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Indentation and external pressure on subsea single wall pipe and pipe-in-pipe

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ABSTRACT

A trawl gear impact on an underwater pipeline can create a dent that pushes part of the pipe wall inward. External pressure also tends to push the wall inward. Because of that interaction, an impact under external pressure dents the pipeline more severely than the same impact with no external pressure. The interaction has been investigated as part of a wider study of overtrawlability of pipe-in-pipe systems carried out by the National University of Singapore. The problem is important because the need to protect pipelines against trawl gear impact leads to a requirement to trench medium and small-diameter pipelines. Trenching is costly and a frequent source of delays and disputes, and so it is worthwhile to search for ways to eliminate unnecessary trenching. A finite-element model of denting under external pressure for single wall pipe and pipe-in-pipe using hydrostatic fluid element has been established and verified by comparison against published data and current experiment data. Parametric study of different external pressures shows the effect of external pressure on the denting process. The combinations of the internal pressure, external pressure and indentation are considered. The study shows that when the internal pressure of a dented subsea pipe is decreasing, the possibility of buckle propagation for the single wall pipe is higher than it is for the pipe-in-pipe.

1. Introduction

Pipeline damage caused by trawl gear happens occasionally in some offshore oil fields. Trawl gear is heavy and moving at a low velocity of around 3 m/s. When trawl gear crosses the pipeline, it will impact the pipe first and then pull over it (DNV, 2010).This interaction may give the pipeline a dent and lateral deformation, which can be severe and may have to be repaired. Trenching is one way to protect the pipeline, but it is expensive. In order to eliminate unnecessary costly protection, a correct estimation of the overtrawlability of the pipeline is required, in other words, the accurate relationship of trawl gear force and pipeline deformation is essential in the design process to avoid over-conservative design and keep the pipeline safe.

Research has been carried out to study the indentation issue. De Oliveira et al. (1982) have developed the theory of tube members under lateral concentrated loading, and his work forms the theoretical base of the relationship between the indentation force and dent depth (Eq. 3.5) in DNV-RP-F111 (Mellem et al., 1996). Wierzbicki and Suh (1988) improved the theory by eliminating the approximation of using the square cross section to represent the circular cross section, and gave a simple closed form equation to describe the relationship between the indentation force and dent depth. This equation has been validated against various test data by Palmer and King (2008) and Alexander (2007). Jones and Shen (1992) proposed a different cross section deformed geometry, and based on that they gave a more elaborate theory and equations. Besides purely theoretical work, various experiments have been conducted and semi-empirical equations have been developed. Ellinas and Walker (1983) developed a semi-empirical model for the relationship by inserting a coefficient into an equation based on experiments carried out by Thomas et al. (1976), and this equation has been adapted by Guidelines for Trenching Design of Submarine Pipeline developed by Trevor Jee Associates (1999). However, all these theories or experiments were investigating a pipeline in air, but not in water. Kyriakides and Corona (2007) have pointed out that the pipe with an imperfection (ovality, dent etc.) is much easier to collapse or buckle. Kyriakides (2002) and Kyriakides and Vogler (2002) studied the buckle propagation for pipe-in-pipe systems by both experimental and numerical methods. Park and Kyriakides (1996) has investigated the behaviour of a dented pipe under external pressure using experimental work and FE models. However, this is not the situation in the case of trawl gear impacting

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the pipeline because the impact is taking place under the external pressure when the trawl gear impacting the pipeline, instead of the pipeline being impacted first and then collapsing under external pressure. Extensive experimental and numerical work has been conducted on the denting of pressurised pipe. Denting under external pressure has not been widely studied.

Moreover, an increasing number of pipe-in-pipe systems are used for transportation of oil nowadays because of their significantly better thermal insulation than the single wall pipe system. Pipe-in-pipe consists with an inner pipe, an outer pipe and several spacers. The inner pipe carries the fluid and the outer pipe provides mechanical protection. In between there is an annulus for insulation material, which brings the major advantage for pipe-in-pipe systems that it could achieve high thermal insulation. The outer pipe of pipe-in-pipe is not required to resist internal pressure and can accommodate a greater level of indentation than a single, pressure-containing pipe; therefore relaxed criteria might be possible to apply to the outer pipe over the trawling aspects. However, as the outer pipe is with zero internal pressure or very low pressure, the trawl impact might generate a bigger dent under external pressure, possibly triggering the collapse and propagation. This needs to be investigated.

This paper is based on the situation in the field that the trawl gear impacts the pipeline on the seabed. It develops an FE methodology to analyse the pipeline (both single wall pipe and pipe-in-pipe) under the interaction of the indentation, the internal pressure and the external pressure altogether. This research fills the gap left by denting models with no external pressure, and also shows how an FE model can be used to determine whether a buckle will propagate for single wall pipe and pipe-in-pipe when decreasing the internal pressure.

2. FE modelling methodology and validation

The strategy to develop the FE model of denting with external pressure is first to establish and validate the FE model of pipe indentation and FE model of pipe collapsing under external pressure respectively, and then combine these two FE models. The validation of the FE model of denting is assisted by comparison with the current experimental data, and the validation of the FE model of external pressurising is achieved by comparison with published results, including both numerical results and experiment results.

2.1. FE modelling of denting

Two experiments on pipeline dented by a knife edge indenter were conducted in National University of Singapore, and the indentation FE model is built based on them. The specimens' details are shown in Table 1. They were API grade B pipe, and the material properties obtained from the tensile coupon tests are shown in Fig. 1. Following the nomenclature adopted for the whole experiment programme, the specimens are denoted as SPS4 and PPSB2-nylon. SPS4 is a single wall pipe specimen, and PPSB2-nylon is a pipe-in-pipe specimen with two nylon spacers. They are small scale models of a 14 in. single wall pipe, and a 14 in. outer pipe – 8 in. inner pipe pipe-in-pipe respectively. The outer pipe of PPSB2-nylon is the same as the SPS4. The inner pipe of PPSB2-nylon has smaller diameter, and is supported by two spacers in the outer pipe. Firstly the spacers are installed on the inner pipe, and then the inner pipe with spacers installed is pushed into the outer pipe. The outer diameter of the spacer therefore has to be a little bit smaller than the inner diameter of the outer pipe. The distance between the two spacers is 1.5 m, which is scaled down accordingly to the prototype 14–8 in. pipe-in-pipe, where the spacing is about 2–4 m. For a long pipe-in-pipe, every few metres there is a spacer. In the current experiment, only one section of the pipe-in-pipe is cut out. The section is 1.5 m, about 10 times outer diameter, and contains two spacers at the ends. The boundary condition of the two experiments was simple supported as Fig. 2 shows (Zheng et al., 2012). The pipe was sitting on the saddle support which can rotate freely. The left saddle support was fixed and the right saddle support could freely move sideways.

Table 1
Specimen details.

Specimen	Outer diameter (*D*) (mm)	Thickness (mm)	Yield stress (MPa)	Tensile strength (MPa)
Single wall pipe specimen (SPS4)	168.3	7.11	324	473
Pipe-in-pipe specimen (PPSB2-nylon)				
Outer pipe	168.3	7.11	324	473
Inner pipe	101.6	5.74	276	452

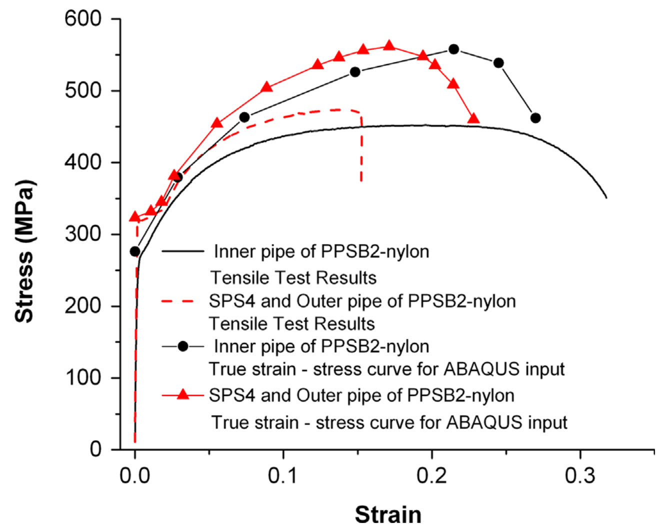

Fig. 1. Tensile test results and FE inputs of SPS4 and PPSB2-nylon.

The FE model is built with the software ABAQUS. Solid elements C3D20R are used to build the pipe. The knife edge indenter and the saddle supports are all idealised as rigid bodies. A quarter model instead of a full model is used for computational efficiency as this simplification does not bring much different results. According to different specimens, FE models have been built as shown in Figs. 3 and 4 show. The details of the contact settings are described in Table 2. In the same way as in the experiments, the indenter is moving downwards in the loading phase, and moving back to the original position in the unloading phase. According to the experiments, there were no relative movements between the contact surfaces of the support and the pipe, as well as the contact surfaces of the inner pipe and the spacer; therefore, they are tied together in the finite element model. With this tie setting, the two contact surfaces are fused together.

The comparisons between the experiment results and the FE results are illustrated in Fig. 5. The *x*-axis is the indenter's displacement, which is controlled to move back to 0 mm in the unloading step. The pipe cannot rebound back to the original shape because of the plastic deformation. Therefore, at some point, the indenter is