

Structural Health Monitoring of Steel Strip Reinforced Thermoplastic Pipe Under Internal Pressure

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ABSTRACT

This study aims to support structural health monitoring (SHM) of offshore pipelines by characterizing the strain-pressure behavior of steel strip reinforced thermoplastic pipe (SSRTP). An innovative split-ring test method and validated finite element model (FEM) are used to analyze the progressive strain development under internal pressure. The study further explores the influence of interlayer friction and winding angle on the strain response, providing essential insights for accurate SHM interpretation and damage prediction of offshore pipelines. It is found that the friction between layers effectively reduces the hoop strain on the external surface. A large winding angle results in smaller hoop strains.

1 INTRODUCTION

SSRTP is a type of unbonded flexible pipe, belonging to the family of flexible composite pipe (FCP). FCP normally consists of three layers: inner carcass, armor, and outer sheath. The inner carcass is used to transport oil and gas. The armor layer reinforces the mechanical strength during the installation and service life of the pipeline. The outer sheath provides external protection for the pipeline. The inner carcass of FCP is made of thermoplastic materials, which have better resistance against permeability and corrosion. FCP with the steel armor is known as the SSRTP, as shown in Figure 1. The SSRTP of interest has a four-layer reinforced steel armor

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layer. Figure 2 shows the configuration of one of the armor layers. The first and second armor layers are wound at a winding angle (ϕ) of +55 degrees, and the strips in the second armor layer cover the gap left by the first armor layer. A similar configuration is for the third and fourth armor layers except they have a winding angle of -55 degrees.

The SSRTP has been widely used in practical engineering in the oil and gas industry. However, the mechanical behaviors of SSRTP are not widely reported in the literature.

Analytical solutions have been reported in a few studies for SSRTP under internal pressure in the last decade. Xia et al. [1] and Bai et al. [2] developed analytical solutions for SSRTP based on classical lamination theory, assuming idealized elastic, isotropic materials, though they showed discrepancies with experiments due to neglected the nonlinearity of high density polyethylene (HDPE) [3]. Akcay et al. [4] and Bakaiyan et al. [5] proposed 2D and 3D elastic solutions for filament-wound pipes, focusing on stress responses under internal pressure and thermal loading. However, these theoretical studies focused on ultimate capacity rather than the detailed strain behavior needed for SHM of SSRTP.

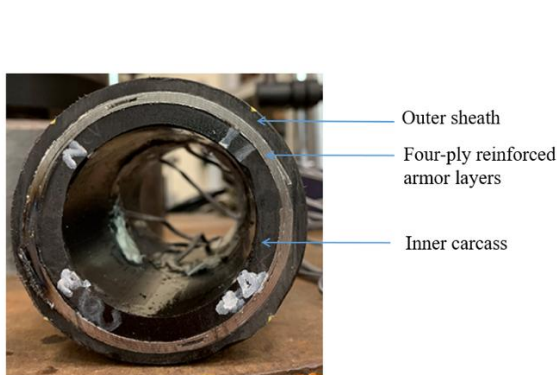


Figure 1 Configuration of SSRTP

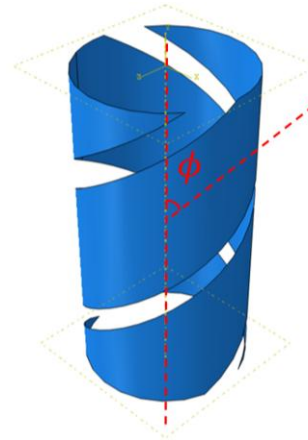


Figure 2 Winding angle of the armor layers in SSRTP

Most studies on composite pipes under internal pressure have focused on burst pressure capacity. Xiong et al. [6], Bai et al. [7], and Gao et al. [8, 9] investigated burst pressure in PSP and SSRTP using numerical, experimental, and analytical approaches, while Qiao et al. [10] applied Knapp's model to RTP under combined loading. However, these numerical and experimental works emphasized capacity prediction without reporting detailed strain-pressure behavior, which is critical for SHM applications.

Existing studies focus on burst pressure, with little focus on progressive strain response. Detailed strain-pressure data for SSRTP under internal pressure remain limited, hindering SHM development. Therefore, this study aims to bridge that gap

by experimentally and numerically characterizing the strain-pressure behavior and its key influencing factors relevant to SHM.

2 EXPERIMENTAL SETUP

Internal pressure tests were conducted at the National University of Singapore using a split-ring setup (Figure 3) to simulate pressure without fluid injection. The lateral force was applied via tapered cylinders (loading rings) to generate uniform internal pressure on short SSRTP specimens. Three pressure sensors were installed 120° apart on the internal surface of SSRTP specimens at midspan, aligned with the centerline of each ring segment to prevent damage from sharp edges. Strain gauges were installed at corresponding positions on the outer surface of the SSRTP specimens to capture hoop strain. A total of three specimens were tested, and their strain-pressure responses are presented in Section 4.

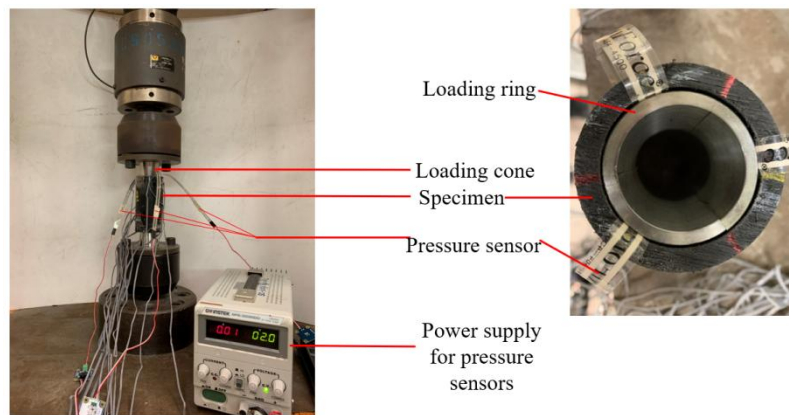


Figure 3 Experimental setup of internal pressure tests

3 FINITE ELEMENT MODELING

A FEM of SSRTP (see Figure 4) was built in ABAQUS/Explicit, featuring an inner carcass, four $\pm 55^\circ$ armor layers, and an outer sheath. C3D8R elements (3 mm mesh) were used for the carcass and sheath, while S4R shell elements (5 mm mesh) modeled the armor layers. General contact with varying friction was applied between layers. To prevent unwanted rotation, four points on both the inner carcass and outer sheath were constrained at 90° intervals in two cross-sections. The model enabled efficient strain extraction to support experimental validation.

Material properties of HDPE and steel were obtained from uni-axial tensile tests on ISO 527-2:2012 specimens using an Instron machine. Key material parameters, provided by OPR company, are summarized as follows. For HDPE, Young's modulus $E_{HDPE} = 1.052$ GPa, yield strength $f_{y,HDPE} = 11.83$ MPa, ultimate

strength $f_{u,HDPE} = 23.48$ MPa. For steel, Young's modulus $E_{Steel} = 191.37$ GPa, yield strength $f_{y,Steel} = 384.65$ MPa, ultimate strength $f_{u,Steel} = 690$ MPa.

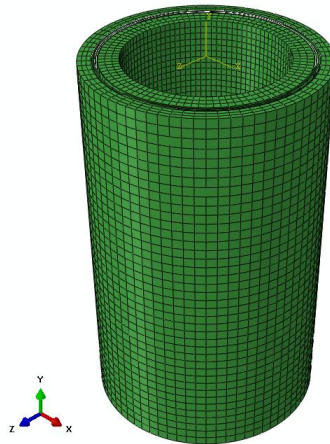


Figure 4 Mesh of the FEM of SSRTTP

4 RESULTS AND DISCUSSION

In this section, experimental results are compared with numerical results and analytical results. The analytical result is obtained by a multi-layered pipe theory [11, 12]. The factors affecting hoop strain-pressure relation are discussed by sequence: friction, and winding angle.

4.1 Experimental results

Figure 5 presents the experimental strain-pressure results, averaged from three circumferential locations on each SSRTTP specimen. Variations among the specimens may be attributed to differences in strip winding, geometric imperfections (e.g., ovality) from cutting a 3 m-long offshore pipeline, and sensor variability. Below 10 MPa, the strain-pressure response is largely linear with minor variation. Above 10 MPa, nonlinearity becomes more pronounced, likely due to yielding in the inner steel armor.

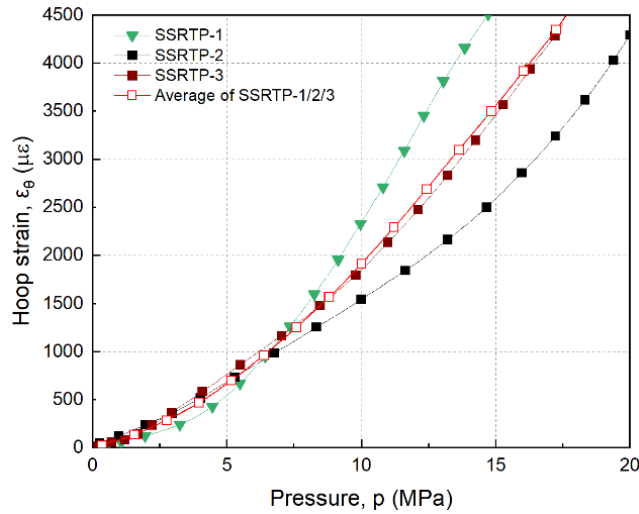


Figure 5 Strain-pressure relation from tests

4.2 Effect of friction on strain-pressure relationship

The influence of interlayer friction on the strain-pressure relationship was investigated through numerical simulations, as direct measurement of the coefficient of friction (COF) is challenging. COF values ranging from 0.1 to 0.5 (in 0.1 increments) were modeled in ABAQUS.

Figure 6 presents the strain-pressure relation when different COFs are applied between interlayers of SSRTP. As shown in Figure 6, higher friction significantly reduces external strain by limiting axial sliding between layers. The analytical model (black dashed line), which assumes fully bonded layers (equivalent to a COF of 1.0), predicts lower strain than both experimental and FEM results. This highlights the limitation of analytical solutions in capturing the relative motion between layers, which is critical in SSRTP behavior under pressure.

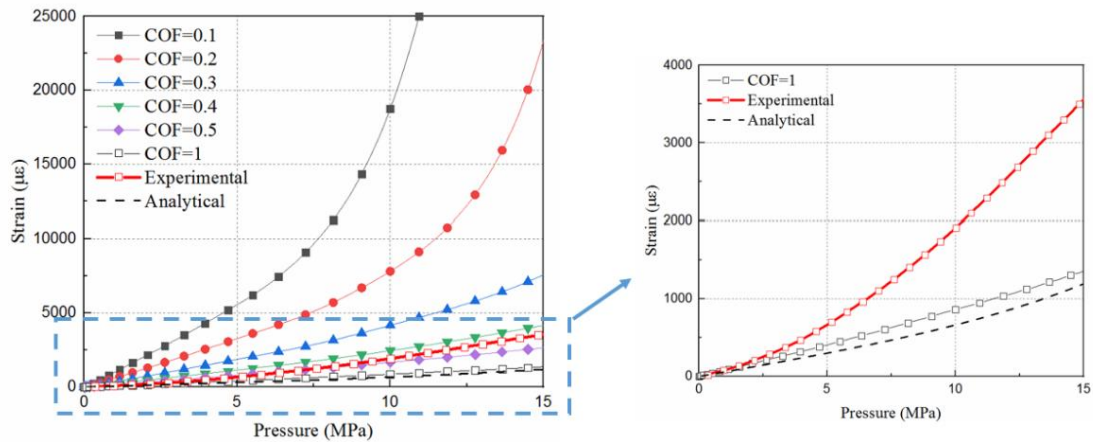


Figure 6 Strain-pressure relations under different COFs

4.3 Effect of winding angle on strain-pressure relationship

To study the influence of winding angle ϕ on the strain-load relation, pipes with different winding angles were modeled in ABAQUS. The steel strips were assigned winding angles ϕ of 45° , 55° and 60° along the pipe axis. The four-ply reinforcement layer and a COF of 0.5 were assumed in all cases. Figure 2 displays the configurations of the armor layer of SS RTP when different winding angles ϕ are adopted in numerical simulations.

Figure 7 shows the strain-pressure relation at mid-span under the internal pressure loading of 0-20 MPa for the different winding angles (45° , 55° , and 60°). As it can be seen, for winding angle ϕ between 45° and 60° , the variation of the strain is relatively small, especially when the pressure is below 10 MPa. The variation starts to increase when the pressure is up to 20 MPa. For the winding angle of 60° , the strain increases slowly as the pressure increases. The reason is that when the winding angle is 60° , the steel layer is more effective in constraining the expansion of the pipe in the hoop direction. As the winding angle increases, the contribution to the hoop stiffness increases, and correspondingly the hoop strain on the external sheath decreases. Similarly, the analytical solution indicates that as the winding angle ϕ increases, axial stiffness contribution decreases while hoop stiffness contribution increases.

In summary, when SS RTP is subjected to internal pressure only, by increasing the winding angle, the tensile properties of steel strips could be more effectively used to withstand internal pressure. As observed from Figure 7, the strains on the outer sheath decrease when the winding angle increases. This means the hoop stiffness of the structure is increasing. The analytical solution ignores slippage between layers. Consequently, the strain on the outer sheath in the analytical solution is less than the strain in the FEM results.

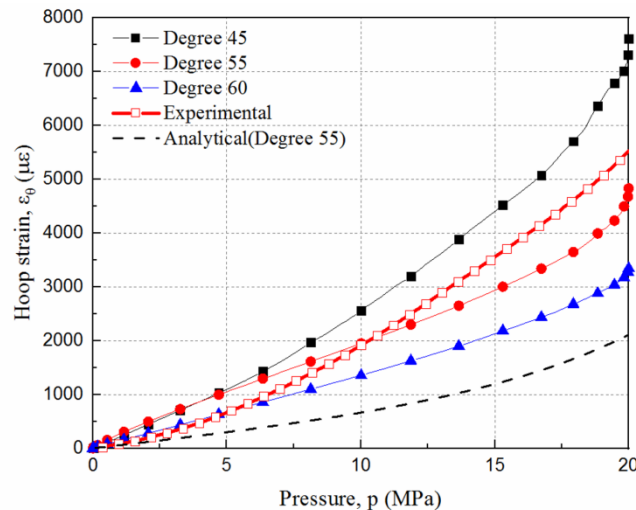


Figure 7 Strain-pressure relations for steel reinforcement layers with different winding angles

5 CONCLUSIONS

This study provides key insights into the strain-pressure behavior of SSRTP under internal pressure, supporting SHM of offshore pipelines. Both experimental and FEM results show that interlayer friction and winding angle significantly influence hoop strain. The findings aid in SHM system design by identifying parameters that affect strain readings and structural response.

A new mechanical way of applying internal pressure on specimens using split rings is designed and proposed. The three-part split ring can provide uniform pressure for experimental purposes. The hoop strain-pressure results were obtained through both experimental and numerical methods. Although the analytical solutions are also calculated, they underpredict both the experimental and numerical results as the relative motions among layers are not considered in the theory.

The factors such as COF and the winding angle ϕ , on the strain-load relation, were investigated. The friction between interlayers is a key factor that cannot be ignored. When a larger COF was assumed, the friction tended to restrict the sliding of steel strips along its winding direction. Consequently, the external hoop strains on the sheath are smaller. The effect of the winding angle ϕ of the armor layers on the outer surface of the sheath was also studied. The strain of the pipe increases rapidly with pressure when the winding angle is low.

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