The mathematical study of compression behaviours of silicone rubber composites reinforced by warp-knitted spacer fabrics

DOI: 10.35530/IT.074.03.2022138

ZHOU ZI-XIANG CHEN SI

ABSTRACT – REZUMAT

The mathematical study of compression behaviours of silicone rubber composites reinforced by warp-knitted spacer fabrics

To synthetically investigate the compressive mechanism of warp knitted spacer fabric reinforced silicone rubber matrix composite (SRWSF) under 20% deformation, a compression meso-mechanics theoretical model was established in this paper. The silicone rubber was processed as isotropic material according to the nonlinear constitutive equation, the spacer yarn was assumed as a continuous uniform element. The compression meso-mechanics theoretical model consists of the mechanical model of silicone rubber and the compression model of warp knitted spacer fabric (WSF), based on the Euler-Bernoulli beam theory and the Spence Invariant constitutive model theory. To verify the feasibility of the compression meso-mechanics theoretical model of SRWSF, the compression test of SRWSF was carried out. The simulated compression stress-strain curve was compared with the results of the experiment. The result shows that the compression theoretical model has a high agreement with the experimental result under 20% strain, as compared with the Polynomial fitting curve. This phenomenon indicates that the compression theoretical model established in this study can reasonably simulate the actual compression behaviours within 20% deformation for SRWSF. Moreover, the theoretical model can help understand the compression mechanism of SRWSF and optimise the designing of silicone-rubber-matrix composite reinforced by WSF for cushioning applications.

Keywords: *warp-knitted spacer fabric, silicone-rubber matrix, compression meso-mechanics model, Euler-Bernoulli beam, Spence Invariant theory*

Studiul matematic al comportamentelor de compresie ale compozitelor din cauciuc siliconic armate cu distanțiere tricotate din urzeală

Pentru a investiga sintetic mecanismul de compresie al compozitului cu matrice de cauciuc siliconic armat cu distanțiere tricotate din urzeală (SRWSF) sub o deformare de 20%, în această lucrare a fost stabilit un model teoretic al mezomecanicii de compresie. Cauciucul siliconic a fost prelucrat ca material izotrop conform ecuației constitutive neliniare, firul distanțier a fost presupus ca un element uniform continuu. Modelul teoretic al mezomecanicii de compresie constă dintr-un modelul mecanic al cauciucului siliconic și modelul de compresie al distanțierului tricotat din urzeală (WSF), bazat pe teoria fasciculului Euler-Bernoulli și teoria modelului constitutiv Spence Invariant. Pentru a verifica fezabilitatea modelului teoretic al mezomecanicii de compresie SRWSF, a fost efectuat testul de compresie SRWSF. Curba simulată de tensiune-deformare sub compresie a fost comparată cu rezultatele experimentului. Rezultatul arată că modelul teoretic de compresie are un grad de conformitate ridicat cu rezultatul experimental sub deformare de 20%, în comparație cu curba de potrivire polinomială. Acest fenomen indică faptul că modelul teoretic de compresie stabilit în acest studiu poate simula în mod rezonabil comportamentele reale de compresie cu o deformare de 20% pentru SRWSF. Mai mult, modelul teoretic poate fi util pentru înțelegerea mecanismului de compresie al SRWSF și optimizarea proiectării compozitului silicon-cauciuc-matrice armat cu WSF pentru aplicații de amortizare.

Cuvinte-cheie*: distanțier tricotat din urzeală, matrice de cauciuc siliconic, model al mezomecanicii de compresie, fascicul Euler-Bernoulli, Teoria Spence Invariant*

INTRODUCTION

Recently, textile fabrics are commonly used as alternative low-cost reinforcement for cushioning applications, due to their special properties like specific modulus, low density and customized development function [1]. However, the fibres are not to be used as the particular structure for the textile, only the knitted fabrics, the woven fabrics and the nonwoven fabrics are used as the unique structure for composites. Warp-knitted spacer fabrics are one of the novel textile materials. Warp-knitted spacer fabrics (WSF) are composed of two separate layers connected by spacer yarns. From this unique construction, the greater ability of compression anti-deformation and rebound elasticity are exhibited for WSF compared with the other textiles. All of these advantages make the warp-knitted spacer fabric have more potential to be used as reinforcement for structural applications.

There have been many types of research on the mechanical features of composites reinforced by WSF [2–8]. In practical engineering, the most concerned problem is to establish a theoretical model to predict composite mechanical properties, rather than only rely on the experiment results. Chen [9, 10] set up a compression meso-mechanics theoretical model of polyurethane-based warp-knitted spacer fabric composite, based on the Winkler elastic foundation beam theory and structure parameters of composite. The compression theoretical model can effectively simulate the actual compressive behaviours of composite. The theoretical model of warp-knitted spacer fabric reinforced syntactic foam was established by Zhi [11], according to the Eshelby-Mori-Tanaka equivalent inclusion method. The theoretical model was suitable for the variation tendency of the compression for samples. The Kelvin-Voigt model was utilized by Mashi [12], and the result showed that 97.7 per cent accuracy existed between the model and the result of the low-velocity impact experiment. It can be concluded from their studies that the processing of the mechanical evolution of composite can be efficiently simulated by the theoretical model. The theoretical model plays an important role and can guide optimizing the designing of composite.

However, in the published study, the mechanical behaviours of silicone-rubber-matrix composite reinforced by warp-knitted spacer fabric were researched only in the experimental phase [13, 14]. The mechanism of silicone-rubber matrix composites reinforced by warp-knitted spacer fabric on the compression behaviours has not been studied, which limits the SRWSF's applications. Therefore, to understand the compression mechanism of SRWSF for achieving governable preparation of SRWSF. It is necessary to analyse the compression processing of SRWSF from a meso-mechanics angle. In this study, two samples of the composite material were prepared with the same processing, and the compression test was conducted on the samples. A compression meso-mechanics theoretical model for SRWSF was established, based on the Euler-Bernoulli beam theory and Spence Invariant constitutive theory. Moreover, the structure parameters of each part of the composite were involved in the model. Additionally, the polynomial curve of the compression experiment of SRWSF was fitted, based on the results of a compressive test of SRWSF. The theoretical model was compared with the polynomial curve and compression experiment of SRWSF to verify the feasibility of the compression meso-mechanics theoretical model of SRWSF. The resulting compression meso-mechanics theoretical model, which was first established in this study, allows for analysing and predicting the compression behaviours of silicone rubber composites reinforced by warp-knitted spacer fabric.

MATERIALS AND METHOD

Material

In this study, the PET monofilament of 0.16 mm in diameter was used as the spacer yarn for warp-knitted spacer fabric. The hexagonal mesh was involved for the surface layer of sample 1. The rhombic mesh was involved for the surface layer of sample 2. The fabric surface was composed of polyester monofilament and the density of polyester is equal to 1.4 g/cm^3. The silicone rubber matrix was made of silicone rubber A and B according to the ratio of 1:1, at room temperature. Then, the warp-knitted spacer fabric was filled with silicone rubber by hand lay-up processing at room temperature for 8 hours. Next, the specimen was placed at room temperature for 24 hours, after vulcanizing. Finally, the composite was generated, which was tested in this study. The production process of composites is shown in figure 1.

The parameters of composites were measured from the two ends and the middle position with a measuring tool whose minimum indexing value is not more than 0.05 mm, along the length and width direction of the sample, and then the average values were computed from the measured parameters. Finally, the chain notations for composites are listed in table 1.

Method

The WSF was characterized for the compression property based on the Chinese standard GB/T 24442.1-2009 (Textile – Determination of compression property – Part 1: Constant method) by using the SHIMADZU Universal testing machine, at a load speed of 4 mm/min in an environment of 23°C and 65% relative humidity. The silicone rubber mechanical experiment was carried out according to the Chinese standard GB/T 528-2009 (Rubber, vulcanized or thermoplastic – Determination of tensile stress-strain properties) by using a SHIMADZU

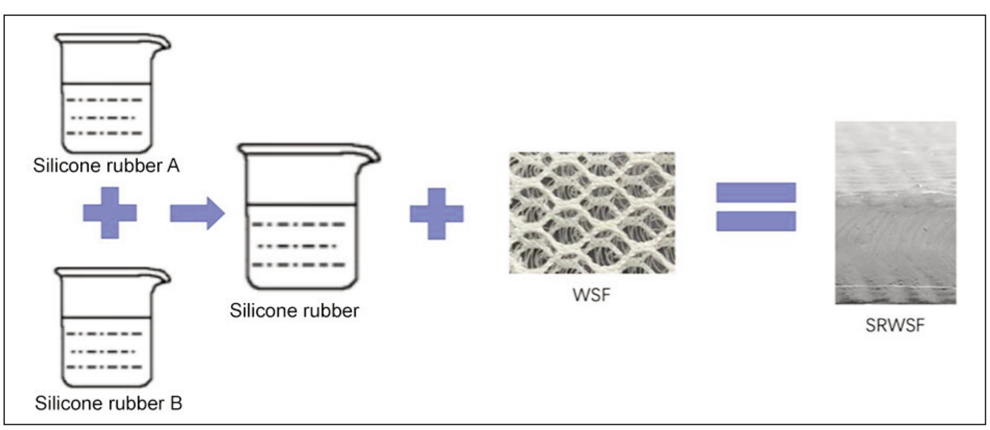


Fig. 1. The production process of composites

Table 1

THE PARAMETERS OF COMPOSITES									
Parameters	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Spacer yarn volume fraction (%)**	**Composite elastic modulus (MPa)**	**Spacer yarn elastic modulus (MPa)**	**Spacer yarn Poisson's ratio**	**Silicone rubber elastic modulus (MPa)**	**Silicone rubber Poisson's ratio**
Sample 1	101.03	49.82	33.12	2.17	0.44	3200	0.22	0.1609	0.47
Sample 2	100.51	49.30	32.97	2.17	0.44	3200	0.22	0.1609	0.47

Table 2

THE VALUE OF THE WSF COMPRESSION EXPERIMENT			
Stress (MPa)	**Strain (%)**	**Stress (MPa)**	**Strain (%)**
0	0	0.02878	19.3929
0.00534	2.7377	0.03015	22.1689
0.01021	5.5140	0.03078	24.9449
0.01523	8.2896	0.03098	27.7209
0.01953	11.0652	0.03069	30.4964
0.02335	13.8412	0.03044	33.2725
0.02648	16.6174	-	-

Table 3

THE VALUE OF SILICONE RUBBER COMPRESSION EXPERIMENT			
Stress (MPa)	**Strain (%)**	**Stress (MPa)**	**Strain (%)**
0	0	1.01397	351.8063
0.14827	48.0562	1.20246	402.4314
0.21235	98.6812	1.36455	453.0562
0.33674	149.3062	1.62213	503.6811
0.45862	199.9314	0.00880	554.3063
0.65966	250.5562	0.02890	604.9313
0.80415	301.1812	-	-

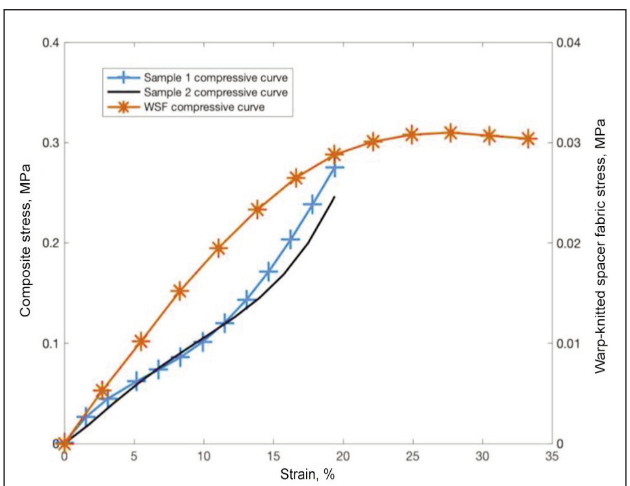


Fig. 2. The stress-strain curve of the compressive experiment

Table 4

THE VALUE OF THE SRWSF COMPRESSION EXPERIMENT			
Stress (MPa)	**Strain (%)**	**Stress (MPa)**	**Strain (%)**
Sample 1			
0	0	0.11008	11.5033
0.01064	1.5564	0.13253	13.0830
0.02945	3.1362	0.16103	14.6624
0.06076	5.1844	0.18959	16.2423
0.08691	6.7642	0.21944	17.8220
0.09661	8.3439	0.25127	19.4016
0.10839	9.9234	-	-
Sample 2			
0	0	0.11222	12.2436
0.01377	1.7529	0.14345	13.9921
0.03468	3.5015	0.17394	15.7405
0.06022	5.2501	0.20604	17.4891
0.08739	6.9985	0.24055	19.2376
0.09638	8.7470	0.24392	19.4015
0.11121	10.4952	-	-

Universal testing machine, at a load speed of 450 mm/min in an environment of 23°C and 65% relative humidity. The SRWSFs were characterized for compression properties based on the Chinese standard GB/T 8171-2008 (Test method for mechanical shock fragility rating of products using packaging cushioning materials) by using the SHIMADZU Universal testing machine, at a load speed of 9 mm/min in an environment of 23°C and 65% relative humidity. The parameters of the compressive experiment of WSF, as shown in table 2. The parameters of the mechanical experiment of silicone rubber, as shown in table 3. The parameters of the compressive experiment of SRWSF, as shown in table 4.
The stress-strain curve of the compressive experiment of SRWSF and WSF is shown in figure 2.

Compression meso-mechanics theoretical modelling

As we know, the composite was composed of reinforcement and matrix materials. The external load was mainly absorbed by the reinforcement materials during the compression processing. Furthermore, the deformation degree of the matrix was limited by reinforcement, due to the elastic modulus of reinforcement being greater than the elastic modulus of the matrix. On the other hand, the load was dispersed by the matrix materials, meanwhile, the reinforcement can be protected with matrix materials.

In this study, the warp-knitted spacer fabric was used as reinforcement which contained the spacer yarns and the fabric layers. The spacer yarns were regarded as a fixed hinge according to the connection method between the spacer yarns and the fabric layers. The shearing stress from the contact of spacer yarns and fabric layers can be ignored due to the small diameter of the spacer monofilament. The fabric layers have a slight deformation during the compression test, resulting in the stress being mainly absorbed by the spacer yarns. It is assumed that the cross-section of spacer yarns is evenly distributed along the axial direction, thus, the spacer yarns can be processed as a continuous homogeneous element. The strength of spacer yarns and silicone rubber are distinct. The silicone rubber has a lower elastic modulus and thermoplastic feature, leading to the result that it can be mixed with the spacer yarns well before vulcanization. The spacer yarns obtain a remarkable agreement deformation with silicone rubber. Meanwhile, the regular support of the side wall for the spacer yarns can be provided from silicone rubber, due to the excellent deformation ability of silicone rubber. Moreover, satisfactory synchronization was exhibited between the spacer yarns and silicone rubber. Thus, the produced composites can be processed as the Euler-Bernoulli beam, which means the shear force between spacer yarns and silicone rubber can be ignored during the compression processing [15]. In this study, the analysis of the deformation of spacer yarns was mainly considered in the compression processing of composites. According to the previous research [16], the geometric model of the axis of spacer yarns was established based on the trajectory of the guide bar used in the warp knitting machine, the schematic diagram of the compression deformation state for WSF, as shown in figure 3. As supposed in figure 3, in the initial configuration, the yarn direction was defined by a unit vector field a_0

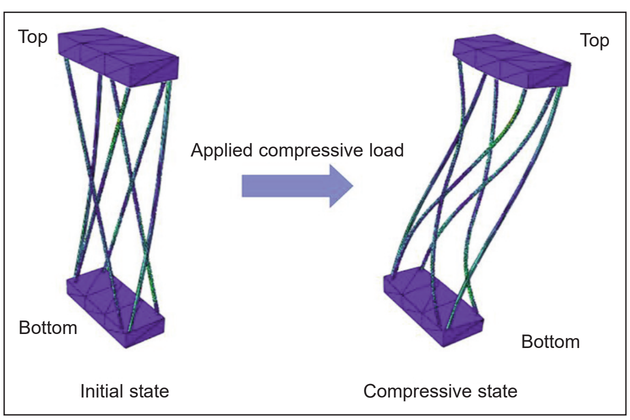


Fig. 3. The schematic of compression deformation of WSF

and it had position vector $\underline{X}$ with components X_R, and the length of yarn is L. In the deformed configuration, the yarn direction may be described by a unit vector field a_i, and the deformed configuration has position vector $\underline{x}$ with coordinates x_i, while the length of yarn is l. The stretch ratio λ can be shown in equation 1:

$$\lambda = l / L \quad (1)$$

The deformation of spacer yarns can be described by equation 2

$$\underline{x} = \underline{x}(\underline{X}) \quad (2)$$

and it follows equation 3:

$$a_i \cdot l = \frac{\delta xi}{\delta XR} \cdot a_R^{(0)} \cdot L \quad (3)$$

Thus:

$$\lambda a = F \cdot a_0 \quad (4)$$

where $a_0 = (\cos\alpha, 0, \sin\alpha)$, α is the angle between spacer yarns and the bottom horizontal plane of the matrix material. It can be calculated based on geometric parameters of spacer yarns that $\sin\alpha$ is equal to 0.882, $\cos\alpha$ is equal to 0.116. F can be expressed by:

$$F = \begin{bmatrix} \delta x1/\delta X1 & \delta x1/\delta X2 & \delta x1/\delta X3 \\ \delta x2/\delta X1 & \delta x2/\delta X2 & \delta x2/\delta X3 \\ \delta x3/\delta X1 & \delta x3/\delta X2 & \delta x3/\delta X3 \end{bmatrix} \quad (5)$$

The deformation of spacer yarns consisted of rotation and compression of spacer yarns. Exactly, the local rotation and completed compression of spacer yarns are absorbed by deformation gradient F. It supposes that the compression was caused first, then the compressed body rotated. The resolution expression of F can be calculated, as shown in equation 6:

$$F = R \cdot U \quad (6)$$

where U is Right extension tensor, R – rotation matrix. However, in the actual deformation, the computing difficulty of the rotation matrix of deformation was tremendous. In this study, supposing the composite was deformed in a material coordinate system to reduce the cost of calculation and ensure the accuracy of the calculation. The rotation matrix can be eliminated by equation 7.

$$F^T \cdot F = (R \cdot U)^T \cdot R \cdot U = U^T \cdot R^T \cdot R \cdot U = \\ = U^T \cdot U = U^2 = C \quad (7)$$

where C is Right Cauchy-Green deformation tensor. The eigenvalues of U are λ_i ($i = 1, 2, 3$), which represent the stretch ratio for X, Y, and Z axis direction respectively. Finally, C can be expressed as:

$$C = \begin{bmatrix} \lambda_1^2 & 0 & 0 \\ 0 & \lambda_2^2 & 0 \\ 0 & 0 & \lambda_3^2 \end{bmatrix} \quad (8)$$

The deformation of spacer yarns in the compression processing can be described by equation 9:

$$\lambda^2 = a_0 \cdot F \cdot F^T \cdot a_0^T = a_0 \cdot C a_0^T \quad (9)$$

From equation 9, the deformation of spacer yarns can be determined by the initial direction of spacer yarns a_0 and the Right Cauchy-Green deformation tensor C.

As a result of the previous analysis, the silicone-rubber-matrix composite reinforced by WSF can be used as one family fibre reinforced composite. Based on the Spence Invariant Theory [17], the invariants I_i ($i = 1, 2, 3, 4, 5$) were utilized in this study to build up the model of the composite under external compressive load, where:

$$I_1 = trC = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{10}$$

$$I_2 = \frac{1}{2}\left[(trC)^2 - trC^2\right] = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_1^2\lambda_3^2 \tag{11}$$

$$I_3 = det\,C = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{12}$$

$$I_4 = a_0 \cdot C \cdot a_0^T \tag{13}$$

$$I_5 = a_0 \cdot C^2 \cdot a_0^T \tag{14}$$

In conclusion, the total strain-energy of the composite can be expressed as $W = W_s + W_f = W(I_1, I_2, I_3, I_4, I_5)$. The strain-energy of isotropy-matrix material absorbed under outward load was represented by $W_s = W(C) = W(I_1, I_2, I_3)$. When the material is an incompressible element, the value of I_3 is equal to 1. Silicone rubber is an isotropic incompressible material, thus the $W_{(C)}$ can be described from Equation (15), which is named the Mooney-Rivlin model:

$$W_{(C)} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{15}$$

Assuming that the function $W_{(C)}$ is continuously differentiable with tensor C, and it followed that:

$$\begin{aligned}\frac{\partial W(C)}{\partial C} &= \sum_{i=1}^{2} \frac{\partial W(C)}{\partial I_i} \cdot \frac{\partial I_i}{\partial C} = \\ &= \frac{\partial W(C)}{\partial I_1} \cdot \frac{\partial I_1}{\partial C} + \frac{\partial W(C)}{\partial I_2} \cdot \frac{\partial I_2}{\partial C}\end{aligned} \tag{16}$$

Among equation 16:

$$\frac{\partial I_1}{\partial C} = \frac{\partial trC}{\partial C} = \boldsymbol{I} \tag{17}$$

$$\frac{\partial I_2}{\partial C} = \frac{1}{2}\left(2trC\boldsymbol{I} - \frac{\partial tr(C^2)}{\partial C}\right) = I_1\boldsymbol{I} - C \tag{18}$$

where $\boldsymbol{I}$ is unit tensor. Second Piola-Kirchhoff stress T can be described by:

$$T = 2\frac{\partial W(C)}{\partial C} \tag{19}$$

The relationship between Second Piola-Kirchhoff stress T and Cauchy stress σ, is shown in equation 20:

$$\sigma = J^{-1} \cdot F \cdot T \cdot F^T \tag{20}$$

Substituting equation 19 into equation 21, it can obtain:

$$\sigma = \frac{1}{J}\left[W_1 \cdot B + W_2 \cdot (I_1 \cdot B - B^2)\right] \tag{21}$$

where B is the Left Cauchy-Green deformation tensor, and the structure of the eigenvalues matrix of B is equal to C. W_i is a partial derivative for the invariant ($I = 1, 2$). J is the rate of volume change. Due to the material being incompressible, the value of J is equal to 1. Supposing the compression direction was the 3 direction, during the compression processing. As a result, $\lambda_3 = \lambda$, $\lambda_1 = \lambda_2 = \lambda^{-1/2}$, $\sigma_3 = \sigma$, $\sigma_1 = \sigma_2 = 0$. The relationship between stress and strain for the matrix can be described by equation 22:

$$\sigma_s = 2\left[C_{10}(\lambda^2 - \lambda^{-1}) + C_{01}(\lambda - \lambda^{-2})\right] \tag{22}$$

The strain-energy absorbed by the reinforced structure from the external pressure was represented by $W_f = W(C, a_0 \otimes a_0^T) = W(I_4, I_5)$. The W_f was connected with the degree of deformation of spacer yarns, thus the polynomial about $(I_4 - 1)$ and $(I_5 - 1)$ was utilized to construct the strain-energy function, which was absorbed by reinforced structure, as shown following:

$$\begin{aligned}W_f &= A_1(I_4 - 1) + A_2(I_4 - 1)^2 + A_3(I_5 - 1) + \\ &+ A_4(I_5 - 1)^2 + A_5(I_4 - 1)^3\end{aligned} \tag{23}$$

In equation 23:

$$\begin{aligned}\frac{\partial W(C, a_0 \otimes a_0)}{\partial C} &= \sum_{i=4}^{5} \frac{\partial W(C)}{\partial I_1} \cdot \frac{\partial I_1}{\partial C} = \\ &= \frac{\partial W(C)}{\partial I_4} \cdot \frac{\partial I_4}{\partial C} + \frac{\partial W(C)}{\partial I_5} \cdot \frac{\partial I_5}{\partial C}\end{aligned} \tag{24}$$

$$\frac{\partial I_4}{\partial C} = a_0 \otimes a_0^T \tag{25}$$

$$\frac{\partial I_5}{\partial C} = 2a_0 \cdot C \cdot a_0^T \tag{26}$$

The relationship between stress and strain for reinforcement can be expressed as follow:

$$\begin{aligned}\sigma_f &= 2A_1(\lambda^2 - \lambda^{-1}) + \\ &+ 2A_2\left[0.78(\lambda - \lambda^{-2}) + 0.01(\lambda^4 - \lambda) + (\lambda^{-1} - \lambda^2)\right] + \\ &+ 2A_3\left[0.78(\lambda - \lambda^{-2}) + 0.01(\lambda^4 - \lambda)\right] + \\ &+ 4A_4\left[0.61(\lambda^{-1} - \lambda^{-4}) + 0.01(\lambda^2 - \lambda^{-1}) + 0.02(\lambda^3 - 1)\right] + \\ &+ 3.54A_5 + 6A_5(0.02\lambda^3 - 0.61\lambda^{-3}) + 6A_5(\lambda^2 - \lambda^{-1}) + \\ &+ 12A_5(-0.78\lambda + 0.78\lambda^{-2}) + 12A_5(-0.01\lambda^4 + \lambda)\end{aligned}$$

The parameters C_{10} and C_{01} can be calculated from the nonlinear function fitting instruction by MATLAB software, based on the data of mechanical experiment for silicone rubber. The parameters A_i ($i = 1, 2, 3, 4, 5$) can be obtained based on the result of the compression experiment of WSF.

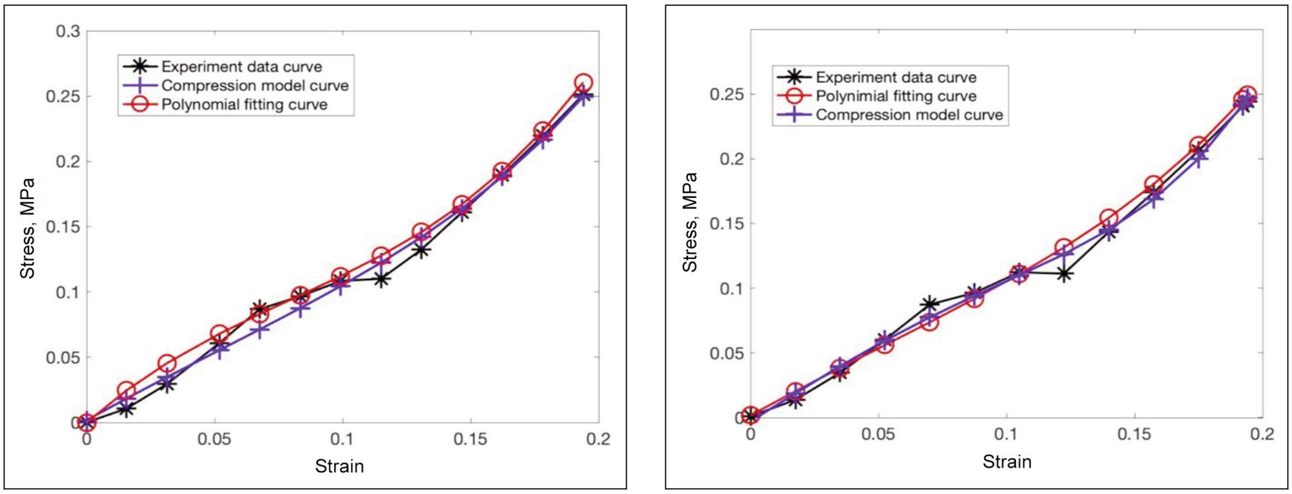
RESULTS AND DISCUSSION

The value of parameters from equation 21 and equation 26 was computed from the WSF compression experiment and the Silicone rubber mechanical experiment, as shown in table 5.

The Polynomial curve was fitted by MATLAB, based on the compression experiment data to conduct a more comprehensive analysis of the compressive behaviour of the composite. The strain value from the compression experiment of the composite was brought into the compression meso-mechanics

Table 5

THE PARAMETERS OF THE THEORETICAL MODEL							
Parameters	C_{10}	C_{01}	A_1	A_2	A_3	A_4	A_5
Value	0.0161	0.037	–5.9835	–4.5746	6.7614	–0.3910	0.000146



a *b*

Fig. 3. The comparison of compression model, compression experiment and Polynomial fitting curves: *a* – Sample 1; *b* – Sample 2

theoretical model, and then the curve of stress-strain for the theoretical model was established. The curves of the compression model, compression experiment and Polynomial fitting were compared, as shown in figure 4.

It is obvious from figure 4, that the Polynomial fitting curve was mainly above the experiment data curve with a little intertwining. However, uniform contact was shown between the curve of the theoretical model and the curve of experimental results. In figure 4, *a*, the average value of the relative error between the experiment and the polynomial is 5.7453%, and the average value of the relative error between the experiment and the theoretical model is 4.9542%. In figure 4, *b*, the average value of the relative error between the experiment and the polynomial is 5.7201%, and the average value of the relative error between the experiment and the theoretical model is 4.9434%. The theoretical model had a high agreement with the experimental results, as compared with the Polynomial fitting curve. Moreover, the slope of the polynomial fitting curve has a better agreement with the experiment curve under the 12% deformation. While the slope of the theoretical curve shows a better agreement with the experimental curve between the deformation of 12% and 20%. On the other side, the deformation abilities of sample 1 and sample 2 exist difference, due to the difference within the mesh structure of the surface layer between sample 1 and sample 2. Therefore, the invariants I_i (i = 1, 2, 3, 4, 5) of sample 1 and sample 2 are different. The compression evolution of composite can be effectively simulated by the compression meso-mechanics theoretical model. However, some deviations were shown between those curves. It is supposed that in the evolution of compression, there was no shearing force existed between the reinforcement and matrix material. During the compression processing, the composite only supported compressive load and there was no friction between the spacer yarns and silicone rubber. On the other hand, the measurement error occurred, when the structure parameters were measured. Moreover, the spacer yarns are regarded as a straight bar to calculate the angle, but the spacer yarns are not completely straight, of which angle is changed. Based on the above mention, the deviation between the theoretical model and experiment results is observed during the actual compression process.

CONCLUSION

The compressive evolution of silicone-rubber-matrix composite reinforced by warp-knitted spacer fabric within 20% deformation can be efficiently simulated from the compression meso-mechanics theoretical model, which was established based on the Euler-Bernoulli beam theory and Spence Invariant constitutive theory. At the same time, the compression theoretical model shows great potential for further compressive evolution. Additionally, the elastic modulus of the composite at each stage can be approximately consulted by the slope of the theoretical model, leading to the result that the slope of the theoretical model can serve as a reference for actual production designing. It can also be a reference for the further investigation of the compression property of SRWSF, and hopefully be expanded to predict the compression feature for the variety of SRWSF.

REFERENCES

[1] Sun, Z., Jiang, X., Zhao, K., et al., *A comparative analysis of bending-torsion coupling characteristics of three-dimension angle interlocking woven and biaxial warp knitted composite blade*, In: Journal of Inner Mongolia University of Technology, 2022

[2] Si, C., Hairu, L., *Mechanical properties of 3D-structure composites based on warp-knitted spacer fabrics*, In: Autex Research Journal, 2015, 15, 2, 127–137

[3] Chao, Z., Hairu, L., *Flexural Properties of Syntactic foam Reinforced by Warp Knitted Spacer Fabric*, In: Autex Research Journal, 2016, 16, 2, 57–66

[4] Wanli, X., Pibo, M., Liwei, W., et al., *Low-velocity impact properties of composite reinforced by auxetic warp-knitted spacer fabric*, In: Journal of Sandwich Structures & Materials, 2020, 23, 6, 1972–1986

[5] Velosa, S., Rana, J.C., Fangueiro, R., et al., *Mechanical behavior of novel sandwich composite panels based on 3D-knitted spacer fabrics*, In: Journal of Reinforced Plastics and Composites, 2012, 31, 2, 95–105

[6] Wanli, X., Yaxin, S., Haitao, L., et al., *Preparation of soft composite reinforced with auxetic warp-knitted spacer fabric for stab resistance*, In: Textile Research Journal, 2020, 90, 3–4, 323–332

[7] Datta, M.K., Behera, B.K., Goyal, A., *Prediction and analysis of compression behaviour of warp-knitted spacer fabric with cylindrical surface*, In: Journal of Industrial Textiles, 2019, 48, 9, 1489–1504

[8] Zhenqian, L., Liwei, W., Bohong, G., et al., *Numerical simulation of the impact behaviors of shear thickening fluid impregnated warp-knitted spacer fabric*, In: Composites Part B: Engineering, 2015, 69, 191–200

[9] Si, C., *The Compression Meso-Mechanics Theoretical Model and Experimental Verification of Polyurethane-Based Warp-Knit Spacer Fabric Composites*, In: AATCC Journal of Research, 2021, 8, 5, 30–38

[10] Si, C., Hairu, L., *Investigation on compression properties of polyurethane-based warp-knitted spacer fabric composites for cushioning applications Part II: theoretical model and experimental verification*, In: Industria Textila, 2014, 65, 6, 340–344

[11] Chao, Z., Mingjuan, D., Zhaoling, S., et al., *Warp-Knitted Spacer Fabric Reinforced Syntactic Foam: A Compression Modulus Meso-Mechanics Theoretical Model and Experimental Verification*, In: Polymers, 2020, 12, 2, 286

[12] Yousefpour, M., Payvandy, P., Salehahmadi, M., *Investigation of physical models accuracy optimized by PSO for determining low-velocity impact behavior of warp-knitted spacer fabrics*, In: Journal of The Textile Institute, 2018, 109, 3, 312–321

[13] Zhenqian, L., Xiaoying, J., *Impact property of silicone rubber filled warp knitted spacer fabrics*, In: Textile Research Journal, 2014, 35, 9, 298–313

[14] Xiaohui, Z., Pibo, M., Huilin, X., *Compression fatigue-resistance behaviors of silicone rubber filled warp-knitted spacer fabrics*, In: Fibers and Polymers, 2017, 18, 5, 1011–1016

[15] Wang, C.M., Reddy, J.N., Lee, K.H., *Shear Deformable Beams And Plates Relationships With Classical Solutions*, Elsevier, Amsterdam-Lausanne-New York-Oxford-Shannon-Singapore-Tokyo, 2000, 14

[16] Zixiang, Z., Si, C., *Finite Element Analysis of Compression Behaviors of Silicone Rubber Composites Reinforced by Warp-Knitted Spacer Fabrics*, In: AATCC Journal of Research, 2022, 9, 5, 240–247

[17] Spencer, A.J.M., *Continuum theory of the mechanics of fiber-reinforced composites*, Springer-Verlag, Wien-New York, 1984, 16–18

Authors:

ZHOU ZI-XIANG, CHEN SI

College of Light Industry and Textile, Inner Mongolia University of Technology, Hohhot, China

Corresponding author:

CHEN SI
e-mail: ansn9119@126.com