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Research on Constitutive Equation for Steel Wire Wound Reinforced High-pressure Hose

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Abstract. According to the features of reinforced layer of steel wire wound reinforced high-pressure hose (hereinafter referred to as SRH), 9 classical models for predicting the engineering elastic modulus of reinforced layer of continuous filament reinforced composite material were contrastively analyzed. As a result, Chinese engineering empirical formula should be conformable for predicting the engineering elastic constants of SRH reinforced layer in material normal coordinates. Based on composite microscopic theory and tensor theory, constitutive equation of SRH reinforced layer in structural cylindrical coordinates in three-dimensional case was obtained.

Introduction

Many scholars have made extensive research on filament reinforced plastic pipe (hereinafter referred to as FRP/PVC) from the aspects of static mechanical response, strength failure and structure stability. During the research, first take FRP/PVC as a two-dimensional laminating structure composed of matrix layer and reinforced layer, and then perform the research with plate theory or shell theory.

Steel wire wound reinforced pipe is a new composite pipe, which takes reticulate structure wound with high-tensile steel wires as reinforcement and resin or rubber as matrix. Wherein, steel wire wound reinforced plastic pipe (hereinafter referred to as SRP) is mainly applied in municipal construction. The structure of SRP is similar to that of FRP/PVC, and both of them are low-pressure thin-wall pipe. Therefore, research methods for FRP/PVC are also applicable to SRP.

Steel wire wound reinforced high-pressure hose (hereinafter referred to as SRH) is similar to SRP structurally, however, SRH takes rubber as matrix which is not soluble in organic solution. With its good corrosion resistance and fatigue resistance, SRH is gradually taking the place of traditional steel pipes as undersea oil pipeline. Internal service pressure of undersea oil pipeline is about 16 MPa, therefore, SRH is generally thick-wall composite pipe with 4~6 reinforced layers. Plate theory or shell theory are applicable to low-pressure SRP and FRP/PVC, but not high-pressure thick-wall SRH.

In recent years, research on composite pipe with three-dimensional elastic theory appears. Regarding composite pipe as a thick-wall laminating structure, based on anisotropic three-dimensional elastic theory, Chouchaoui [1], Xia [2,3], Tarn [4] and Bakaiyan [5] made researches on stress-strain response under action of internal pressure, external pressure, axial load or lateral load. During the research, constitutive equation of reinforced layer is a known condition. Although engineering elastic constants of reinforced layer could be determined by test, the microscopic research on quantitative relationship between material properties of matrix phase, reinforced phase, interface phase and macroscopic engineering elastic constants of reinforced layer is still very important. Recently, scholars have put forward some predictive models for predicting two-dimensional engineering elastic constants of reinforced layer of various composite materials. Establishing a predictive model for predicting three-dimensional constitutive equation of SRH reinforced layer is the precondition for mechanical response research of SRH with anisotropic three-dimensional elastic theory. Besides, internal mechanism of SRH property could be obtained through microscopic analysis, which provides theoretical basis for revealing failure mechanism of SRH and optimizing design.

Engineering elastic constants prediction for SRH reinforced layer based on microscopic theory

Two-dimensional engineering elastic constants prediction for SRH reinforced layer. Simplify the SRH reinforced layer to the model in Fig.1 (a) and establish material normal coordinates O*123*, wherein, *1*-axis is the steel wire direction, *2*-axis is the direction perpendicular to steel wire in-plane and *3*-axis is the normal direction of reinforced layer. Take representative volume element from SRH reinforced layer, as shown in Fig.1 (b). Round steel wires (shadow part) are put in rectangle matrix, i.e. outside rectangle-inside round model. Length of this model is half of center distance of steel wire $b/2$ and width is half of thickness of monolayer plate (i.e. steel wire radius R). For reinforced layer wound spirally with steel wire, length of outside rectangle - inside round model could be $b/2=R$.

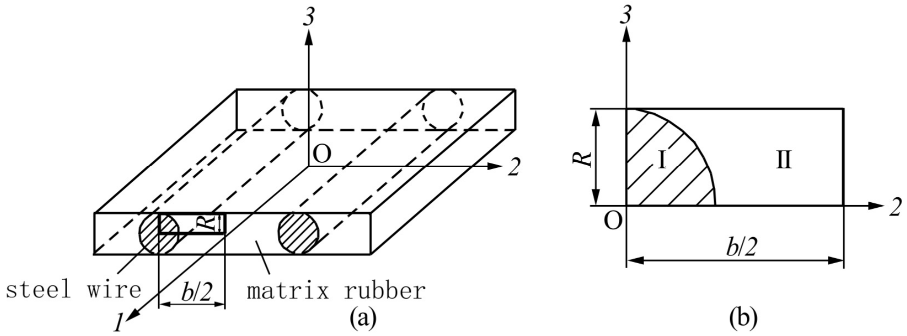


Fig. 1 Representative volume element of SRH reinforced layer

Microscopic analytical methods for composite material mainly include material mechanics method, elasticity mechanics method and semi-empirical method, wherein, material mechanics method and semi-empirical method not only reflect practical situation, but also be easy and practical. At present, scholars have proposed various kinds of two-dimensional predictive models [6-8] for reinforced layer of continuous filament reinforced composite material. Taking 10 inch SRH produced by a Chinese manufacturer as an example, material properties of each component are as follows: elastic modulus of steel wire E_S=2.07×10^{5}Mpa, shear modulus G_S=8.21×10^{4}Mpa, Poisson's ratio ν_S=0.26. Matrix rubber is NBR and CR. As ultimate strain of hyper-elastic material NBR and CR could reach over 3.0, so NBR and CR could be approximatively taken as linear elastic material before SRH is damaged. Initial elastic modulus of NBR and CR E_R=3.0Mpa, shear modulus G_R=1.0Mpa, Poisson's ratio ν_R=0.499. Substitute material properties of each component of SRH into 9 classic predictive models, two-dimensional predictive engineering elastic constants for SRH reinforced layer in material normal coordinates could be obtained, as shown in Table 1.

Table 1 Predictive engineering elastic constants for SRH reinforced layer in normal coordinates

	Longitudinal elastic modulus E_1 [MPa]	Latitudinal elastic modulus E_2 [MPa]	In-plane shear modulus G_{12} [MPa]	Longitudinal Poisson's ratio υ_1
Plate series model	1.63×10^5	13.95	4.65	0.311
Plate parallel model	1.63×10^5	1.63×10^5	6.44×10^4	0.259
Series-parallel connection	1.63×10^5	22.66	7.89	0.290
Rectangle-round parallel model	1.63×10^5	1.32×10^5	5.23×10^4	0.311
Rectangle-round series model	1.63×10^5	1.75×10^3	6.35×10^2	0.311
Uemura-Yamawaki formula	1.63×10^5	4.71×10^4	1.86×10^4	0.296
Tsai-Hahn modifier formula	1.63×10^5	36.33	13.82	0.311
Halpin-Tsai formula	1.63×10^5	35.86	11.95	0.259
Chinese engineering formula	1.63×10^5	4.71×10^4	1.86×10^4	0.295–0.311

Table 1 shows that two-dimensional predictive engineering elastic constants for SRH reinforced layer in material normal coordinates are different from each other by different predictive models. Contrasted with basic mechanics performance testing of SRH [9], Chinese engineering empirical formula should be conformable for predicting the engineering elastic constants of SRH reinforced layer in material normal coordinates, the predictive expression is:

$$\begin{cases} E_1 = E_f v_f + E_m v_m , \quad \upsilon_1 = K(v_f \upsilon_f + v_m \upsilon_m), \\ G_{12} = c(G_f v_f + G_m v_m) + \dfrac{G_f G_m (1-c)}{G_m v_f + G_f v_m}, \quad E_2 = c(E_f v_f + E_m v_m) + \dfrac{E_f E_m (1-c)}{E_m v_f + E_f v_m}. \end{cases} \tag{1}$$

Wherein: E_f and E_m are respectively elastic modulus of filament and matrix. G_f and G_m are respectively shear modulus of filament and matrix. υ_f and υ_m are respectively Poisson's ratio of filament and matrix. v_f and v_m are respectively volume ratio of filament and matrix. K is correction factor of longitudinal Poisson's ratio, experiment research shows that K=0.95~1.0. Factor c is contact coefficient, which is 0~1 and could be determined by test. Besides, through experiment research, Uemura-Yamawaki [7] proposed the empirical formula $c = 0.4v_f - 0.025$, when $0.3 < v_f < 0.7$.

Three-dimensional engineering elastic constants prediction for SRH reinforced layer. When mechanical analysis is made for thick-wall SRH with three-dimensional anisotropic elastic theory, three-dimensional engineering elastic constants of SRH reinforced layer should be predicted.

Take a representative volume element of SRH reinforced layer, as shown in Fig.1 (b), as for reinforced layer wound spirally with steel wires, i.e. $b/2=R$, the compound mode of steel wire and rubber in plane *12* and plane *13* is isomorphic, so elastic modulus in *3*-axis direction is equivalent to that in *2*-axis and shear modulus in plane *13* is equivalent to that in plane *12*, i.e. $E_3 = E_2$, $G_{13} = G_{12}$.

In three-dimensional case, double-subscript expression is adopted for Poisson's ratio. Make υ_{ij} stand for poisson strain in i direction caused by strain in j direction, as the compound mode of steel wire and rubber in plane *12* and plane *13* is isomorphic, we can get $\upsilon_{31} = \upsilon_{21}$ and $\upsilon_{13} = \upsilon_{12}$.

In plane *23*, steel wire is not equivalent to continuous filament. Product of shear modulus G_{12} in plane *12* and coefficient α could be taken as G_{23}, shear modulus in plane *23*, i.e. $G_{23} = \alpha \cdot G_{12}$.

Plane *23* can be regarded as round steel wire inlayed in square matrix rubber, so the material property of SRH reinforced layer in plane *23* is similar to isotropy. As a result, two Poisson's ratio in plane *23* is equal, i.e. $\upsilon_{32} = \upsilon_{23}$. By adopting the same method as above, take the product of Poisson's ratio υ_{21} in plane *12* and coefficient β as the Poisson's ratio in plane *23*, i.e. $\upsilon_{32} = \upsilon_{23} = \beta\upsilon_{21}$.

Because of G_{23} and $\upsilon_{32} = \upsilon_{23}$ being not independent, the coefficient α and β are not independent. Take E_1, E_2=E_3, G_{12}=G_{13}, G_{23} and $\upsilon_1 = \upsilon_{21} = \upsilon_{31}$ as independent engineering elastic constants of transversely isotropic material, the Poisson's ratio $\upsilon_{12} = \upsilon_{13}$ and $\upsilon_{32} = \upsilon_{23}$ can be determined by relevant expression. Meanwhile, according to the fact that the steel wire in directions of *2*-axis and *3*-axis is not totally equivalent to that of continuous filament, the value of Poisson's ratio $\upsilon_{32} = \upsilon_{23}$ should be between $\upsilon_{12} = \upsilon_{13}$ and υ_m, which is the limited condition of finding value of coefficient α. Through static load test of SRH in literature [9], coefficient $\alpha \approx 0.95$ can be determined. To sum up, the predictive formula of three-dimensional engineering elastic constants of SRH reinforced layer in material normal coordinates shall be as follow:

$$\begin{cases} E_2 = E_3 = c(E_f v_f + E_m v_m) + \dfrac{E_f E_m (1-c)}{E_m v_f + E_f v_m} , \quad G_{12} = G_{13} = c(G_f v_f + G_m v_m) + \dfrac{G_f G_m (1-c)}{G_m v_f + G_f v_m} , \\ E_1 = E_f v_f + E_m v_m , \quad G_{23} = \alpha \cdot G_{12} , \\ \upsilon_{21} = \upsilon_{31} = K(\upsilon_f v_f + \upsilon_m v_m) , \quad \upsilon_{12} = \upsilon_{13} = E_2 \cdot \upsilon_{21} / E_1 , \quad \upsilon_{23} = \upsilon_{32} = E_2 / (2G_{23}) - 1 , \\ c = 0.4v_f - 0.025 , \quad K = 0.9 - 1.0 , \quad \alpha \approx 0.95. \end{cases} \tag{2}$$

Constitutive equation of SRH reinforced layer in structural cylindrical coordinates

Establish structural cylindrical coordinates *rθz* of SRH, as shown in Fig. 2 (a), φ is the steel wire wound angle. Take a shell element from SRH reinforced layer and establish material normal coordinates *123* and material off-axis coordinates *xyz*, as shown in Fig. 2 (b).

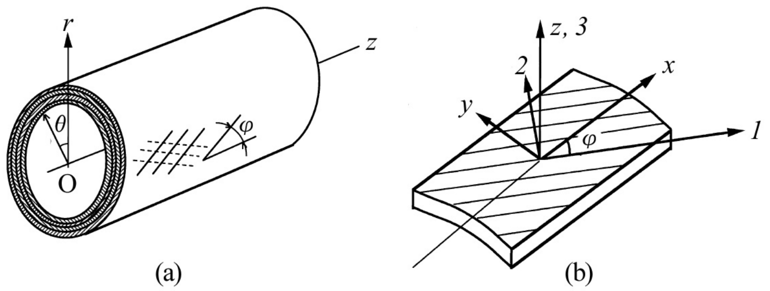


Fig. 2 Structural cylindrical coordinates, material normal coordinates &. off-axis coordinates of SRH

Regard SRH reinforced layer as transversely isotropic material, take E_1, E_2=E_3, G_{12}=G_{13}, G_{23} and $\upsilon_1 = \upsilon_{21} = \upsilon_{31}$ as independent engineering elastic constants, the constitutive flexibility equation of SRH reinforced layer in material normal coordinates shall be as follows:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\upsilon_1/E_1 & -\upsilon_1/E_1 & 0 & 0 & 0 \\ -\upsilon_1/E_1 & 1/E_2 & -\upsilon_1/E_1 & 0 & 0 & 0 \\ -\upsilon_1/E_1 & -\upsilon_1/E_1 & 1/E_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{23} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{bmatrix}, \quad \text{simply as: } \{\varepsilon\} = [S]\{\sigma\}. \tag{3}$$

As shown in Fig. 2 (b), take steel wire wound angle φ of SRH reinforced layer as the direction angle from *x*-axis to *1*-axis, and counterclockwise direction is positive, the stress tensor in material off-axis coordinates and material normal coordinates shall respectively be as follows:

$$\boldsymbol{\sigma} = \bar{\sigma}_{ij}\bar{\boldsymbol{e}}_i\bar{\boldsymbol{e}}_j = \{\bar{\boldsymbol{e}}\}^{\mathrm{T}}[\bar{\sigma}]\{\bar{\boldsymbol{e}}\} = [\bar{\boldsymbol{e}}_1 \quad \bar{\boldsymbol{e}}_2 \quad \bar{\boldsymbol{e}}_3] \begin{bmatrix} \bar{\sigma}_{11} & \bar{\sigma}_{12} & \bar{\sigma}_{13} \\ \bar{\sigma}_{21} & \bar{\sigma}_{22} & \bar{\sigma}_{23} \\ \bar{\sigma}_{31} & \bar{\sigma}_{32} & \bar{\sigma}_{33} \end{bmatrix} \begin{bmatrix} \bar{\boldsymbol{e}}_1 \\ \bar{\boldsymbol{e}}_2 \\ \bar{\boldsymbol{e}}_3 \end{bmatrix}. \tag{4}$$

$$\boldsymbol{\sigma} = \sigma_{ij}\boldsymbol{e}_i\boldsymbol{e}_j = \{\boldsymbol{e}\}^{\mathrm{T}}[\sigma]\{\boldsymbol{e}\} = [\boldsymbol{e}_1 \quad \boldsymbol{e}_2 \quad \boldsymbol{e}_3] \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \begin{bmatrix} \boldsymbol{e}_1 \\ \boldsymbol{e}_2 \\ \boldsymbol{e}_3 \end{bmatrix}. \tag{5}$$

Wherein: $\bar{\boldsymbol{e}}_1$, $\bar{\boldsymbol{e}}_2$, $\bar{\boldsymbol{e}}_3$ and $\boldsymbol{e}_1$, $\boldsymbol{e}_2$, $\boldsymbol{e}_3$ are respectively basis vectors of material off-axis coordinates and normal coordinates, $\bar{\sigma}_{ij}$, σ_{ij} are respectively stress tensor component in these two coordinates.

Basis vectors of two coordinates above can be converted as: $\{\boldsymbol{e}\} = [\beta]\{\bar{\boldsymbol{e}}\}$, and $[\beta]$ is direction cosine matrix. Substitute $\{\boldsymbol{e}\} = [\beta]\{\bar{\boldsymbol{e}}\}$ to Eq. (5), it can be obtained as:

$$\boldsymbol{\sigma} = \{\bar{\boldsymbol{e}}\}^{\mathrm{T}}[\beta]^{\mathrm{T}}[\sigma][\beta]\{\bar{\boldsymbol{e}}\}. \tag{6}$$

Compare Eq. (6) and Eq. (4), and notice $[\beta]^{\mathrm{T}} = [\beta]^{-1}$, it can be obtained as:

$$[\bar{\sigma}] = [\beta]^{\mathrm{T}}[\sigma][\beta] , \qquad [\sigma] = [\beta][\bar{\sigma}][\beta]^{\mathrm{T}}. \tag{7}$$

Substitute direction cosine matrix $[\beta]$ to Eq. (7), and suppose that $m = \cos\varphi$, $n = \sin\varphi$, we can get:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{bmatrix} = \begin{bmatrix} m^2 & n^2 & 0 & 2mn & 0 & 0 \\ n^2 & m^2 & 0 & -2mn & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -mn & mn & 0 & m^2-n^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m & -n \\ 0 & 0 & 0 & 0 & n & m \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix}, \text{ simply as: } \{\sigma\} = [T_\sigma]\{\overline{\sigma}\}. \tag{8}$$

Similarly, the transformation matrix of engineering strain component can be gotten as:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{31} \end{bmatrix} = \begin{bmatrix} m^2 & n^2 & 0 & mn & 0 & 0 \\ n^2 & m^2 & 0 & -mn & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -2mn & 2mn & 0 & m^2-n^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m & -n \\ 0 & 0 & 0 & 0 & n & m \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{bmatrix}, \text{ simply as: } \{\varepsilon\} = [T_\varepsilon]\{\overline{\varepsilon}\}. \tag{9}$$

Substitute Eq. (8) and Eq. (9) to Eq. (3), we can get flexibility matrix of SRH reinforced layer in material off-axis coordinates. Similarly, the rigidity matrix of that can be obtained, as follows:

$$[\overline{S}] = [T_\varepsilon]^{-1}[S][T_\sigma], \quad [\overline{Q}] = [T_\sigma]^{-1}[Q][T_\varepsilon]. \tag{10}$$

The constitutive rigidity equation of SRH reinforced layer in material normal coordinates can be obtained through inversion of Eq. (3), and constitutive rigidity equation of SRH reinforced layer in material off-axis coordinates can be obtained through the second formula of Eq. (10) as:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{13} & \overline{Q}_{14} & 0 & 0 \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{23} & \overline{Q}_{24} & 0 & 0 \\ \overline{Q}_{13} & \overline{Q}_{23} & \overline{Q}_{33} & \overline{Q}_{34} & 0 & 0 \\ \overline{Q}_{14} & \overline{Q}_{24} & \overline{Q}_{34} & \overline{Q}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \overline{Q}_{55} & \overline{Q}_{56} \\ 0 & 0 & 0 & 0 & \overline{Q}_{56} & \overline{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{bmatrix}. \tag{11}$$

Wherein: $\overline{Q}_{ij}$ is the rigidity coefficient of SRH reinforced layer in material off-axis coordinates.

The structural cylindrical coordinates and material off-axis coordinates of SRH have the following congruent relationship: $r \leftrightarrow z$, $\theta \leftrightarrow y$ and $z \leftrightarrow x$. Because the cylindrical coordinates is orthogonal curvilinear coordinates, Lame's coefficient shall be 1 when the basis vectors of θ-axis adopts length measurement unit. As a result, constitutive rigidity equation of SRH reinforced layer in structural cylindrical coordinates can be directly obtained by equation (11):

$$\begin{bmatrix} \sigma_z \\ \sigma_\theta \\ \sigma_r \\ \tau_{z\theta} \\ \tau_{\theta r} \\ \tau_{rz} \end{bmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{13} & \overline{Q}_{14} & 0 & 0 \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{23} & \overline{Q}_{24} & 0 & 0 \\ \overline{Q}_{13} & \overline{Q}_{23} & \overline{Q}_{33} & \overline{Q}_{34} & 0 & 0 \\ \overline{Q}_{14} & \overline{Q}_{24} & \overline{Q}_{34} & \overline{Q}_{44}^{*} & 0 & 0 \\ 0 & 0 & 0 & 0 & \overline{Q}_{55} & \overline{Q}_{56} \\ 0 & 0 & 0 & 0 & \overline{Q}_{56} & \overline{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_z \\ \varepsilon_\theta \\ \varepsilon_r \\ \gamma_{z\theta} \\ \gamma_{\theta r} \\ \gamma_{rz} \end{bmatrix}. \tag{12}$$

Citing Example

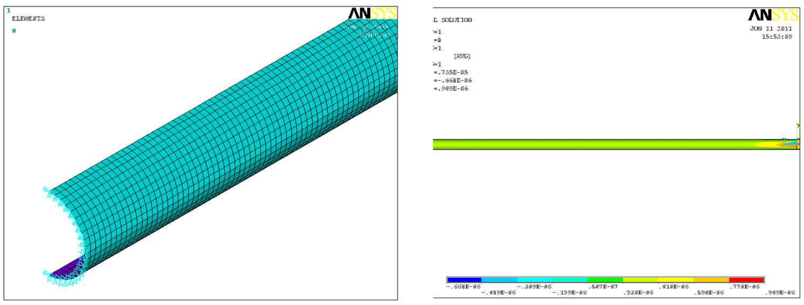
Take10 inch SRH for undersea oil transportation produced by a Chinese manufacturer as an example, the material property of each component is as what mentioned before. Predict elastic constants for SRH reinforced layer in material normal coordinates by Eq. (2), as shown in Table 2.

Table 2 Predictive engineering elastic constants for SRH reinforced layer in material normal coordinates

Longitudinal elastic modulus E_1, [MPa]	1.63×10^5
Latitudinal elastic modulus E_2, Elastic modulus of cross section E_3, [MPa]	4.71×10^4
In-plane shear modulus G_{12}, In-plane shear modulus G_{13}, [MPa]	1.86×10^4
Shear modulus of cross section G_{23}, [MPa]	1.77×10^4
Major in-plane Poisson's ratio, $\upsilon_{21}=\upsilon_{31}$	0.296
Minor in-plane Poisson's ratio, $\upsilon_{12}=\upsilon_{13}$	0.0857
Poisson's ratio of cross section, $\upsilon_{23}=\upsilon_{32}$	0.327

Taking the three-dimensional engineering elastic constants of SRH reinforced layer in material normal coordinates in Table 2 as the known conditions, constitutive equation of SRH reinforced layer in structural cylindrical coordinates can be obtained by present method. Then SRH would be regarded as cylindrical thick-wall shell composed of anisotropic reinforced layer and isotropic matrix layer. Analytical solutions of circumferential deformation of SRH under internal pressure can be obtained by adopting the method proposed in literature [9].

On the basis of Table 2, select shell 46 element taking as anisotropic reinforced layer of SRH, select shell 81 element taking as isotropic rubber layer of SRH, and establish SRH semi-structure FEM model with ANSYS, as shown in Fig. 3(a). Radial displacement nephogram of SRH under internal pressure can be obtained, as shown in Fig. 3 (b).



(a) (b)

Fig. 3 FEM model of SRH &. radial displacement nephogram of SRH

Static load test under internal pressure was performed for 10inch SRH test specimen produced by a Chinese manufacturer, and the test was finished in mechanics laboratory of Dalian University of Technology. Test device and measuring apparatus for radial displacement is as shown in Fig. 4.

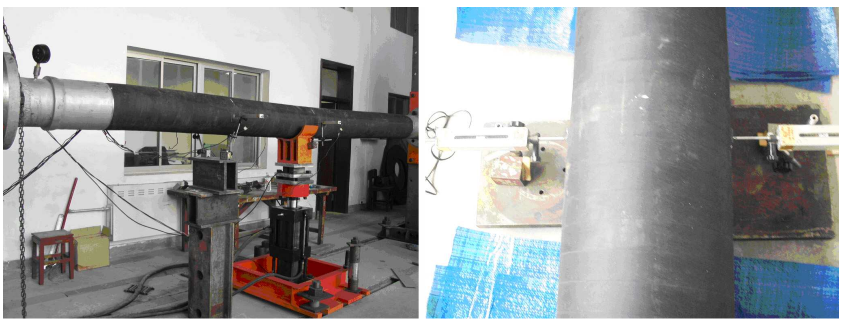


Fig. 4 Static load test device &. measuring apparatus for radial displacement of SRH

Based on the predictive formula of engineering elastic constants and constitutive equation of SRH reinforced layer in structural cylindrical coordinates proposed in this paper, the relation curve of outer diameter increments of SRH vs. internal pressure can be obtained by adopting analytic method in literature [9] and FEM numerical simulation. Compared with internal pressure static test data of SRH, the results show that the method in this paper has certain accuracy, as shown in Fig. 5.

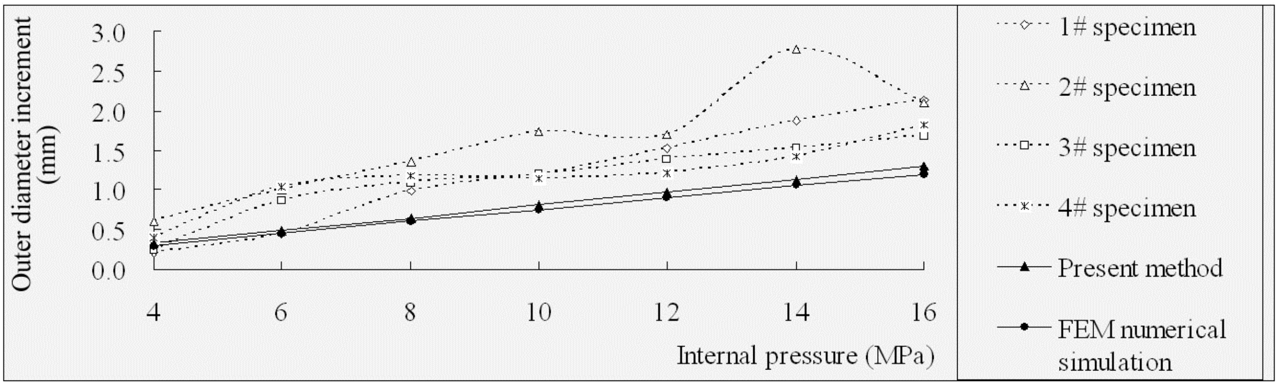


Fig. 5 Outer diameter increments of SRH vs. internal pressure

Conclusions

Combined with SRH micro-structure, based on composite microscopic theory and tensor theory, three-dimensional constitutive equation of SRH reinforced layer in structural cylindrical coordinates was obtained. The results of citing example show that the method in this paper has certain accuracy.

Acknowledgments

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