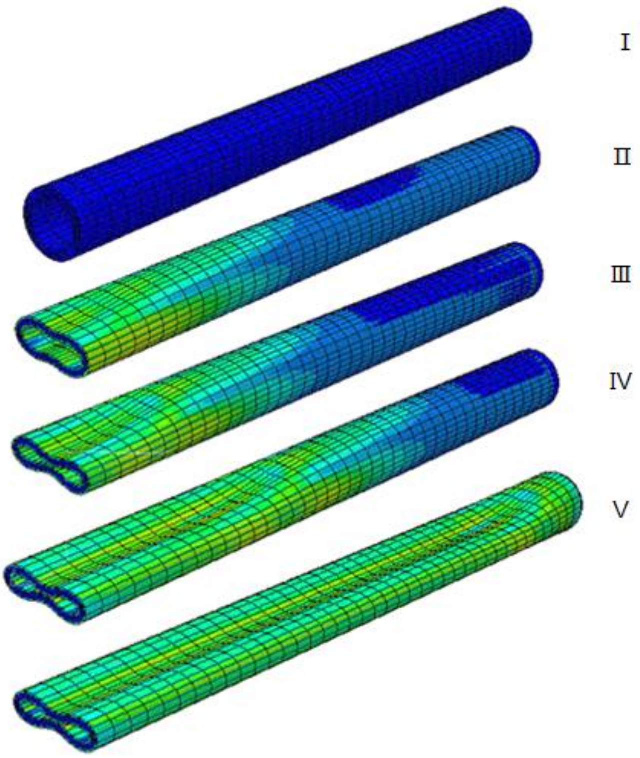

Fig. 4 A sequence of deformed configurations for sandwich pipe

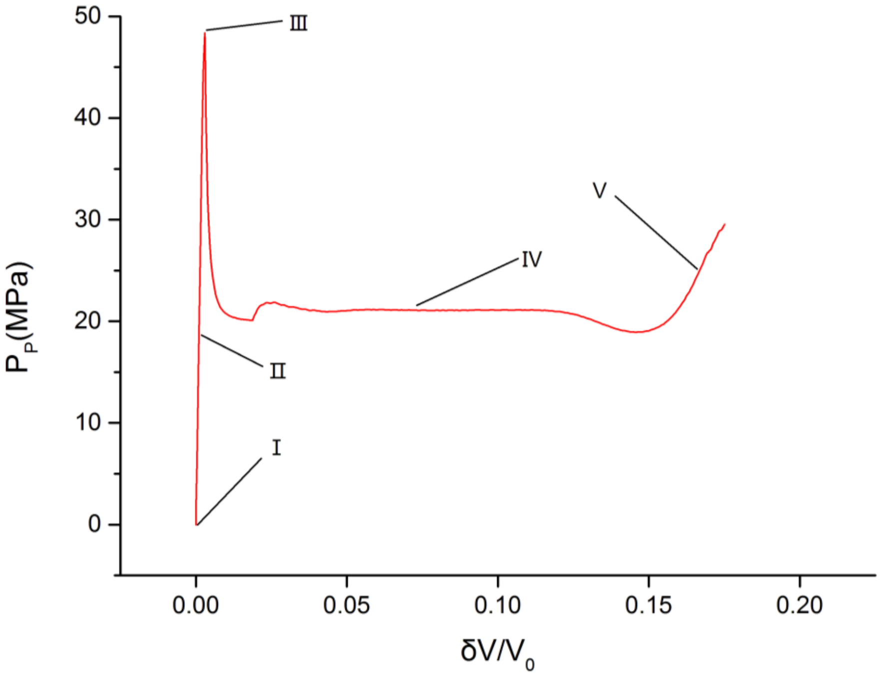

Fig. 5 Pressure–change in volume responses for sandwich pipe

Fig. 5 shows the calculated pressure-change in volume responses for SP (V_0 is the initial internal volume of the tube, and δV is the absolute value of the change of volume evaluated for each deformed configuration). As can be seen in the figure, local collapse of the SP results in a precipitous decrease in pressure, and the subsequent pressure plateau represents steady-state propagation of the buckle. Finally, the end of the SP is engaged by the buckle, the pressure in the closed vessel once again starts rising.

3. THE PROPAGATION PRESSURE OF DIFFERENT CORE MATERIALS

To explore the performance of different core materials on the propagation pressure, the geometry and the outer and inner material properties of the SP are assumed to be identical. We change the core material of SP. The simulation results are shown in Fig.6 and propagation pressures of different core materials are listed in Table 4. Do not leave extra apace between paragraphs.

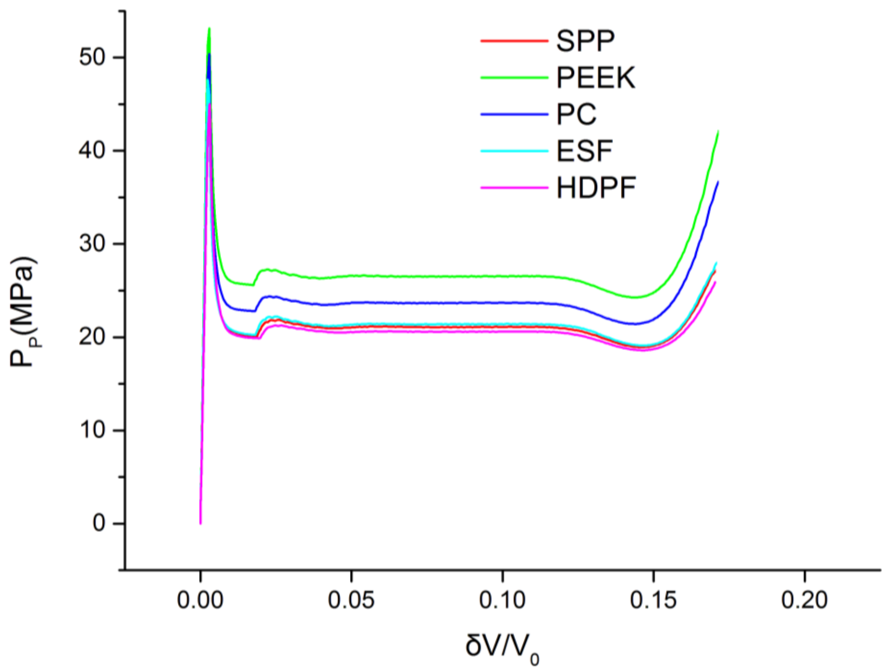

Fig. 6 Pressure–change in volume responses for sandwich pipes

Table 4 Propagation pressures of sandwich pipe for different core materials

Material	P_p(MPa)
SPP	21.14
PEEK	26.51
PC	23.65
ESF	21.40
HDPF	20.62

4. CONCLUSION

This paper presents a propagating buckle prediction of sandwich pipes under external pressure in the quasi-static steady-state conditions. A three-dimensional finite element model for sandwich pipe within the frame of ABAQUS is developed to model the buckle propagation phenomenon. To study the performance of different core materials on the propagation pressure, a series of sandwich pipes with different core materials ranging from SPP to HDPF listed in Table 4 study on the propagation mode and propagation pressure of sandwich pipe is conducted adopting the numerical simulation technique. The following conclusions can be drawn.

(1) From the numerical results, we can see the buckle propagation pressure of sandwich pipes filled with different core materials can be ordered as follows: PEEK>PC>ESF>SPP>HDPF>15MPa. We can see that all the core materials selected in this paper can meet the requirements in 1500 meters.

(2) SPP, with good thermal insulation properties and high compressive strength, has given the most attention as the feasible core material of SP. Besides, considering the relatively low thermal insulation capacity of SP with SPP core, other polymer-based materials with lower thermal conductivity can be employed, such as ESF and HDPF.

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