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Buckling stability of steel strip reinforced thermoplastic pipe subjected to external pressure

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ABSTRACT

Throughout this report, the collapse behaviors of steel strip reinforced thermoplastic pipe (SSRTP) subjected to external pressure are investigated experimentally and numerically. A hyperbaric chamber is utilized to conduct the full-scale laboratorial tests of SSRTP, and the commercial software ABAQUS is used to simulate its collapse behavior. The results obtained from the experiment and the simulations are in good coincidence with each other, which further prove the reliability and accuracy of the proposed finite element model. Also, a simplified estimation is presented to calculate the collapse pressure of SSRTP, which can be regarded as its lower limit value. In addition, a series of parametric studies were performed to investigate the influential factors on the collapse pressure of the pipe, such as the initial imperfection, the geometrical configurations, the friction coefficient between contact surfaces, etc. The relative results may be of interest to the manufacture factory engineers.

1. Introduction

Composite pipes are extensively used in the offshore engineering due to their various structural configurations. A common example is reinforced thermoplastic pipe (RTP), it has stood out for its good characters of corrosion resistance, high pressure resistance, high impact strength, etc. However, because of its low mass density, it may result in on-bottom instability in the installation or during the service. Recently, the steel strip reinforced thermoplastic pipe (SSRTP) is founded to be a better solution to the on-bottom stability problem of RTP in transporting oil/gas in shallow water. The typical configurations of SSRTP are shown in Fig. 1. Generally, the principal components of a SSRTP are: an outer HDPE layer to provide protection from external damage, an even number of helical windings of continuous reinforcement tapes to supply resistance for internal pressure, and an inner HDPE layer to provide leakage-proof and corrosion resistance for the transported materials. Since SSRTP is a relatively new kind of reinforced unbonded pipe, a few amount of research has been done on it. Collapse behavior of offshore pipelines subjected to external pressure is a primary concern for ultimate limit state design criteria of structural integrity [1–2]. Thus, in order to ensure the security and reliability of SSRTP in application, its collapse behavior should be more focused on.

Over the last few decades, many advances have been made in the area of reinforced composite pipes, and a range of researches have been conducted on their mechanical behaviors when subjected to external pressure or combined loads. Bai et al. [3] investigated the collapse of RTP (a kind of bonded flexible pipe whose reinforced layers are made from fiber-reinforced PE composites) under uniform external hydrostatic pressure, and developed a 2D theoretical model, which is extended from the nonlinear ring model initially proposed by Kyriakides and his co-worker [4]. Based on this nonlinear theory, Bai and his team [5–7] did further in-depth research on the buckling behaviors of RTP under different combined loads, and conducted an extensive parametric study of various affecting factors. Formulas of RTP collapse under pure external pressure, pure bending, and combined loads have also been developed. Li and Zheng et al. [8] designed the testing devices for short-term buckling and creep buckling of PSP (plastic pipe reinforced by cross helically wound steel wires), and conducted tests to obtain its buckling behavior. They [9] proposed a theoretical model to investigate the effect of visco-elasticity on the hold pressure through combining a long-term mechanical model of PSP and water state equation. Bai et al. [10] have also done some research on PSP, and developed an equivalent method on the reinforced layer in the theoretical analysis which was verified by FEM

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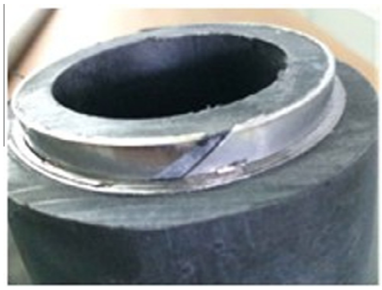

Fig. 1. Cross section of SSRTP.

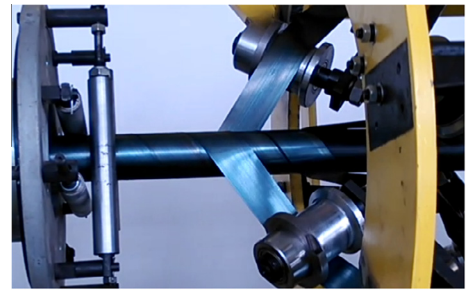

Fig. 2. The wrapping process for steel strip layers.

and experiment, and concluded that the steel wires layer has little effect on the behavior of PSP when subjected to external pressure.

As for unbonded flexible pipes, some numerical simulations focusing on the wet collapse were conducted by Gay Neto et al. [11–12], with the situation that the external sheath happens to be deactivated, and the simulation are only limited to certain pressure armor layers. Meanwhile, they [13] constructed a full 3D model that not only included the internal and external polymeric layer, but also the interlocked carcass and the pressure armor, which can be used as both the wet and dry collapse simulation. Cooke et al. [14] considered the friction between layers through the finite element simulation and drew the conclusion that increasing the friction coefficient can improve collapse integrity. In spite of the great endeavor of the scholars, the mechanical behaviors of the unbonded flexible pipe are still not fully understood. This may be due to the complex response and interaction between multiple layers within the pipe system, which brings great difficulties to the engineering analysis.

Unlike the above composite pipes, a novel reinforced unbonded flexible pipe with wide and broad reinforcement bands, such as the SSRTP is much more complex in the analysis compared with the wires or braids reinforcement layers. Currently, not much research about SSRTP could be found in the published literature. Bai et al. [15] studied the mechanical properties of SSRTP subjected to internal pressure and found that the continuity condition is still applicable in the case of internal pressure. However, there are hardly any research done involving SSRTP subjected to external pressure, and SSRTP will inevitably experience significant ambient pressure during the installation and application. Thus, this topic will be studied here.

In this article, both experimental and numerical approaches are used to investigate the ultimate strength of SSRTP under external pressure. The full-scale laboratorial tests of SSRTP were performed using a hyperbaric chamber, and the finite element model of this pipe was established using the commercial software ABAQUS. Also, a simplified estimation for the buckling pressure of unbonded flexible pipe is further developed here to assess the lower limit value of SSRTP when subjected to external pressure. In addition, extensive parametric analyses were conducted to illustrate the effects of initial imperfections, geometrical configurations and friction coefficient on the collapse pressure of SSRTP. The reported results in this report will provide some reference in the design and practical application of SSRTP.

2. Experiments

The experiment specimens used in this research are produced by Ningbo-OPR industry by means of the helical tape wrapping method, which can be seen from Fig. 2. After winding the reinforcement layers, the papery polyester tapes (PET) are wrapped over the steel strips to protect the outer sheath of PE in case that the steel strip would curl up when subjected to tension or other kind of loads. The manufacturing dimensions of SSRTP and the geometric parameters of the steel strips are listed in Tables 1 and 2.

In this following part, the experimental method used to study the mechanical behavior of SSRTP subjected to external pressure are stated in details.

2.1. Material characteristics

The mechanical characteristics of HDPE and the steel strips used for SSRTP are evaluated through uniaxial tensile tests by the electronic universal testing machine.

Extensometer is applied to conduct the tensile test of the steel strips, which can be seen in Fig. 3. The axial deformation rate is set to be 0.2 mm/min, and the acquired results are shown in Fig. 4. Curve fitting method is used to obtain the elastic modulus E of the steel strip. The fitting result of E and the proportional limit stress are listed in Table 3.

The tensile test of PE is accomplished by using the same testing machine. Before the test, HDPE was made into the dumb-bell shape from the extruded PE tube through compression molding. The physical dimensions of the specimen were in accordance with the standard ISO527-2012 [16]. The loading rate is controlled to be 20 mm/min, and the processed data of the nominal and true stress–strain are illustrated in Fig. 5.

The elastic modulus of HDPE is calculated as the secant modulus when the strain is 0.05% and 0.25% on the basis of the code. The elastic limit stress is defined at the point where the trend of the curve starts to drop in comparison with the pure elastic straight line. The parameters of those two materials used in the latter FEM are shown in Table 3.

2.2. Collapse experiment

The full-scale laboratorial tests of SSRTP are conducted by means of increasing the external pressure at a constant rate to investigate its collapse behavior. The testing equipment includes pressurization system, hyperbaric chamber and automatic record system with the computer. The pressure pump of the pressurization system is controlled by computer to ensure the steady increasing rate. The hyperbaric chamber and its concrete details are shown in Fig. 6. As can be seen from this picture, there are two hoses attached to the cap of the chamber, one is used to inject water and feedback the data of pressures to the computer; the

Table 1
Geometric parameters of inner and outer PE tubes.

PE tube	Inner radius (mm)	Thickness (mm)
Inner PE tube	25	6
Outer PE tube	33	4

Note: The thickness of the PET is quite small compared with the one of outer PE pipe. For simplicity, its thickness is added to the outer sheath in the depiction.