LIMIT STRENGTH OF SANDWICH PIPES FILLED WITH STRAIN HARDENING CEMENTITIOUS COMPOSITES

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Abstract

Sandwich Pipes (SP) can be an effective solution for the ultra-deepwater submarine pipeline, combining high structural resistance with thermal insulation. Besides polymer, strain hardening cementitious composites (SHCC), a micromechanically designed material with the characteristic of high tensile ductility, can be another choice for the annular material. The purpose of this work is to investigate numerically the limit strength of SP with SHCC under external pressure and longitudinal bending. The mechanical behaviors of SHCC are simulated using a damaged plasticity model whose parameters are estimated by the tension and compression tests. The pressure-curvature \((P-K)\) failure envelopes for SP with unbonded and fully bonded interface conditions are presented. The results show that the interface condition and the thickness of the annulus are the main influence factors on the overall structural behaviour. Besides, the lateral confinement effect caused by the inner and outer tubes and the ultra high ductility of SHCC itself lead to the new observations of the pressure-curvature collapse envelops.

1. INTRODUCTION

SP is a composite structure consisting of two concentric steel tubes and a polymeric or cement-based core, whose structural resistance and thermal insulation performance have been extensively studied due to their application as an effective solution for the ultra-deepwater submarine pipelines and risers [1]. Recently, Castello and Estefen [2] analyzed numerically the ultimate strength of SP filled with solid polypropylene under external pressure and longitudinal bending, estimated the reeling effect on the ultimate strength and observed that the ultimate strength is strongly dependent on the inter-layer adhesion by performing the numerical simulation with a contact surface model. Extending previous work, Castello and Estefen [3] conducted the collapse simulation of three SP employing different annular materials (solid polypropylene, epoxy foam and polyimide foam) and showed that both steel weight and submerged weight are reasonably lighter than a pipe-in-pipe (PIP) system when designed for a hypothetic oil field with specific requirements, such as inner diameter, maximum heat transfer coefficient and water depth. In another study, Castello et al. [4]
investigated the effects of relative ovality direction and temperature-dependent polymer stiffness on the collapse mode. Moreover, Arjomandi and Taheri [5] presented an analytical approach for estimating the elastic buckling capacity of sandwich pipes with different inter-layer bonding configurations under external hydrostatic pressure. Arjomandi and Taheri [6] studied the influence of certain structural parameters on the plastic buckling pressure capacity of sandwich pipelines based on the finite element approach and presented an optimization procedure on the material and geometry of the SP system to minimize a desired cost function. Besides, Su et al. [7] studied the transient heat transfer in sandwich pipelines with active electrical heating and showed that SP with active heating is a viable solution to meet severe flow assurance requirements of ultra-deepwater oil production even under unplanned and prolonged cool-down conditions.

Based on the philosophy of the annular materials selection for SP, viz. low cost materials with high compression strength [1], cement-based material can be also adopted. This double skin sandwich structure was firstly introduced as a new form of construction for deep water vessels to resist external pressure [8, 9], then used for submerged tube highway tunnel [10, 11], legs of offshore platforms [12, 13] and high-rise bridge piers [14]. With the advantages of enhanced global and local stability, lighter weight, good damping characteristics and good cyclic performance [15], a similar concept, concrete-filled double skin steel tubular (CFDST) columns, has been widely investigated for its potential application in building structures [16-19].

Figure 1: Typical stress-strain response and crack pattern of SHCC specimens under monotonic tensile loading [24].

Beginning as early as the 1980s, interest in creating a fiber-reinforced concrete (FRC) material with tensile ductility has been gaining ground [20]. Li et al. [21] analyzed the conditions for steady-state and multiple cracking for a 3-D randomly distributed discontinuous fiber-reinforced composite, known as the fundamental of engineering the cementitious composites with ductile tensile behaviour. Li et al. [22] developed a high-performance polyvinyl alcohol fiber-reinforced engineered cementitious composite (PVA-ECC) for structural applications using the performance-driven design approach, where the effects of fiber surface treatment and sand content on the composite performance were experimentally investigated. As an extension of their work, Li et al. [23] engineered the fiber/matrix interface by applying oil coating to the fiber surface to improve the tensile strain capacity of ECC to 4%. Jun and Mechtcherine [24] addressed the Strain-hardening Cement-based Composites (SHCC) which exhibited strain-hardening, quasi-ductile behavior due to the bridging of fine multiple cracks by short, well-distributed fibres. The favourable
mechanical properties of this material offered many possible applications in new and old structures as well as in the strengthening and repair of structural elements made of reinforced concrete or other traditional materials [25, 26]. It should be noted that, although a large body of literature has been developed around SHCC based on polyvinyl alcohol fiber, commonly referred to as PVA-SHCC, other fibers have been successfully utilized. These include high-modulus polyethylene (PE) fibers [27] and polypropylene (PP) fibers [28].

The characteristic behaviour of SHCC under monotonic tensile loading is shown in Fig. 1 and can be described as follows: Microscopic defects trigger the formation of matrix cracks at so-called first-crack stress $\sigma_1$. As the first crack forms, the fibres bridge the crack, transmitting tensile stresses across the crack surfaces. The applied load must be increased in order to force further crack formation. This leads to the subsequent development of another crack at the second weakest cross-section. The scenario then repeats itself, resulting in a set of almost uniformly distributed cracks. The strain capacity is reached at the maximum load (tensile strength $\sigma_t$) when the localization of the failure occurs, namely when one main crack develops. Due to a moderate opening of a large number of fine cracks, a strain capacity of several percent can be observed.

In this paper, the limit strength of sandwich pipes for combined external pressure and longitudinal bending is studied using a finite element (FE) modeling based on commercial FE package, ABAQUS/Standard 6.9-1 [29]. Strain hardening cementitious composites (SHCC), a micromechanically designed material with the characteristic of high tensile ductility, is proposed herein as the core material. The material properties of SHCC used in the FE modeling are adopted from the compression and tension tests. The mechanical behaviors of SHCC with different fiber content were simulated using a damaged plasticity model whose parameters were estimated by the tension and compression tests. To verify the accuracy of the finite element model in Abaqus, the full-scale models of SP with two different geometries are tested in the pressure vessel and bending apparatus. The pressure-curvature (P-K) failure envelope for SP is presented. Besides, a parametric study was then performed in order to investigate the effect of the thickness of each layer on the pressure-curvature collapse envelopes of the SP.

### 2. FINITE ELEMENT MODELLING

The two different geometrical properties of the sandwich pipes with SHCC are employed in this work, as presented in Table 1, where $D_n$, $t$, $R_i$ and $R_o$ present the nominal diameter, the pipe thickness, the inner and outer radius, respectively. In this section, initial ovality ($\Delta_0 = 0.4\%$) is introduced in the numerical model.

<table>
<thead>
<tr>
<th>Sandwich Pipes</th>
<th>$D_n$ (in)</th>
<th>$R_i$ (mm)</th>
<th>$R_o$ (mm)</th>
<th>$t$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-01</td>
<td>6</td>
<td>74.2</td>
<td>76.2</td>
<td>2</td>
</tr>
<tr>
<td>Annular</td>
<td></td>
<td>84.15</td>
<td>103.15</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>103.15</td>
<td>109.55</td>
<td>2</td>
</tr>
<tr>
<td>SP-02</td>
<td>4</td>
<td>48.8</td>
<td>50.8</td>
<td>2</td>
</tr>
<tr>
<td>Annular</td>
<td></td>
<td>50.8</td>
<td>61.5</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>61.5</td>
<td>63.5</td>
<td>2</td>
</tr>
</tbody>
</table>


2.1 Material characteristics

Stainless steel 304 is used for inner and outer pipes, with yield stress 205 MPa, Poisson coefficient 0.3 and Young modulus 220 GPa, which are data from the company Grupo Elinox. It is modelled by Hooke’s law of elasticity theory and the J2 flow theory of plasticity associated with von Mises yielding criteria and isotropic hardening for the proposed model under combined external pressure and bending loads.

Table 2: Mixture proportions of SHCC [30]

<table>
<thead>
<tr>
<th>Mixture</th>
<th>c</th>
<th>A</th>
<th>cv</th>
<th>w</th>
<th>SP (CC583)</th>
<th>Ratio (c:a:cv:w)</th>
<th>PVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF01</td>
<td>505</td>
<td>404</td>
<td>605</td>
<td>404</td>
<td>15</td>
<td>1:0.8:1.2:0.8</td>
<td>26</td>
</tr>
</tbody>
</table>

The cementitious composite materials, viz., SHCC with PVA fiber volume content of 2%, are made of commercially available materials in Brazil. Mixture proportion for per cubic meter of SHCC is given in Table 2, where ‘c’ is cement, ‘a’ fine sand with maximum grain size equal to 0.212 mm, ‘cv’ fly ash, ‘w’ water and ‘SP’ superplasticizer. The CDP model defined in ABAQUS/Standard 6.9-1 [29] is used to simulate the mechanical properties of SHCC, which represents the inelastic behaviour using the concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity. The stress-strain relationship for the general three-dimensional state is governed by the scalar damage elasticity equation:

\[ \sigma = (1 - d)D^0_{el}; (\epsilon - \epsilon^{pl}) = D^{el}; (\epsilon - \epsilon^{pl}) \]

where \( D^0_{el} \) is the initial elastic stiffness matrix of the material, \( D^{el} \) the degraded elastic stiffness matrix and \( d \) the scalar stiffness degradation variable, varying from zero to one. In terms of effective stress, the yield function takes the form

\[ F = \frac{1}{3} \alpha (\bar{q} - 3 \alpha p + \beta \epsilon^{pl}) (\bar{\sigma}_{\max}) - \gamma (\bar{\sigma}_{\max}) - \bar{\sigma}_t (\bar{\epsilon}^{pl}) = 0 \]

with \( \alpha \) and \( \gamma \) are dimensionless material constants, \( \alpha = \alpha (\sigma_{ut}/\sigma_{co}) \), \( \sigma_{ut}/\sigma_{co} \) the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress, \( \beta = (1 - \alpha) \bar{\sigma}_t (\bar{\epsilon}^{pl}) / \bar{\sigma}_t (\bar{\epsilon}^{pl}) - (1 + \alpha) \), \( \bar{\sigma}_t (\bar{\epsilon}^{pl}) \) the effective tensile cohesion stress, \( \bar{\sigma}_t (\bar{\epsilon}^{pl}) \) the effective compressive cohesion stress, \( \bar{\sigma}_{\max} \) the maximum principal effective stress, \( \bar{\sigma}_t \) the hydrostatic pressure stress, \( \bar{q} = \sqrt{2 \bar{S} : \bar{S}} \) the Mises equivalent effective stress and \( \bar{S} \) the effective stress deviator.

Plastic flow is governed by a flow potential function \( G(\sigma) \) according to nonassociated flow rule \( d\epsilon^{pl} = d\lambda \delta(\sigma) \). The flow potential \( G \) used for the model is the Drucker-Prager hyperbolic function,

\[ G = \sqrt{(\epsilon_{ut} \tan \psi)^2 + \bar{q}^2 - \rho \tan \psi} \]

where \( \psi \) is the dilation angle measured in the \( p - q \) plane at high confining pressure, \( \sigma_{ut} \) the uniaxial tensile stress at failure and \( \epsilon \) is a parameter, referred to as the eccentricity, that defines the rate at which the function approaches the asymptote (the flow potential tends to a straight line as the eccentricity tends to zero). In this work, the dilation angle \( \psi = \frac{\pi}{3} \) is adopted, where \( \phi \) is the internal-friction parameter.

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angle as a critical parameter of the Mohr-Coulomb failure criterion model and can be measured from triaxial compression test.

In ABAQUS/Standard 6.9-1, the stress-strain curves for uniaxial tension and compression are needed to define elastic, plastic and damage behaviours. For simplification, the uniaxial damage variables for tension and compression are neglected, which means that the damage plasticity concrete model is naturally a plasticity concrete model. The experimental stress-strain behaviours of tension and compression, obtained by Magalhaes [30], are shown in Fig. 2. For the ABAQUS input, the simplified data in Fig. 3 are adopted.

For the material definition of SHCC, the Poisson’s ratio $\nu$ is set to 0.2, and the internal-friction angle $\phi$ can be adopted as $37^\circ$. Besides, a small value for the viscosity parameter ($\mu = 0.0001$) is defined to improve the convergence rate in the concrete softening and stiffness degradation regimes, following the suggestion from Barth and Wu [31].
2.2 Element type and mesh generation

The half ring model validated in [1] and [2] is adopted again in this work. ABAQUS C3D8R continuum-brick elements are used for modeling both the steel tubes and the SFRC core, which can be used for linear analysis and for complex nonlinear analyses involving contact, plasticity and large deformations [32]. A standard mesh-sensitivity analysis is carried out for SP-01 considering the effect of the element size on the collapse pressure ($P_{co}$), observing that the results tend to converge for 70 elements in the circumferential direction, one element for each steel layer and six elements for the SHCC annular in the radial direction with lengths (L) of 2 mm, as shown in Fig. 4(a). Similar mesh-sensitivity analyses are carried out for SP-02, obtaining 50 elements in the circumferential direction and three elements for the SHCC annular in the radial direction, as shown in Fig. 4(b).

![Figure 4](image)

(a) (b)

Figure 4: A schematic view of the finite element mesh for (a) SP-01 and (b) SP-02

2.3 Steel tube-SFRC interface

For SP, the adhesion between annulus and steel tubes, which exhibited strong influence on the ultimate strength [1,2], should be carefully examined. Therefore, two layer interface conditions are simulated numerically, including perfect adhesion and no adhesion between steel tubes and SHCC. As proposed by Castello and Estefen [2] and Huang et al. [33], the contact interaction model is applied to the steel tube-SFRC interface, which is defined by a contact pressure model in the normal direction and a Coulomb friction model in the tangential direction. For the unbonded condition, the "Hard Contact" relation with "Allow separation after contact" is selected as normal mechanical property, while the "frictionless" is taken as tangential behaviour, as depicted in Fig. 5b. The fully bonded condition is simulated through the "Hard Contact" relation without "Allow separation after contact" for the normal behaviour and the "Penalty" method for the tangential behaviour, respectively. For the latter case, friction coefficient = 1 and "No limit" for shear stress are set, as presented in [2].

2.4 Load and boundary condition

Ultimate limit strength analysis of SP subjected to external pressure and bending moment independently employs Riks method (the arc-length method) and automatic increment control
3. NUMERICAL EVALUATION

3.1 Numerical analysis of sandwich pipes under external pressure

By simulating the behaviour of sandwich pipes under hydrostatic pressure using ABAQUS/Standard 6.9-1, the collapse pressures \( P_{co} \) of SP-01 with unbonded and fully bonded condition between stainless steel tubes and SHCC are 34.5 and 38.3 MPa, while the ones of SP-02 are 20.2 and 44.4 MPa, respectively. It can be seen that the gap between the \( P_{co} \) of SP-02 with fully bonded condition and the one of SP-02 with unbonded condition is much greater than the gap between those values of SP-01. Note that the thickness of stainless steel tubes for both SP is the same, 2 mm. Compared with the thickness of the annulus for SP-01, the one for SP-02 is smaller, about 46% of the preceding value. When SP-01 is subjected to external pressure, although the fully bonded condition between layers can increase the \( P_{co} \), the \( P_{co} \) is actually dominated by the resistance of annulus. On the other hand, for SP-02 with
unbonded condition, the localized incompatibility between the strain of stainless steel tubes and that of SHCC causes the separation in the normal direction and slippage in the tangential direction of the layers, thus the annulus and the inner tube do not contribute the strength to the overall SP strength as much as their contribution of the case for SP-02 with fully bonded condition. It is worth to note that similar observation on the gaps can be found in the literature accomplished by Estefen at al. [1], where the SP annular was filled with pure cement mortar.

3.2 Numerical analysis of sandwich pipes under combined external pressure and bending

The limit strength analysis is performed for the SP with unbonded or fully bonded condition between stainless steel tubes and SHCC under combined external pressure and bending. The pressure-curvature \((P - K)\) collapse envelopes for the analyzed SP are shown in Fig. 5. Each envelope is described by six points, corresponding to constant pressure of 0%, 20%, 40%, 60%, 80% and 100% of the corresponding collapse pressure \((P_{\text{cr}})\). The results show that the ultimate curvatures for the both SP with fully bonded condition are greater than the ones with unbonded condition, proving that the good adhesion between layers can improve the bending resistance of the structure.

Some unexpected results are obtained for SP-01 with unbonded condition or fully bonded condition and SP-02 with fully bonded condition, the relationship between the pressure and ultimate curvature is not monotonous, which is different from the results reported by Estefen at al. [1]. For all of these three cases, the ultimate curvatures firstly diminish with the increasing of the pressure, then increase to a certain value even higher than that of pure bending, and finally diminish again till the zero value is reached. The phenomenon can be explained by the material modelling of SHCC and the ultra high ductility itself. Remember that the flow potential \(g\) is the Drucker-Prager hyperbolic function, which can describe the lateral confinement effect on stress-strain relation of the cement material, and as a result, when the SP are subjected to the high external pressure, the von Mises stress levels of
annuluses for those cases can reach to a value that are much greater than the one obtained from uniaxial compression test of SHCC. Moreover, the high ductility of SHCC may avoid the annulus being overloaded due to the tension stress caused by bending moment. This behaviour can be further understood as the confined SHCC dominating the overall structural behaviour of the SP, since for SP-01 the thickness of the stainless steel tubes is much smaller than the one of SHCC, and for SP-02 the fully bonded condition improves the contribution of SHCC to the overall structural strength. On the other hand, for SP-02 with unbonded condition the ultimate curvature decreases monotonously with the increasing of the external pressure. The reason is that the unbonded condition weakens the contribution of the annulus to the overall structural strength. In other words, the overall structure presents the characteristics of the stainless steel tubes. The feature of the relatively higher bending resistance for SP filled with SHCC under the high external pressure can be of great benefit to the free span design of the deepwater pipelines, since a much greater free-span length is allowed at the seabed.

4. CONCLUSIONS

SP filled with SHCC are analyzed for ultimate strength under combined external pressure and bending, using a ring section model. To reduce the numerical instabilities due to the detection of cracks using the smeared crack concrete model, the material behaviour of SHCC is modelled by the damage plasticity model in ABAQUS 6.9-1, where the experimental data of the uniaxial compression and tension tests are adopted. The SP with unbonded and fully bonded condition in the interface are analyzed in relation to the collapse pressures and pressure-curvature collapse envelopes. The results show that the interface condition and the thickness of the annulus are the main influence factors on the overall structural behaviour. Besides, the lateral confinement effect caused by the inner and outer tubes and the ultra high ductility of SHCC itself lead to new observed behaviour of the pressure-curvature collapse envelopes. Although the results from numerical simulations give some new understanding of this kind of SP filled with SHCC, experimental studies are needed to verify the numerical models and then confirm the results from the present paper.

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