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Research on the damage characteristics of buoyant materials under compressive load

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Abstract: *The study of the failure characteristics of buoyancy materials is of great significance for improving the safety and usability of manned/unmanned submersibles. This paper adopts a research method that combines experiments and simulations to investigate the impact mechanisms of various variables on the collapse sequence and failure strength of hollow glass microspheres. These variables include the ratio of inner to outer diameter, outer diameter size, and the volume fraction of hollow glass microspheres in the buoyancy material. Using ABAQUS software, a two-dimensional multi-microsphere model is constructed. By setting different single variables, the failure process of the buoyancy material is analyzed, and the variations in compressive strength and the collapse sequence of the hollow glass microspheres under different single-variable conditions are presented. The finite element analysis results are compared with experimental data, showing good agreement between the two, which demonstrates the effectiveness and reliability of the simulation model.*

Keywords: *Buoyancy material; Compressive strength; Numerical simulation; Destruction*

1. Introduction

Solid buoyancy materials are composite materials obtained by uniformly dispersing fillers such as hollow glass beads, hollow resin beads, and hollow metal beads into a polymer matrix (resin, etc.) through a certain preparation process. It has high specific strength, good impact resistance and good energy dissipation capacity, and is widely used in deep-sea submersibles and aerospace fields. The mechanical properties of composite materials mainly depend on the matrix properties and filler properties[1], and their mechanical properties under compressive load are important technical indicators that researchers pay attention to. Research on the mechanical behavior of microbead composite foam mainly involves strength theory, numerical simulation and experimental research. Lorenzo Bardella[2-6]and others predicted the quasi-brittle compression properties of syntactic foam by establishing a three-dimensional finite element model of multi-microbeads; Lu Zixing[7-11] and others determined that composite foam containing coated hollow spheres Explicit expressions for modulus prediction were used to study the mechanical properties of syntactic foam under tension using the four-phase sphere model. Possible damage was analyzed and it was found that the foam strength prediction results given by the model after degradation were consistent with the experimental results. The values are relatively consistent, theoretical calculation results usually represent the average level of the material and cannot fully reflect the differences in local properties; therefore, experiments and finite element simulation calculations are required. Researchers' studies on the damage of buoyant materials are usually based on certain assumptions, such as the size of microbeads and uniform wall thickness. There are few studies on the impact of factors such as different sizes of microbeads and different ratios of inner and outer diameters on their damage characteristics. Since the particle distribution in hollow particle composite materials has the characteristics of non-uniformity, disorder and randomness[12], it is necessary to fully consider the difference in microbead size, different volume fractions and microbead wall thickness when conducting analysis. Distinguish the effects of buoyant materials on the failure process. This paper uses ABAQUS software to establish a two-dimensional finite element model of various combinations of hollow glass microsphere volume fraction, microsphere size, ratio of inner and outer diameters, etc., analyzes the collapse sequence and buoyancy material strength of glass microspheres under compression conditions, and designs and implemented compression tests to verify the reliability of the numerical analysis. Through this research, we will gain a deeper understanding of the performance of solid buoyancy materials and provide more reliable design and application guidance for their use in engineering applications.

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2. Experimental Study

2.1 Experimental Materials

(1) Select HZ-42 solid buoyancy material from Engineered Syntactic Systems (ESS) Company. The material size is 610 mmx305 mmx100 mm, the density is 0.67±0.3g/cm3, and the volume fraction is 60%, and the hydrostatic pressure experiment is carried out.

(2) The density of the solid buoyant material in the uniaxial crush experiment is 0.68g/cm3, the epoxy resin is E51, the elastic modulus of the epoxy resin is 4.5GPa, and the Poisson's ratio is 0.35. The hollow glass beads are the K1 model produced by 3M Company, with a density of 0.46 g/cm3 and a volume fraction of 60%. The sample is a regular cylinder with a base diameter of 25.4mm and a height of 50.8mm. The material dimensions are shown in Figure 1.

2.2 Experimental method

(1) Hydrostatic pressure test: pressurize to the test pressure value of 165MPa at a uniform speed of 2-3MPa/min, maintain the pressure for 2 hours, and release the water pressure to 0MPa at a speed of 2-3MPa/min. Subsequently, the experimental materials were placed under a scanning electron microscope to observe the damage morphology of the glass beads, and specific areas were magnified 250 times for detailed analysis.

(2) Uniaxial crush test: Place the sample on a universal testing machine for uniaxial compression according to GB/T 228.1-2010, with a loading speed of 1mm/min, and carefully observe the deformation and rupture of the sample, as shown in Figure 2.

2.3 Experimental results

(1) Hydrostatic pressure experiment: It can be seen from the SEM image that the cell body has undergone obvious cracking under high pressure, and it is found that most of the damaged particles in the image are large microbeads, indicating that buoyant materials are often large microbeads when they are damaged under pressure. The beads are more damaged and the small microbeads are relatively complete. The SEM is shown in Figure 4.

(2) Uniaxial crush experiment: It is observed that as the loading time increases, the damage of buoyant materials is mostly shear failure, as shown in Figure 3. Observing the SEM image of the buoyant material after crushing, it was found that most of the damaged particles were large microspheres, which is similar to the results of the hydrostatic pressure experiment, as shown in Figure 5.

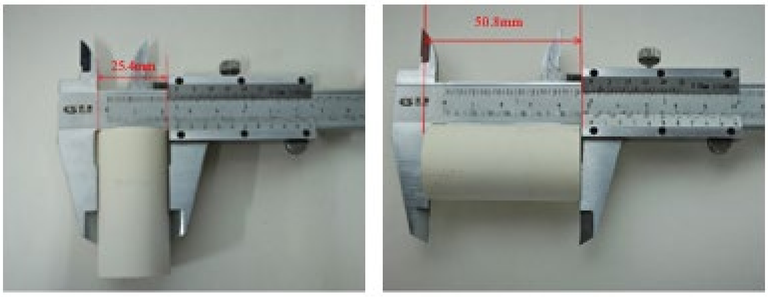

Figure 1: Material Dimension Drawing

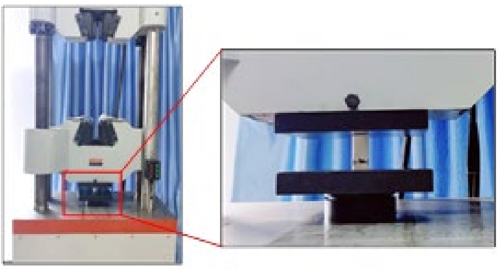

Figure 2: Universal testing machine

Figure 3: Material crush diagram

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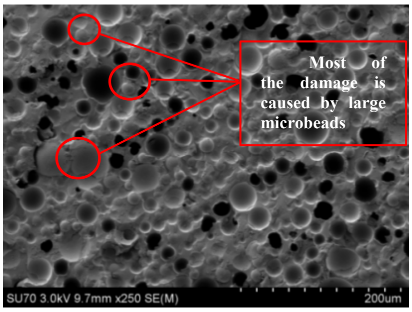

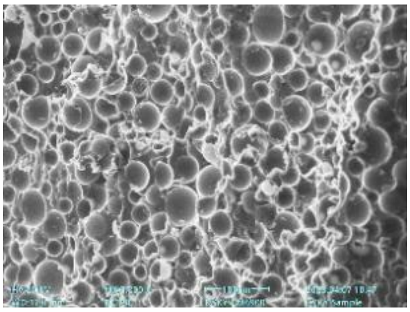

Figure 4: SEM image of material cross-section after hydrostatic pressure (Left)

Figure 5: SEM image of uniaxial crushing section (Right)

3. Numerical analysis of failure behavior of buoyant materials

3.1 Analyze working conditions

The volume fraction, ratio and size of the hollow glass beads in the buoyancy material are important factors that affect the compressive strength of the buoyancy material. When analyzing the failure behavior of the buoyancy material, this paper designs separate isolation models (ideal models) for various factors., that is, idealizing other factors, leaving only one factor that can be changed, and theoretically studying the influence of this factor quantitatively. There are mainly the following three types of situations: (1) The size and wall thickness of microbeads remain consistent, and the volume fraction of microbeads is changed to analyze the effect of volume fraction on compressive strength; (2) The wall thickness and volume fraction of microbeads remain consistent, and the volume fraction of microbeads is changed. The size of the microbeads, analyze the influence of the size of the microbeads on the collapse sequence of the microbeads; (3) Keep the size and volume fraction of the microbeads consistent, change the wall thickness of the microbeads, and analyze the influence of the wall thickness on the collapse sequence of the microbeads. See Table 1 for specific analysis conditions.

Table 1: Calculation conditions

category		Bead radius(um)	Ratio of inner and outer diameter of microbeads	Microbead volume fraction%
Bead size same	A1	21	0.90	40/45/50/55/60
	A2	21	0.92	40/45/50/55/60
	A3	21	0.94	40/45/50/55/60
	A4	21	0.96	40/45/50/55/60
	A5	20	0.92/0.94	50/55/60
	A6	20	0.92/0.96	50/55/60
	A7	20	0.94/0.96	50/55/60
Bead size different	B1	20, 30	0.90	45/50/55/60
	B2	20, 30	0.92	45/50/55/60
	B3	20, 30	0.94	45/50/55/60
	B4	20, 30	0.96	45/50/55/60

3.2 Finite element numerical analysis model

(1) Finite element model

Based on the analyzed working conditions in Section 3.1, a two-dimensional finite element model containing 20 random distributions was established using ABAQUS software. Figure 3 shows a model in which the volume fraction of microbeads is 60%, the radius is 21um, and the ratio of inner and outer diameters is 0.96.

(2) Meshing

An unstructured mesh is used for division, in which a quadrilateral mesh is selected for the matrix and a triangular mesh is selected for the microbeads. After meshing, the mesh is as shown in Figure 6,

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and the material properties are as shown in Table 2.

Table 2: Material properties

characteristic	Unit/Symbol	Epoxy resin	Microbeads
Young's modulus	E/GPa	2.3	70
Poisson's ratio	v	0.38	0.21
density	$\rho/(g/cm^3)$	1.17	2.53

(3) Boundary conditions and loads

A fixed constraint is applied to end A, and a downward displacement load is applied to end B. The displacement size is 1/100 of the side length of the base body, as shown in Figure 6 below.

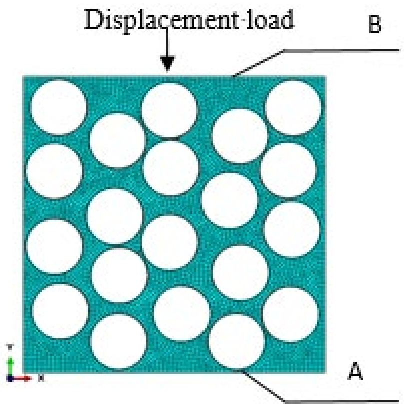

Figure 6: 2D model

4. Numerical simulation results

4.1 Collapse sequence of hollow glass beads

(1) The effect of microbead size on its collapse sequence

When calculating the numerical model containing 10 microbeads with a radius of 0.02mm and 10 microbeads with a radius of 0.03mm, it was found that when the calculation reaches step 39, the microbeads with a radius of 0.03mm begin to collapse. At this time, the maximum force exerted on the microbeads is 1.214e2MPa, and the point of maximum force is on the large microbead; when the calculation reaches step 41, the microbead with a radius of 0.02mm begins to collapse. At this time, most microbeads with a larger radius have collapsed. Therefore, it can be understood that under the same equivalent density conditions, microbeads with a larger radius will collapse earlier than microbeads with a smaller radius, as shown in Figure 7. The results of the numerical simulation are consistent with the results of the uniaxial compression experiment, further verifying the accuracy and effectiveness of the numerical simulation. In addition, it can also be observed from the results of the hydrostatic pressure test that larger microbeads are also damaged, which once again confirms the numerical simulation results, and this result is consistent with the literature [13].

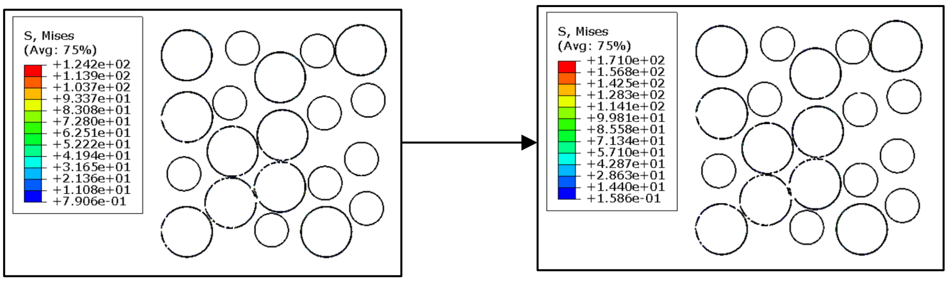

Figure 7: Finite element analysis damage diagram when the microbead radius is different.

(2) The effect of the ratio of the inner and outer diameters of microbeads on the collapse sequence of microbeads

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When calculating a numerical model containing 10 microbeads with a ratio of inner and outer diameters of 0.94 and 10 beads with a ratio of inner and outer diameters of 0.96, it was found that when the calculation reaches step 20, the ratio of inner and outer diameters is 0.96 (that is, the wall thickness is thinner) The microbeads collapse; when the calculation reaches step 44, the microbeads with a ratio of inner and outer diameters of 0.94 also begin to collapse. At this time, most of the microbeads with thinner walls have collapsed, as shown in Figure 8. Explanation: Under the same circumstances, microbeads with a larger ratio of inner and outer diameters (i.e., thinner wall thickness) collapse earlier than microbeads with a smaller ratio of inner and outer diameters (i.e., thicker wall thickness). This conclusion is consistent with the literature [13] consistent. Through data analysis, it is found that the maximum stress when the microbeads collapse decreases with the increase of the equivalent density of the microbeads, and the downward trend gradually becomes gentle, as shown in Figure 9.

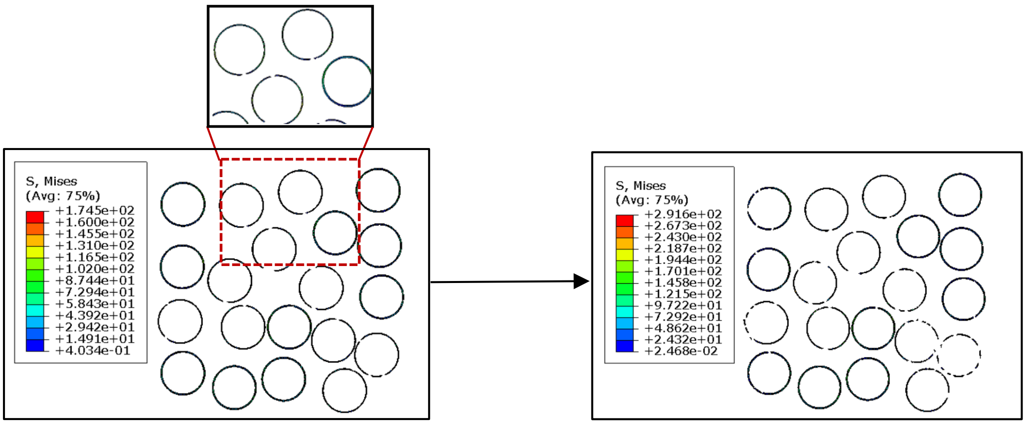

Figure 8: Finite element analysis damage diagram when the microbead radius is the same

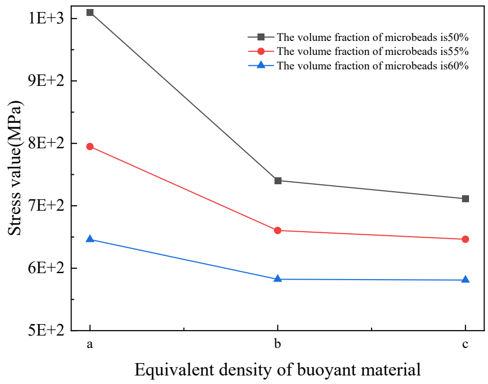

Figure 9: Maximum stress changes with equivalent density when the volume fraction is the same

Note: The abscissa a represents a model clock containing 10 microbeads with an inner and outer diameter ratio of 0.92 and 10 inner and outer diameter ratios of 0.94; b represents a model clock containing 10 inner and outer diameter ratios of 0.92 and 10 inner and outer diameters. microbeads with a ratio of 0.96; c represents a model clock containing 10 microbeads with a ratio of inner and outer diameters of 0.94 and 10 microbeads with a ratio of inner and outer diameters of 0.96.

4.2 Failure form of buoyant materials

Through in-depth research on uniaxial compression experiments and numerical simulations, it is found that the buoyant material studied in this article mainly exhibits quasi-brittle shear failure during the failure process. By analyzing the numerical models of different microbead sizes and comparing the numerical simulation results with the experimental results, it was found that the two are consistent in the damage form, as shown in Figure 10. This discovery provides strong support for a deeper understanding of the failure mechanisms of buoyant materials. This also verifies the accuracy of the numerical simulation and provides an important basis for performance evaluation and failure prediction of buoyancy materials.

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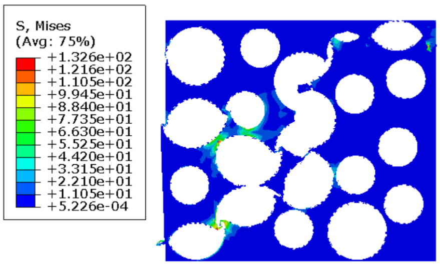

Figure 10: Finite element analysis damage diagram

4.3 Analysis of compressive strength of buoyant materials when microbeads are of the same size

During the analysis process, the working conditions are selected as A1-A4, in which the ratio of the inner and outer diameters includes four conditions: 0.9, 0.92, 0.94, and 0.96. While keeping the ratio of the size of the microbeads and the inner and outer diameters of the microbeads unchanged, the impact of different volume fractions on the compressive strength of the buoyant material will be analyzed, and the damage of the buoyant material will be studied; then the same method will be used to analyze the different internal and external diameters. Effect of diameter ratio on the compressive strength of buoyant materials. During the analysis process, it was found that in the selected working conditions, the hollow glass beads broke first. Therefore, the failure strength of the beads was used to represent the compressive strength of the buoyant material, and the maximum stress value when the beads were destroyed was regarded as the microbead. The compressive strength of beads.

(1) Effect of microbead volume fraction on compressive strength

In the study, it was found that when the size of the microbeads and the ratio of the inner and outer diameters of the microbeads remain consistent, and the volume fraction of the microbeads increases, the maximum stress when the microbeads are damaged shows a decreasing trend. This phenomenon shows that as the volume of the microbeads increases, the as the fraction increases, the compressive strength of the buoyant material shows an obvious downward trend, as shown in Figure 11. On the one hand, it is mainly because the interaction between microbeads increases, resulting in a decrease in the overall strength of the material; on the other hand, when the ratio of the inner and outer diameters of microbeads increases to a certain extent, it belongs to the weak phase of the buoyant material.

(2) Effect of the ratio of inner and outer diameters of microbeads on compressive strength

As shown in Figure 11, when the size of the microbeads and the volume fraction of the microbeads are the same, under the same load, as the ratio of the inner and outer diameters of the microbeads increases, the maximum stress becomes smaller. The reason is that as the ratio of the inner and outer diameters of the microbeads becomes larger, the equivalent elastic modulus of the microbeads will decrease. As the volume fraction increases, the maximum stress of the microbeads shows a downward trend, and as the ratio of the inner and outer diameters of the microbeads increases, the change of the maximum stress tends to be gentle. At this time, when observing the stress distribution of the microbeads, it was found that the maximum stress of the microbeads usually occurs on the microbeads with a larger ratio between the inner and outer diameters.

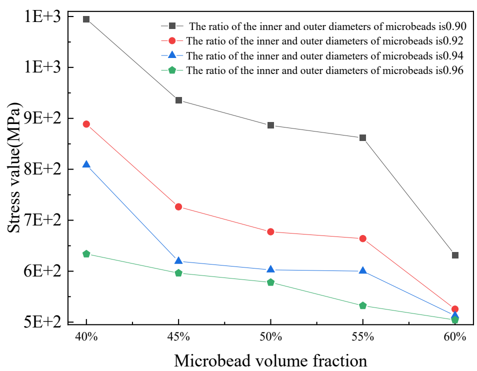

Figure 11: The variation curve of maximum stress with the ratio of inner and outer diameters when the volume fraction of microbeads is different

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4.4 Analysis of compressive strength of buoyant materials when microbead sizes are different

During the analysis process, the working conditions were selected as B1-B4. When the microbead sizes were different, the effects of different volume fractions and different ratios of inner and outer diameters on the compressive strength of the buoyant material were explored in turn, and their damage was observed.

(1) Effect of microbead volume fraction on compressive strength

Through data analysis, it was found that when the volume fraction is the same and the size of the microbeads is different, the material strength will decrease as the ratio of the inner and outer diameters of the microbeads increases. In addition, when observing the stress distribution of microbeads, it was found that the maximum stress of microbeads usually occurs on larger microbeads.

(2) Effect of the ratio of inner and outer diameters of microbeads on compressive strength

When the ratio of the inner and outer diameters of the microbeads remains constant but the size of the microbeads is different, it is observed that the maximum stress of the microbeads gradually decreases as their volume fraction increases. This is because when the volume fraction of microbeads increases, the interaction between microbeads will be enhanced, resulting in a gradual decrease in the maximum stress of microbeads. In addition, it can be clearly seen from Figure 12 that when the volume fraction reaches a higher level, the decrease in the maximum stress of the microbeads is also more significant.

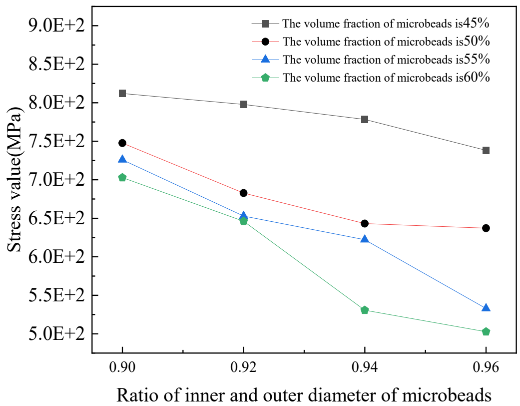

Figure 12: Maximum stress versus volume fraction curve for different ratios of inner and outer diameters of microbeads

5. Conclusion

This paper studies the damage characteristics of buoyant materials, analyzes the collapse sequence of microbeads, conducts finite element analysis of the mechanical properties of buoyant materials using a two-dimensional model constructed with ABAQUS software, and verifies the effectiveness of numerical analysis through experiments, and obtains the following in conclusion:

(1) When the ratio of the inner and outer diameters of microbeads is the same and the radius is different, the microbeads with a larger radius will be destroyed first than the microbeads with a smaller radius. When the radii of the microbeads are the same but the ratio of the inner and outer diameters of the microbeads are different, the wall thickness thinner beads are more likely to be damaged first.

(2) When the size of the microbeads and the ratio of the inner and outer diameters of the microbeads remain consistent, the maximum stress when the microbeads are damaged gradually decreases as the volume fraction of the microbeads increases; in addition, when the size of the microbeads and the volume fraction of the microbeads remain consistent, the increase in the ratio of the inner and outer diameters of microbeads will lead to a decrease in their maximum stress.

(3) When the size of microbeads is different and the volume fraction is the same, the compressive strength of the material will decrease as the ratio of the inner and outer diameters of the microbeads increases. When the sizes of the microbeads are different and the ratio of the inner and outer diameters of the microbeads is the same, the compressive strength of the material decreases as the volume

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fraction of microbeads increases, and the larger the volume fraction, the more significant the decrease in the compressive strength of the microbeads.

References

[1] Li P, Petrinic N, Siviour C R, et al. Strain rate dependent compressive properties of glass microballoon epoxy syntactic foams[J]. Materials Science and Engineering: A, 2009, 515(1-2): 19-25.

[2] Bardella L, Malanca F, Ponzo P, et al. A micromechanical model for quasi-brittle compressive failure of glass-microballoons/thermoset-matrix syntactic foams[J]. Journal of the European Ceramic Society, 2014, 34(11): 2605-2616.

[3] Bardella L, Sfreddo A, Ventura C, et al. A critical evaluation of micromechanical models for syntactic foams[J]. Mechanics of Materials, 2012, 50: 53-69.

[4] Bardella L, Genna F. Some remarks on the micromechanical modeling of glass/epoxy syntactic foams. In: Ko FK, Palmese GR, Gogotsi Y, Wang ASD, editors. Proceedings of the 20th annual technical conference of the American Society for Composites. 2005, ISBN 1-932078-50-9.

[5] Bardella L. Mechanical behavior of glass-filled epoxy resins: experiments, homogenization methods for syntactic foams, and applications. Italy: University of Brescia; 2000 [PhD thesis].

[6] Bardella L, Genna F. On the elastic behavior of syntactic foams[J]. International Journal of Solids and Structures, 2001, 38(40-41): 7235-7260.

[7] Lu Zixing, Gao Zhentong. Application of Differential Method to Determine the Elastic Modulus of Syntactic Foam Plastics [J]. Journal of Beijing University of Aeronautics and Astronautics, 1996, 22(6): 692-695.

[8] Lu Zixing, Gao Zhentong. Determination of effective modulus of composite materials containing hollow spheres [J]. Journal of Beijing University of Aeronautics and Astronautics, 1997, 23(4): 461-466.

[9] Ying-long Y, Zi-xing L. Modulus prediction and discussion of reinforced syntactic foams with coated hollow spherical inclusions [J]. Applied Mathematics and Mechanics, 2004, 25: 528-535.

[10] Zou Bo, Lu Ziying. Determining the effective modulus of coated hollow microsphere composites based on the five-phase sphere model [J]. Acta Materiae Compositae Sinica, 2006, 23(5): 137-142.

[11] Lu Zixing, Zou Bo. Theoretical Prediction of Modulus and Yield Strength of Syntactic Foam Plastics [J]. Acta Materiae Compositae Sinica, 2014, 31(04): 998-1005.

[12] Liang Xi. Research on numerical simulation strategies for mechanical properties of hollow particle composite materials [D]. Yanshan University, 2014.

[13] Gao Bo, Chen Zhanglan, Sun Chengmeng, etc. Study on the mechanical properties of buoyant materials with different microstructures under compressive load [J]. Journal of Ship Mechanics, 2023, 27 (10):1529-1541.