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Finite element simulation and experimental verification of quasi-static compression properties for 3D spacer fabric/hollow microspheres reinforced three phase composites

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Abstract

To enhance the compressive properties of syntactic foams, a new type of ternary composite named 3D spacer fabric/hollow microspheres reinforced composite (3DSMRC) was designed by adding warp-knitted space fabric (WKSF) into traditional syntactic foam. In order deeply understand the meso-mechanical properties of 3DSMRC composites, the compression tests of 3DSMRC were carried out and the quasi-static compression finite element models were established based on COMSOL Multiphysics. The results show that the compression properties of 3DSMRC were obviously controlled by structures of WKSF. To be specific, the 3DSMRC composites with more spacer yarns per unit area could withstand higher critical load, and with denser surface layers and larger spacer yarns inclination-angle could gain better compression capacities. Meanwhile, different types of microspheres also had important impact on the compression capacities of specimens, which could be improved by using smaller radius ratio (higher strength) microspheres. In addition, the finite element model can accurately reproduce the compression process and stress-strain curves of representative 3DSMRC samples, and then accurately simulate the values of compressive modulus and yield strength. The simulation and experimental studies of 3DSMRC can help to obtain a better and deeper understanding of the compression properties of this new type of composite, and finally provide a useful theoretical reference for the optimization design of 3DSMRC.

1. Introduction

The syntactic foam is a type of composite which is fabricated by incorporating hollow glass microspheres, fly ash spheres, ceramic or metal hollow microspheres into matrix [1, 2]. Syntactic foams have attracted considerable interest due to their unique combination of properties such as low density, high stiffness, good strength-to-weight ratio, excellent impact energy-absorption capability and ductility [3]. These desirable properties have made the syntactic foam a versatile material for both structural and non-structural uses in aerospace, deep sea exploitation, automotive, and building materials [4, 5]. However, traditional syntactic foams cannot resist large force and impact, which restricts the application of traditional syntactic foams [6]. In response to this problem, many scholars have conducted a lot of researches. Up to now, there are two main solutions. One is choosing high-strength microspheres and the other is adding reinforced filler materials in syntactic foams system. Ozkutlu et al [7] produced poly (methyl methacrylate) syntactic foams using three different types of hollow glass
microspheres with low, medium and high density. They found that increasing the density of hollow glass microspheres can realize greater density reduction and enhance mechanical properties of the composite. Huang et al.[8] prepared epoxy matrix syntactic foams reinforced with treated microsphere and short carbon fibers. The results showed that a decrease in compressive properties of syntactic foam while a high degree of weight saving would occur when increasing hollow glass microsphere contents. In addition, the incorporation of carbon fibers can improve the mechanical properties of syntactic foams. John et al.[9] also found substantial improvements in mechanical properties when syntactic foams were reinforced by nanoclay. However, all these solutions may be shadowed by such limitations as the difficulties in controlling mechanical properties and dispersing short fibers or other fillers in the matrix evenly.

Warp-knitted spacer fabric (WKSF) is a kind of three-dimensional fabric consisting of two outer substrates that are joined together and kept from being apart by spacer yarns [10–12]. Due to the good performance in cushioning, conduction, absorption, and ventilation, WKSF has been extensively applied to different fields, such as construction, automotive, and aerospace [13]. Based on the good cushioning properties and special three-dimensional structure, WKSF is particularly adapted for the use of skeleton materials in composites. Meanwhile, the great structural integrity of WKSF could prevent the clustering and bunching of reinforced fibers. Related researches [14–17] showed that the addition of WKSF could enhance the mechanical properties such as compression and impact of composite to a certain extent.

For the above reasons, as previously shown [18], the WKSF has been added to the traditional syntactic foam with hope to explore a new way to enhance the compression performance. And then, the compression tests were carried out for this new type ternary composite named 3DSMRC (3D spacer fabric/hollow microspheres reinforced three phase composite). The results indicated that the syntactic foam enhanced with preferable WKSF showed better compression properties compared to neat syntactic foam (NSF). The results also demonstrated that all the parameters of WKSF, including inclination-angle of spacer yarns, surface layer structures, fineness of spacer yarns, and the contents and types of hollow microspheres had significant effects on the compression properties of 3DSMRC. In addition, two meso-mechanics theoretical model based on the Eshelby-Mori-Tanaka equivalent inclusion method and fiber buckling theory, respectively, were established to predict the compression modulus and compression strength of 3DSMRC [19, 20].

Although the relatively systematic research of compression performance for 3DSMRC have been conducted as mentioned above, the research depth is still insufficient. In particular, the compression deformation process and the stress distribution cannot be reproduced from the theoretical level according to the existing research, which seriously hinders the performance improvement and design optimization of this new type ternary composite.

Due to the above reason, in this work, we studied the compression process of 3DSMRC based on the quasi-static compression finite element models and the compression test; then, an in-depth analysis of the compression performance of 3DSMRC was carried out based on the experimental and simulation results; meanwhile, the simulation results were compared with the experimental and theoretical model results to verify the accuracy and availability of finite element models.

2. Experimental

2.1. Materials and sample preparation

In this paper, four kinds of WKSFs respectively named B1, B2, B3 and B4 were knitted on a double-needle-bed raschel machine with six guide bars (GB1–GB6). A kind of ambient-temperature curing epoxy resin system consisting of bisphenol-A epoxy resin (E-51) and amine epoxy hardener (100-1B) (Wuxi Singmen Electronic Materials Co., Ltd, China) was used as the matrix materials. Three types of hollow glass microspheres (3 M Co., MN) with the trade names K1, S35 and S60HS were used as the hollow fillers. The parameters of spacer yarns and WKSFs are shown in tables 1 and 2, and the specifications of microspheres used in this research are listed in table 3.

The epoxy resin and the hardener were taken in a beaker with mass ratio of 100:33. The weighed quantity of microspheres was added to the epoxy resin through four times, with 1/2, 1/4, 1/8, 1/8 batches of the total microballoons weight for each time. Mixing was conducted throughout the whole addition process and was done gently by using a wooden sterrer in order to avoid making the microspheres break. The slurry was filled into a cylindrical silicon mould, and the WKSF was carefully pressed into the mixture. Then the specimens were cured for 24 h at room temperature according to product instruction. The specifications of all samples are shown in table 4. Taking CWS60–30–B1 as an example, ‘CW’ represents the composite (syntactic foam) reinforced by WKSF, ‘S60’ represents the type of hollow microspheres which is S60HS in this case, ‘30’ represents the volume fraction of microspheres which is 30% in this composite, and ‘B1’ represents the type of WKSF embedded in this composite which is B1 in this example.
2.2. Compression test

The quasi-static properties of 3DSMRCs were tested by MTS810 materials tester. The constant deformation rate was set as 2 mm min$^{-1}$ and the specimens were pressed to a deformation of 25%. At least five specimens of one type composite were tested. The schematic diagram of the test instruments and samples are shown in figure 1.

Load and displacement data obtained from the compression test were used to plot the stress-strain curves. The stress values corresponding to the yield points in the stress-strain curves were determined as the yield strength of samples. The compression modulus of sample was calculated using the following equations:

\[ P = \frac{F}{S} \]  \hspace{1cm} (1)

\[ \varepsilon = \frac{Z}{h} \]  \hspace{1cm} (2)

\[ E = \frac{P}{\varepsilon} \]  \hspace{1cm} (3)

### Table 1. Parameters of spacer yarns.

| Type | Diameter (mm) | Lapping code of spacer yarn guide bars | Threading of spacer yarn guide bars |
|------|---------------|---------------------------------------|------------------------------------|
| I    | 0.2           | 1-0 3-2/3-2 1-0/3 3-2/3-2            | 1 full 1 empty                     |
| II   | 0.2           | 1-0 4-3/4 3-1/4 3-1 1-0/4 3-1/4 3-1 1-0 | 1 full 1 empty                     |
| III  | 0.16          | 1-0 4-3/4 3-1 1-0/4 3-1 1-0/4 3-1 1-0 | 1 full 1 empty                     |

### Table 2. Parameters of WKSFs.

| Sample | Structure of surface layer | Spacer yarn type | Lapping movements of spacer yarn guide bars |
|--------|---------------------------|-----------------|--------------------------------------------|
| B1     | Chain + Inlay             | I               | 3                                          |
| B2     | Chain + Inlay             | II              | 4                                          |
| B3     | Hexagonal mesh            | I               | 3                                          |
| B4     | Chain + Inlay             | III             | 4                                          |

* The larger value of spacer yarn guide bar lapping movements, the spacer yarns will have smaller inclination-angle. For example, the spacer yarns inclination-angle of B1 is bigger than that of B2.

### Table 3. Specifications of microspheres.

| Microspheres type | Density (g cm$^{-3}$) | Mean particle size (μm) | Radius ratio | Pressure for 90% survival (MPa) |
|-------------------|-----------------------|-------------------------|--------------|--------------------------------|
| K1                | 0.125                 | 65                      | 0.98         | 1.72                           |
| S35               | 0.350                 | 40                      | 0.95         | 20.67                          |
| S60HS             | 0.600                 | 30                      | 0.91         | 124.02                         |

### Table 4. Specifications of samples.

| Samples          | Microspheres type | Thickness (mm) | Volume percent of microspheres (%) | WKSF type | Density (g cm$^{-3}$) |
|------------------|-------------------|---------------|-----------------------------------|-----------|----------------------|
| CWS60-30-B1      | S60HS             | 8             | 30                                | B1        | 0.975                |
| CWS60-30-B2      | S60HS             | 8             | 30                                | B2        | 0.968                |
| CWS60-30-B3      | S60HS             | 8             | 30                                | B3        | 0.937                |
| CWS60-30-B4      | S60HS             | 8             | 30                                | B4        | 0.958                |
| CWK1-30-B1       | K1                | 8             | 30                                | B1        | 0.825                |
| CWSS35-30-B1     | S35               | 8             | 30                                | B1        | 0.902                |
| NSF              | S60HS             | 8             | —                                 | —         | 0.953                |

2.2. Compression test

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Load and displacement data obtained from the compression test were used to plot the stress-strain curves. The stress values corresponding to the yield points in the stress-strain curves were determined as the yield strength of samples. The compression modulus of sample was calculated using the following equations:

\[ P = \frac{F}{S} \]  \hspace{1cm} (1)

\[ \varepsilon = \frac{Z}{h} \]  \hspace{1cm} (2)

\[ E = \frac{P}{\varepsilon} \]  \hspace{1cm} (3)
Where $E$, $P$, $F$ and $S$ are the compression modulus, compression stress, compression load and sample sectional area, respectively. Meanwhile, $\varepsilon$, $Z$ and $h$ represent the compression strain, displacement value of the upper head and the thickness of the sample, respectively.

3. Finite element simulation

COMSOL Multiphysics (ver.5.3) was used to simulate the quasi-static compression properties of samples in this research. The finite element analysis was carried out on a high-performance workstation with AMD Ryzen9 3.8 GHz processor, 128 GB RAM, NVIDIA Quadro Professional Graphics card and Windows 10 operating systems. In order to reduce the heavy calculation, a $1/4$ representative model of sample CWS60-30-B1 was used to analyze the quasi-static compression capacity of 3DSMRC. The representative model consists of two parts: the syntactic foam matrix (microspheres reinforced epoxy resin) and the WKSF.

Before the establishment of 3DSMRC model, the simulation environment should be constructed. The model selection wizard was used to create a new model, with the spatial dimension selected as 3D, and solid mechanics determined as the physical field. To ensure the convergence of the simulation results, some assumptions were made in the simulation process:

1. The surface layers of WKSF and syntactic foam were simplified as solid panels.
2. The spacer yarns were independent of each other during the compression process, with no contact between them.
3. The syntactic foam matrix was considered as homogenized in the modeling process.
4. During the compression process, the spacer yarns only exhibited rotation and elastic bending without horizontal displacement.
5. In the initial stage of compression, the sample was considered as an elastomer.

Based on the above assumptions, the 3D structural model of CWS60-30-B1 was established. The surface layer model of WKSF was created by the following steps. First, two working planes according to the actual size of WKSF were established; After that, two circular sectors (with the radius of 3.5 cm and central angle of 90°) were separately created in the two work planes as the surface layers of WKSF; Then, the spacer yarn model was created by adding a torus and setting radius of the torus to 0.1 mm; And then, the torus was rotated to obtain two cross-spacer yarns, followed by using the ‘union’ commands of Boolean operation to allow the two spacer yarns to combine into a whole; Afterwards, the spacer yarns were arrayed along the X, Y direction and combined with the surface layer models through the ‘union’ command to complete the WKSF model. It should be noted that in the process of connecting the spacer yarns to the surface layers, the overlap of the surface layers with the spacer yarns needs to be subtracted to simulate the intermeshing situation of spacer yarns between surface loops; And then, a
quarter cylinder model was built as the syntactic foam matrix; Finally, using the Boolean operation, the syntactic foam matrix and WKSF were combined into a whole, during which we also need to subtract the syntactic foam matrix model that overlaps the WKSF model based on the Boolean operation. At this point, the 3DSMRC model has been established. The modeling process and mesh scheme of 3DSMRC are displayed in figure 2(a). The WKSF and syntactic foam matrix were defined as linear elastic material and nonlinear-inelastic isotropic material, respectively. The material parameters of the finite element model are shown in table 5. Among them, the parameters (elasticity modulus, Poisson’s ratio and density) of WKSF were determined by the Polyethylene Terephthalate Polyester data sheet provided by Goodfellow. Meanwhile, the density of syntactic foam matrix is the same as that of NSF shown in table 4, while the elasticity modulus, yield strength and tangent modulus of the syntactic foam matrix were obtained through the compression test on NSF. The Poisson’s ratio of syntactic foam matrix can be calculated from equation (4):

\[ \nu_s = \frac{3K_s - 2G_s}{6K_s + 2G_s} \]  

(4)

Where \( \nu_s \), \( K_s \) and \( G_s \) are the Poisson’s ratio, bulk modulus and shear modulus of the syntactic foam matrix, respectively, and the values of \( K_e \) and \( G_e \) can be determined by the equations (5) and (6) according to the Mori-Tanaka method, respectively.

\[ K_e = K_e \left[ 1 + \frac{3V_m(1 - \nu_v)(K_m - K_e)}{3K_e(1 - \nu_v) + (1 + \nu_v)(1 - V_m)(K_m - K_e)} \right] \]  

(5)

\[ G_e = G_e \left[ 1 + \frac{3V_m(1 - \nu_v)(G_m - G_e)}{15G_e(1 - \nu_v) + 2(4 - 5\nu_v)(1 - V_m)(G_m - G_e)} \right] \]  

(6)

Where \( K_e \), \( G_e \) and \( \nu_v \) are the bulk modulus, shear modulus and Poisson’s ratio of epoxy resin respectively, and \( \nu_v \) is determined as 0.3 in this research, meanwhile, \( K_e \) and \( G_e \) can be described as the following equations.

\[ K_e = E_e \left( \frac{1}{3(1 - 2\nu_v)} \right) \]  

(7)

Table 5. Material parameter of sample.

| Model                  | Elasticity modulus (Pa) | Poisson’s ratio | Density (kg/m³) | Yield stress (Pa) | Tangent modulus (Pa) |
|------------------------|-------------------------|-----------------|-----------------|-------------------|----------------------|
| WKSF                   | 3.39e^5                 | 0.37            | 1380            |                   |                      |
| Syntactic foam matrix  | 1.17e^9                 | 0.30            | 953             | 9.72e^7          | 5.48e^7              |

Figure 2. The modeling process and mesh scheme of (a) 3DSMRC and (b) NSF.
Where $E_e$ is the elasticity modulus of epoxy resin. According to the official manual of manufacturer, the value of $E_e$ is determined to be 3.17 GPa.

In addition, in equations (5) and (6), $K_m$ and $G_m$ represent the bulk modulus and shear modulus of hollow glass microspheres, respectively. They can be obtained by equations (9) and (10), respectively.

$$G_m = \frac{5dE_g}{2r(7 + 5\nu_g)}$$

Where $E_g$ and $\nu_g$ represent the elasticity modulus and Poisson’s ratio of glass, respectively, which are determined according to the Engineering ToolBox and the specific values are 70 GPa and 0.23, respectively. In addition, $d$ and $r$ in equations (9) and (10) are the wall thickness and radius of the hollow glass microspheres, respectively. The $d/r$ value can be obtained by the ratio of the inner and outer diameters of the microspheres (table 3).

The model boundary conditions were set based on actual conditions. To prevent movement, the bottom surface layer of the 3DSMRC was fixed. The upper surface layer of the 3DSMRC only exhibited Z-direction translation without rotation. Free triangular mesh was used to mesh the 3DSMRC model. To increase simulation accuracy, the meshes connecting the spacer yarns and the surface layers were taken into consideration in the densification process. The meshing model is illustrated in figure 2(a). After meshing, the models were solved based on a ‘stationary’ mode.

In order to better compare the mechanical properties between 3DSMRC and NSF, an NSF model was also built in this simulation research with the same modeling process, load, material parameters, boundary conditions and solution parameters as syntactic foam matrix of 3DSMRC model. The model and mesh scheme of NSF are displayed in figure 2(b), respectively.

4. Results and discussion

4.1. Compression test results analysis

The compressive stress-strain curves, yield strength, compression moduli of SF-WKSF and NSF after compression tests are presented in figure 3.

It can be seen from figure 3(a) that the stress-strain curves of all samples have similar approximate linear trends at the initial linear region. After that, the stress-strain curves of all 3DSMRC samples yield and display obvious plateau region. However, the curve of NSF enters the plateau region after a relatively obvious downward trend, which indicates that NSF has higher compressive stress peak value compared with 3DSMRC samples. On the other hand, the yield strength of NSF has decreased by 8%, 10% and 7% compared with that of CWS60-30-B1, CWS60-30-B2 and CWS60-30-B4, respectively, just equivalent to the yield strength of CWS60-30-B3. Similar to the situation of yield strength as mentioned above, CWS60-30-B1, CWS60-30-B2 and CWS60-30-B4 have 21%, 17% and 15% higher values in compressive modulus, respectively. In addition, the densities of CWS60-30-B1, CWS60-30-B2, CWS60-30-B3, CWS60-30-B4 and NSF are close to each other (table 4). It can be
concluded that the addition of WKSF can reduce the compressive stress peak value of syntactic foam to a certain extent. On the other hand, although the improvement is not particularly significant, the adding of suitable WKSF can improve the yield strength and compression modulus of syntactic foam with almost no impact on the density. In addition, previous studies [21, 22] on the flexural and impact properties of 3DSMRC show that the 3DSMRC composite displays superior properties than NSF with respect to the flexural strength, flexural modulus, peak impact force and major damage energy. Hence, although the improvement degrees are not the same under different mechanical testing methods, the addition of suitable WKSF can significantly improve the mechanical properties of the syntactic foam.

As an additional reinforcement, WKSF will affect the structural integrity of syntactic foam. Meanwhile, the voids volume fraction of the composite system will also increase due to the presence of WKSF, thereby causing the peak compression stress of 3DSMRC lower than that of NSF as shown in figure 3(a). However, suitable WKSF (like B1, B2 and B4) can act as a reinforcement skeleton in the syntactic foam system. The presence of WKSF can reduce the damage to the hollow microsphere in the syntactic foam. In addition, when the microspheres are squeezed and broken with compressive loads, WKSF can still provide support for the matrix resin and resist compressive loads, so that the compression modulus and yield strength of the 3DSMRC are improved compared with NSF.

The samples CWS60–30–B1 and CWS60–30–B3 have the same type (S60HS) and volume fraction (30%) of microspheres, and the B1 and B3 WKSFs embedded in these two samples also have the same spacer yarn guide bar lapping movement (3) and spacer yarn diameter (0.2 mm). The main difference between the two samples is that they have different surface layer structures, which are Chain+inlay and Hexagonal mesh for CWS60–30–B1 and CWS60–30–B3, respectively. From figures 3(a) and (b), it can be seen that CWS60–30–B1 has higher compression stress peak value, yield strength and compression modulus compared with CWS60–30–B3, so it can be concluded that the compression performance of CWS60–30–B1 is better than CWS60–30–B3. Meanwhile, it also can be found from figures 3(a) and (b) that similar to sample CWS60–30–B1, CWS60–30–B2 and CWS60–30–B4, the compression stress peak value of CWS60–30–B3 is lower than that of NSF. However, the yield strength and compressive modulus of CWS60–30–B3 are similar to NSF, which is different from the case where the addition of other types of WKSF (B1, B2 and B4) can significantly enhance the yield strength and compressive modulus of composite, as shown in figure 3. A reasonable inference for this phenomenon is that the surface layer of B3 is Hexagonal mesh, of which structure is sparse, so the number of spacer yarns per unit area is lower than that of the WKSFs with the dense surface structure (like Chain+inlay). Therefore, SWS60–30–B3 does not have sufficient number of spacer yarns to resist the compression load. In the meantime, the sparse surface layer structure of B3 also weakens the protective effect of the surface layer to the spacer yarns, so the spacer yarns would be directly under the load action and more easily to get damaged. Therefore, the addition of B3 WKSF cannot improve the compression modulus and yield strength of the corresponding syntactic foam.

Specimens SWS60–30–B1 and SWS60–30–B2 have the same structural parameter except for the inclination-angle of spacer yarns, which depends on the spacer yarn guide bar lapping movements. Based on the yield strength and compressive modulus values shown in figure 3(b), it can be suggested that the specimen SWS60–30–B1 with larger inclination-angle presents slightly higher compressive modulus value compared to the corresponding sample SWS60–30–B2.

In WKSF, the spacer yarn fixed by the upper and lower surface layers has a similar structure to the slender compression rod hinged at both ends. Therefore, the influence of spacer yarn guide bar lapping movements on the compression performance of 3DSMRC can be explained by the elastic stability theory of the compression rod as follows:

$$E_c = \frac{\pi E_{ct} I}{L^2}$$  \hspace{1cm} (11)

where $F_c$, $E_{ct}$, $L$ and $I$ are the critical load, elasticity modulus, length and cross-sectional moment of inertia of the compression rod, respectively. According to equation (11), the shorter compression rod has a higher critical load, and the larger inclination-angle of spacer yarns (WKSF B1) causes a shorter length of rod, which leads to better compression properties of WKSF B1, and thus increases the compression properties of sample CWS60–30–B1.

CWS60–30–B2 and CWS60–30–B4 possess the same parameters except for the spacer yarn diameters, which are 0.2 and 0.16 mm, respectively. It can be seen from equation (11) that when $E_{ct}$ and $L$ are equal, the spacer yarn with a larger $I$ value (0.2 mm) has a higher critical force. Therefore, the sample with 0.2 mm spacer yarns (CWS60–30–B2) should have better compression performance than the sample with 0.16 mm spacer yarns (CWS60–30–B4) in theory. However, it can be seen from figure 3(b) that the compression modulus of CWS60–30–B2 and CWS60–30–B4 are relatively close, while the yield strength of CWS60–30–B2 is slightly higher than that of CWS60–30–B4. Thus, it can be considered that compared with CWS60–30–B4, CWS60–30–B2 has only a slight advantage in compression performance. The reason for this may be that the small diameter difference...
(0.04 mm) of the two spacer yarns is not enough to make a significant difference in the compression properties of the specimens. In addition, the mechanical properties of ternary composite are also strongly influenced by the interface combination status among fibers, particle and matrix in the composites. If designed inadequately, the interface combination status will affect the overall performance of the ternary composite [23, 24]. As previously shown [25], a larger diameter of the spacer yarns will reduce the interfacial shear strength between spacer yarns and syntactic foam matrix, thereby negatively affecting the mechanical properties of the material. Based on the above two reasons, the compression performance of the CWS60-30-B2 with coarser spacer yarns are closer to that of the CWS60-30-B4 without obvious advantages.

Specimens CWS60-30-B1, CWS35-30-B1 and CWK1-30-B1 are embedded with different type of microspheres (S60HS, K1 and S35, respectively). As shown in table 3, S60HS, with 0.91 in radius ratio, has the thickest spherical wall among the three types of microspheres. According to the compression stress-strain curves of CWS60-30-B1, CWS35-30-B1 and CWK1-30-B1 as shown in figure 3, it is evident that the order of compressive stress values and yield strength of the composites is CWS60-30-B1 > CWS35-30-B1 > CWK1-30-B1. In addition, as illustrated in figure 3(b), CWS60-30-B1 has 71% and 28% higher compressive modulus values than CWK1-30-B1 and CWS35-30-B1, respectively. Based on the above, one conclusion can be drawn that a specimen with smaller radius ratio microspheres brings better compression properties. The strength of K1 and S35 are lower than that of S60HS (table 3) and they are easily to be fractured during the compression test. Thus, CWK1-30-B1 and CWS35-30-B1 exhibit relatively poor compression capacities compared with CWS60-30-B1.

4.2. Finite element simulation results analysis

The Von Mises stress nephogram about specimen CWS60-30-B1 is shown in figure 4(a). It can be seen that the finite element models can accurately simulate the real deformation conditions of specimens in the quasi-static compression test. In addition, from the deformation condition and stress distribution of CWS60-30-B1 to consider, it is evident that the spacer yarns appear to have unstable status and the central region of the spacer yarns present the highest stress value. Meanwhile, the stress value gradually decreases from the central region to the both ends of the spacer yarns. Moreover, the surface layers of WKSF also show higher stress values in the Von Mises stress nephogram. Therefore, the choice of WKSF structure has a decisive influence on the compression performance of 3DSMRC.

The predicted and measured stress-strain curves of CWS60-30-B1 and NSF are depicted in figures 4(b) and (c), respectively. It is obvious that the CWS60-30-B1 model accurately simulates the compression behavior from the initial phase until yield phase for the stress–strain curve of 3DSMRC with just slightly decreasing. However, although the stress-strain curve of the NSF model has a linear stage similar with the experimental curve, the overall stress values of the curve are obviously lower than that of the experiment results.

Figures 4(b) and (c) also present the finite element simulation and experimental results of yield strength and compression modulus for CWS60-30-B1 and NSF, respectively. From figure 4(b), it can be found the simulation results are close to the experimental results. To be specific, the yield strength and compression modulus
obtained from the simulation are just 7.5% lower and 8.5% higher compared with the corresponding experimental results, respectively. Such a difference may emanate from the simplification of the model in the modeling process. In addition, although the yield strength value is relatively close to that of the experimental result, the compression modulus value of the NSF model is quite different from that of the experimental result. In general, according to figure 4, the finite element simulation results of CWS60-30-B1 model are in agreement with the experimental results. However, the simulation process of NSF model is quite different from the actual test situation, thus further optimization and improvement are needed.

In addition, as mentioned above, two theoretical prediction models used to predict the yield strength \( (\sigma_{\text{max}}) \) \(^{19}\) and compression modulus \( (E_{\text{DSMRC}}) \) \(^{20}\) of 3DSMRC were established and shown as follows.

\[
\sigma_{\text{max}} = 2 \left( V_{\text{SY}} + V_{\text{NSF}} \frac{E_{\text{NSF}}}{E_{\text{SY}}} \right) \sqrt{\frac{E_{\text{NSF}} E_{\text{SY}} V_{\text{SY}}}{3V_{\text{NSF}}}}
\]

\[
E_{\text{DSMRC}} = \frac{9K_{\text{NSF}} G_{\text{NSF}}}{3K_{\text{NSF}} + G_{\text{NSF}}} (1 - V_{\text{v1}}) V_{\text{NSF}} + E_{\text{SY}} V_{\text{SY}}
\]

Where \( E_{\text{NSF}}, V_{\text{NSF}}, K_{\text{NSF}} \) and \( G_{\text{NSF}} \) are the elastic modulus, volume fraction, bulk modulus and shear modulus of NSF, respectively, \( E_{\text{SY}} \) and \( V_{\text{SY}} \) represent the elastic modulus and volume fraction of the spacer yarns in 3DSMRC, respectively. \( V_{\text{v1}} \) refers to the volume fraction of the voids in the composite.

The prediction results of the two theoretical models were also used to compare with the finite element simulation results obtained in this paper as shown in figure 4(b). Obviously, in terms of the yield strength, the finite element simulation results obtained in this research are closer to the experimental results. For the compressive modulus, the results of finite element simulation and theoretical model are relatively close to the experimental results as depicted, only slightly higher and lower compared with test values, respectively. In general, although both displaying good applicability, the results of finite element simulation are closer to the actual situation compared with the theoretical model prediction results.

5. Conclusion

In this paper, a novel syntactic foam composite named 3DSMRC was manufactured based on WKSF, epoxy resin and hollow glass microspheres. The compression tests and corresponding finite element simulation were carried out to provide in-depth analysis of the compression performance of this new type of composite. The following conclusions were established through this research.

1. The 3DSMRC samples with suitable WKSF show superior yield strength and compression moduli compared with NSF, while NSF presents higher compressive stress peak value.

2. The parameters of WKSFs and microspheres have a significant influence on the compression properties of 3DSMRC. It is found that the composites show better compression properties when constructed with larger inclination-angles of spacer yarns, closer WKSF surface layer structure and smaller radius ratio microspheres. In addition, the sample with coarser spacer yarns displays better compression properties, but this performance advantage is not obvious for the samples in this research.

3. COMSOL Multiphysics was used to simulate the compression properties of 3DSMRC in this research. The model prediction of deformation, stress-strain curves, yield strength and compression moduli are in agreement with the experimental results. However, the simulation results of NSF are not ideal in this research. In addition, the finite element simulation results are closer to the actual situation compared with the theoretical model prediction results.

In summary, it can be concluded that most 3DSMRC composites exhibit a better compression performance compared with traditional syntactic foams, and the compression properties of 3DSMRC can be tailored to meet the practical application by varying the parameters of WKSF and hollow glass microspheres. Meanwhile, the compression finite element model built by this research can serve as a reference for practical production and further investigation of the mechanical properties of 3DSMRC. We hope this investigation can provide a good understanding of the 3DSMRC composite, with promising applications of this new type syntactic foam in the field of aviation, navigation, traffic, architecture, and so on.
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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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