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THE STUDY OF HGM/ER FLOATING MATERIAL SANDWICH STRUCTURES ON HIGH-SPEED IMPACT DAMAGE

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ABSTRACT

Hollow glass microspheres/epoxy resin (HGM/ER) floating material sandwich structures are widely used in the field of offshore engineering equipment. However, their complex mechanical properties and diverse failure modes make it difficult to simulate the dynamic process itself, making it difficult to predict the dynamic failure behaviour and dynamic response under the action of high-speed impact load. In this paper, the 3D Hashin failure criterion is used as the initial criterion, and a continuous progressive damage model is constructed and verified by the experimental results. The energy absorption effect of the HGM/ER floating material sandwich structure was accurately simulated. The effects of the mass-filling rate of microbeads and the distribution of core thickness and panel thickness on the high-speed impact response of sandwich structures are discussed. The results show that the panel under high-speed impact is the main energy-absorbing part of the sandwich structure. The high-speed impact resistance of the sandwich structure can be improved by increasing the filling rate of a certain mass of microbeads, and the high-speed impact resistance of the sandwich structure with a thick front panel is more obvious. This research can provide a design basis for applying HGM/ER floating material sandwich structure in offshore engineering equipment.

Keywords: *Dynamic failure behaviour, impact response, progressive damage modelling, sandwich structures*

INTRODUCTION

In the current era of pursuing green sustainable development and efficient resource utilisation, lightweight structural technology has become one of the key strategies to promote energy conversation, environmental protection, and safety performance. It is especially important in the field of extensive development and utilisation of marine resources [1]. In order to improve the payload capacity of offshore structures (such as buoys, submersibles, offshore floating platforms, etc.), that is, to increase the number of instruments, equipment, materials and operators that they can carry without sacrificing their stability and operational performance, a new type of offshore lightweight and high-strength solid buoyancy materials is developed to replace the original traditional buoyancy materials [2]-[6]. Hollow glass microspheres (HGM) are two-phase composites manufactured by filling HGM into epoxy resin (ER), which have the characteristics of low density, high strength, and low water absorption, and have been widely used in the field of navigation, deep diving, and offshore engineering [7]-[11]. Compared with traditional buoyancy materials, hollow glass beads buoyancy materials have lower density and higher strength, which can ensure sufficient buoyancy while significantly reducing the overall weight of marine equipment [12]. Scholars have conducted exhaustive research in the field of modification technology of hollow glass bead material. However, when assessing the mechanical properties of the material, mainly focusing on the analysis of the static properties, but to a certain extent neglecting the material as a buoyant material applied in marine engineering equipment, may encounter structural collapse or explosion impact scenarios, the debris generated by the impact characteristics of the high- speed. High-speed impact and the current study of low-speed impact, there is a big difference between the impact energy being significantly higher, the degree of damage being more intense, and the damaged area being more localised, so high-speed impact will have a devastating impact on the structure of offshore engineering equipment, so the study of the HGM/ER floating material sandwich structure of high-speed impact damage mechanism and impact energy absorption is of great significance.

The failure modes of composite foam sandwich structures under impact loading exist in four main forms: delamination and buckling of composite panels, matrix cracking and fibre fracture, debonding of the panel/sandwich interface, and collapse of the foam core [13]. Bernard and Lagace [14] found that when the sandwich structure of composite foam material is impacted, the delamination damage phenomenon of the panel first appears significantly between those layers with different layering angles. The size of the layered damage does not expand uniformly. However, it starts from the side directly impacted and gradually extends to the interface between layers, and its size shows an obvious increasing trend in this process. The adhesive layer at the panel/core bonding interface is the weak link of the sandwich structure, which is prone to failure under impact loads, thus reducing the overall strength and stiffness of the structure [15]. Interfacial failure has a more significant effect on high-velocity impacts compared to low-velocity impacts, significantly reducing the impact resistance of the structure [16]. In the study on high-speed impact energy absorption of fibre metal laminates (FML)/polyurethane foam sandwich panels, Mehran and Mojtaba [17] found that high-strength and high-mode panel materials are the main energy absorption components and bear most of the impact energy dissipation. In contrast, increasing the density of the foam core has no significant effect on the overall energy absorption performance of the whole structure, indicating that in such structures, the material characteristics of the panel play a dominant role in the energy absorption effect.

Numerical simulation technology can simulate the whole process from the initial damage to the expansion of the material and become an efficient and non-destructive alternative to explore the failure mechanism of the target plate under high-speed impact. Aiming at the complex damage characteristics of fibre-reinforced composites, Nandlall et al. [18] proposed a numerical model based on continuous damage mechanics, introducing independent damage variables to accurately depict the progressive degradation of shear properties during the damage process. Skvortsov et al. [19] found that a mesh size that is too large would cause the simulated residual velocity to be greater than the experimental value. Based on the microstructure of composite laminates, Gu and Xu [20] constructed a three-dimensional viscoelastic damage constitutive model to simulate the mechanical response of single-layer laminates.

At the same time, the interface element is embedded in the finite element model to reproduce the interlayer delamination phenomenon accurately and further explore the ballistic protection performance and complex damage evolution mechanism of composite laminates under high-speed impact conditions. Ivañez et al. [21] used the Hou and compressible foam criteria to describe panel and sandwich materials in the GFPR/PVC foam sandwich structure high-speed impact finite element model. Tie et al. [22] established a numerical simulation model based on the elastoplastic model and elliptic surface failure theory in LS-DYNA. The research focused on the high-speed impact failure of the bonded repair structure of composite laminates. Bandaru and Ahmad [23] proposed a three-dimensional finite element model based on the failure criterion of secondary strain and the damage evolution law to calculate the damage softening behaviour and material stiffness degradation to predict the deformation behaviour of composite materials after ballistic impact. Xu et al. [24] used the Riemann solution to describe the interaction between particles, which improved the calculation accuracy of the interface and was applied to the problem of projectiles impacting thin plates.

High-speed impact numerical simulation research mainly focused on the traditional metal structure and composite laminated structure, a kind of composite structure made of multi-layer materials stacked in a specific direction. There are fewer numerical simulation models for composite foam sandwich structures. A sandwich structure is a special composite material structure consisting of three main parts: two harder panels and a lighter core material with an intermediate adhesive layer. This structure is designed to provide high strength and stiffness while keeping weight low. Compared with traditional composite laminates, the mechanical properties of composite foam sandwich structures are more complex, the failure modes are more diverse, and the difficulty of simulating the dynamic process itself is higher, which leads to the difficulty of better predicting the dynamic failure behaviour and dynamic response under the action of high-speed impact load, so it is necessary to establish a more comprehensive and accurate dynamic damage model of composite foam material sandwich structures.

FINITE ELEMENT MODELING

High-Speed Impact Finite Element Model

ABAQUS nonlinear finite element software was used to establish a high-speed impact finite element model of the HGM/ER composite foam material sandwich structure, which consists of the upper and lower two carbon fibre panels, the interfacial adhesive layer, and the HGM/ER foam core, as shown in Figure 1. The thickness of the carbon fibre panel is 1 mm, the length is 100 mm, the width is 100 mm, the thickness of the interfacial adhesive layer is 0.1 mm to simulate delamination damage, and the thickness of the HGM/ER core material is 20 mm. The material parameters of the carbon fibre panel of the HGM/ER composite foam sandwich structure are shown in Table 1, and the material parameters of the interfacial adhesive layer are shown in Table 2.

In Table 1, E_1, E_2, E_3 are the modulus of elasticity of the material in each principal direction, respectively; v_{12}, v_{13}, v_{23} are the Poisson's ratio in the 12, 13 and 23 directions, respectively; G_{12}, G_{13}, G_{23} are the Shear modulus in the 1-2, 1-3, and 2-3 planes, respectively; X, Y, Z are the strength values of the material in the 1, 2 and 3 axis directions, respectively, where the subscript t denotes tensile strength, c denotes compressive strength; S_{12}, S_{13}, S_{23} are the shear strength in the 1-2, 1-3, and 2-3 planes, respectively; G_{Lt}, G_{Tt}, G_{Lc}, G_{Tc} are longitudinal tensile fracture toughness, transverse tensile fracture toughness, longitudinal compression fracture toughness, and transverse compression fracture toughness.

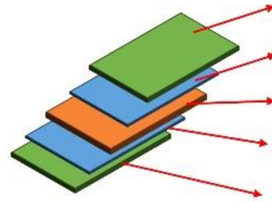

Figure 1 Schematic diagram of HGM/ER composite foam sandwich structure

In Table 2, E is the modulus of elasticity of the binder; G is the shear modulus of the binder; t_n^0 is the tensile strength of the binder; t_s^0 is the shear strength of the binder; G_n^c is the tensile fracture toughness of the binder; G_s^c is the shear fracture toughness of the binder.

Progressive Damage Failure Model

The existing progressive damage analysis model of composite materials in ABAQUS software is a two-dimensional Hashin model, which ignores the influence

Table 1 Carbon fiber panel material parameters

Parameters	Unit	Numerical value	Parameters	Unit	Numerical value
E_1	(GPa)	142	X_c	(MPa)	1100
E_2	(GPa)	9	Y_c	(MPa)	130
E_3	(GPa)	9	Z_c	(MPa)	130
v_{12}	\	0.32	S_{12}	(MPa)	72
v_{13}	\	0.32	S_{13}	(MPa)	72
v_{23}	\	0.46	S_{23}	(MPa)	70
G_{12}	(GPa)	4.6	G_{Lt}	(N/mm)	50
G_{13}	(Gpa)	4.6	G_{Tt}	(N/mm)	0.25
G_{23}	(GPa)	3.08	G_{Lc}	(N/mm)	75
X_t	(MPa)	1900	G_{Tc}	(N/mm)	0.75
Y_t	(MPa)	51	ρ	(N/mm)	1620
Z_t	(MPa)	51			

Table 2 Interface adhesive layer material parameters

Parameters	Unit	Numerical value	Parameters	Unit	Numerical value
E	(GPa)	1.85	t_n^0	(MPa)	17.9
G	(GPa)	0.56	G_n^c	(N/mm)	0.43
t_n^0	(MPa)	21.63	G_s^c	(N/mm)	4.7

of out-of-plane loads and can only be used to analyse in-plane failures. In contrast, out-of-plane loads must be considered in impact events. Therefore, the VUMAT user subroutine is written in Fortran in this paper. Because composite structures accumulate damage until they are destroyed, a simple damage criterion cannot be used to predict structural integrity. The continuous damage model is the damage model that is suitable for evaluating the accumulation of this type of damage, with the intrinsic relationship of $\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$, formulas σ_{ij}, C_{ijkl} and ε_{kl} ($ijkl$ = 1,2,3) representing engineering stresses, engineering strains and stiffness factors, respectively; The subscripts 1, 2, and 3 refer to the in-plane longitudinal, in-plane transverse, and out-of-plane directions, respectively. Each unidirectional layer can be considered a transversely isotropic material for composite panels. The undamaged unidirectional plate can be described by an eigenstructure equation with five independent constants, and the stiffness degradation matrix is shown in the following equation by introducing different damage variables to provide for the degradation of the composite material during loading, using the modified eigenstructural equations to describe its stress-strain relationship.

$$C_d = \frac{1}{H}\begin{pmatrix} d_fE_{11}(1-d_m v_{23}v_{32}) & d_fd_mE_{11}(v_{21}+v_{23}v_{31}) & d_fE_{11}(v_{31}+d_m v_{21}v_{32}) & & & \\ & d_fE_{22}(1-d_f v_{13}v_{31}) & d_mE_{22}(v_{32}+d_f v_{12}v_{31}) & & & \\ & & E_{33}(1-d_fd_m v_{12}v_{21}) & & & \\ & & & Hd_fd_mG_{12} & & \\ & & & & Hd_fd_mG_{23} & \\ & & & & & Hd_fd_mG_{13} \end{pmatrix} \quad (1)$$

formulas $d_f = (1-d_{ft})(1-d_{fc})$; $d_m = (1-d_{mt})(1-d_{mc})$

$H = 1-d_fd_mv_{12}v_{21}-d_mv_{23}v_{32}-d_fv_{13}v_{31}-2d_fd_mv_{21}v_{32}v_{13}$

d_{ft} and d_{fc} denote the damage variable for fibre tensile failure and the damage variable for fiber compression failure; d_{mt} and d_{mc} denote the damage variable for matrix tensile failure and the damage variable for matrix compressive failure.

The 3D Hashin failure criterion was used as a starting criterion for fibre damage and matrix damage as follows:

Fiber stretch failure:

$$S_{ft} = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2, \ \sigma_{11} \geq 0 \quad (2)$$

Fiber compression failure:

$$S_{fc} = \left(\frac{\sigma_{11}}{X_c}\right)^2 . \ \sigma_{11} < 0 \quad (3)$$

Substrate tensile failure:

$$S_{mt} = \left(\frac{\sigma_{22}+\sigma_{33}}{Y_t}\right)^2 + \frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2, \sigma_{22}+\sigma_{33} \geq 0 \quad (4)$$

Substrate compression failure:

$$S_{mc} = \left(\frac{\sigma_{22}+\sigma_{33}}{Y_c}\right)\left[\left(\frac{Y_c}{2S_{23}}\right)-1\right] + \left(\frac{\sigma_{22}+\sigma_{33}}{2S_{23}}\right)^2 + \frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2, \sigma_{22}+\sigma_{33} < 0 \quad (5)$$

formula σ_{ij} (i, j = 1, 2, 3) represents the stress in each direction.

When the three-dimensional Hashin failure criterion is satisfied, the material begins to show damage, the load-bearing capacity of its structure is weakened, and the material properties are degraded. A linear and continuous damage model simulates the progressive damage process in the damaged region. The degree of damage to the material is expressed by the corresponding damage variable, *d*, which is a continuous function of the failure factor and fracture energy expressed as,

$$D = \frac{\delta_{eq}^{f}\left(\delta_{eq} - \delta_{eq}^{0}\right)}{\delta_{eq}\left(\delta_{eq}^{f} - \delta_{eq}^{0}\right)}$$

formula δ_{eq} for equivalent effect variations; δ_{eq}^{0} is the damage onset strain; δ_{eq}^{f} for the final damage strain. $\delta_{eq}^{f} = \frac{2G^{c}}{\sigma_{eq}^{0} L^{c}}$ included among these G^{c} is the critical strain energy release rate. δ_{eq}^{0} is the damage initiation stress. L^{c} is the unit feature length.

Mesh Division and Boundary Conditions

There is a direct correlation between the mesh density of the model and the accuracy of the calculation, and the denser the mesh usually means, the higher the accuracy of the calculation because the physical phenomenon can be captured in more detail. However, a grid element that is too large can easily cause unrealistic excessive deformation under impact load, resulting in failure of calculation. On the other hand, a very small mesh improves accuracy but significantly increases the computational burden. Therefore, it is necessary to weigh the mesh size during modelling to ensure accurate and stable solution results in a reasonable calculation time. This paper uses the unidirectional bias method to divide the grid. The impact region is locally encrypted, and the smooth transition of the mesh size between the impact region and the non-impact region is ensured, as shown in Figure 2. In the numerical simulation model, the CFRP panel, HGM/ER foam core material and warhead use an 8-node first-order reducing integral solid unit (C3D8R), and the interface glue layer of CFRP panel uses an 8-node cohesive force unit (COH3D8). The warhead deforms very little during impact, so in the contact setting of ABAQUS software, the warhead is bound to a reference point set on the warhead and set as a discrete rigid body. The type of predefined field is mechanics, the type used for the selected initial analysis step is velocity, which is loaded on the reference point of the

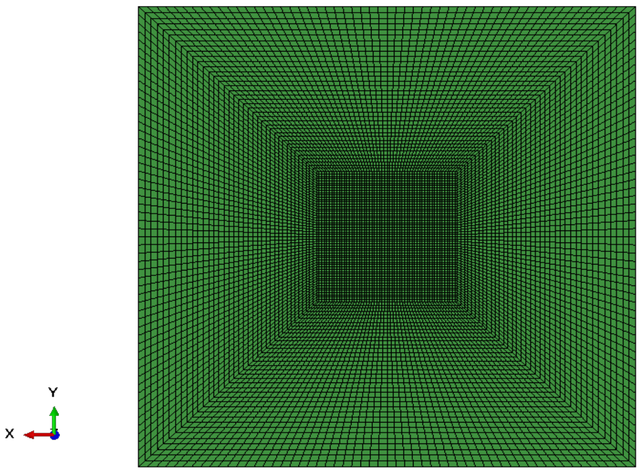

Figure 2 Schematic diagram of grid division

warhead, and the effect of different impact energies is simulated by changing the initial velocity of the probe. In addition, the four sides of the sandwich structure are fully constrained by six degrees of freedom during the impact analysis. The impact simulation work of composite foam sandwich structure in this paper has the characteristics of multiple material types, multiple unit types, multiple contact interfaces and severe unit deformation, and the contact problems involved are highly complex. Therefore, this paper adopts a general contact algorithm. In terms of contact attributes, tangential contact behavior adopts Penalty algorithm, friction coefficient is 0.3, and normal contact is defined as Hard contact.

MODEL VALIDITY VERIFICATION

In order to verify the accuracy of the subroutine and the model, the experimental results were compared with those of Deng et al. [25]. The model is set up according to the experimental conditions. The thickness of the target plate is small relative to the length of the projectile body, and it can be regarded as a thin-walled structure. The simulation is carried out with the S4R shell element. The target plate is a square plate of 150 mm×150 mm, and the area of the impact centre of 30 mm×30 mm is encrypted. Figure 3 shows the simulation model of the positive impact target plate of the missile body. Figure 4 shows the relationship between the experimental data of the warhead's positive impact on the target plate and the velocity curve of the numerical simulation.

It can be seen that the experimental value and the simulation result are in agreement under the impact of higher velocity, and there are some errors near the ballistic limit. The damage morphology of the target plate during impact is also in good agreement with the experimental results, as shown in Figure 5.

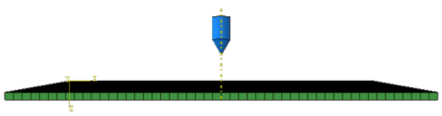

Figure 3 Model of the projectile impacting the target plate

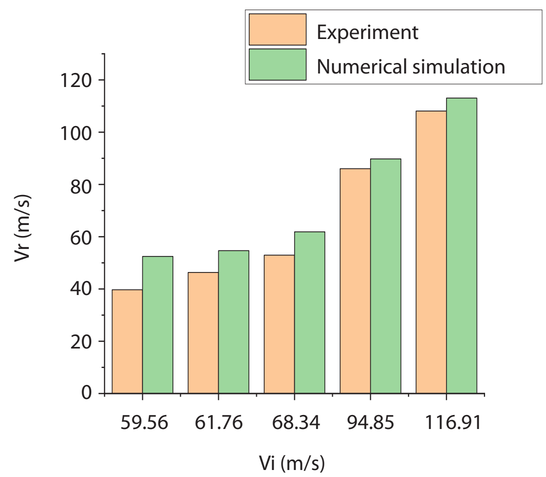

Figure 4 Model validity verification

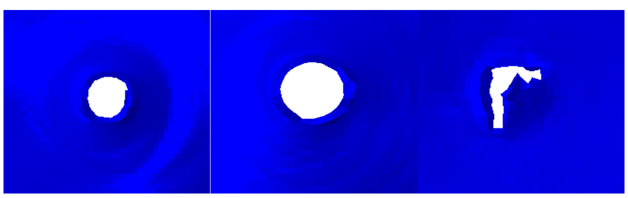

Figure 5 Damage topography of target plate

RESULTS AND DISCUSSION

Influence of Microbead Mass Filling Rate on High-Speed Impact Response of HGM/ER Floating Material Sandwich Structure

Using ER as matrix and HGM as filler to prepare floating materials, the effects of filling rate and impact energy of microbeads on impact energy absorption of foam core materials were investigated. In order to better explore the effect of the filling rate of microbeads with different masses, only foam core material is used for analysis in this section to explore better the effect of filling rate of microbeads with mass on the high-speed impact response of HGM/ER composite foam sandwich structure. The effect of filling rates of 10%, 20% and 30% microbeads on the impact response of foam core material with a thickness of 10 mm was investigated. In this paper, the impact of the energy absorption effect of HGM/ER foam core was investigated using the evaluation indexes residual velocity, surface density, and energy absorption rate. For the target plate with different size parameters, it is inappropriate to use the absolute value of the kinetic energy change of the projectile body as the evaluation index, so the surface density energy absorption E_a is adopted in this paper as a representation of the energy absorption performance of the target plate. Surface density absorbs energy E_a is defined as follows $E_a = \frac{\Delta E_k}{\rho a}$, formula ρa is the surface density of the sandwich plate. Its value is defined as the ratio of the mass m of the target plate to the area s of the target plate, ΔE_k is the kinetic energy change after the projectile penetrates the target plate. The energy absorption rate of the target plate is also one of the important indicators indicating the kinetic energy absorption efficiency of the target plate, which refers to the ratio of the kinetic energy change of the projectile body before and after penetrating the target plate to the initial kinetic energy of the projectile body. Define the following form $R = \frac{\Delta E_k}{E_0}$, ΔE is the kinetic energy change after the projectile penetrates the target plate, E_o is the initial kinetic energy of the projectile.

As can be seen from Figure 6, initial impact velocity - residual velocity curve, the residual velocity after impact of HGM/ER foam core material with 20% microbead mass filling rate is slightly lower than that of HGM/ER foam core material with 10% microbead mass filling rate, but it is similar on the whole. However, the impact residual velocity of HGM/ER foam core material with a 30% microbead mass filling rate is significantly lower than that of HGM/ER foam core material with a 10% and 20% microbead mass filling rate. From the aspect of density energy absorption, it can be seen that the impact resistance effect of the foam core material can be improved by increasing the filling rate of a certain microbead mass. The reason may be that the impact energy breaks the tightly bonded microbeads and resin while the resin acts as a buffer matrix to remove

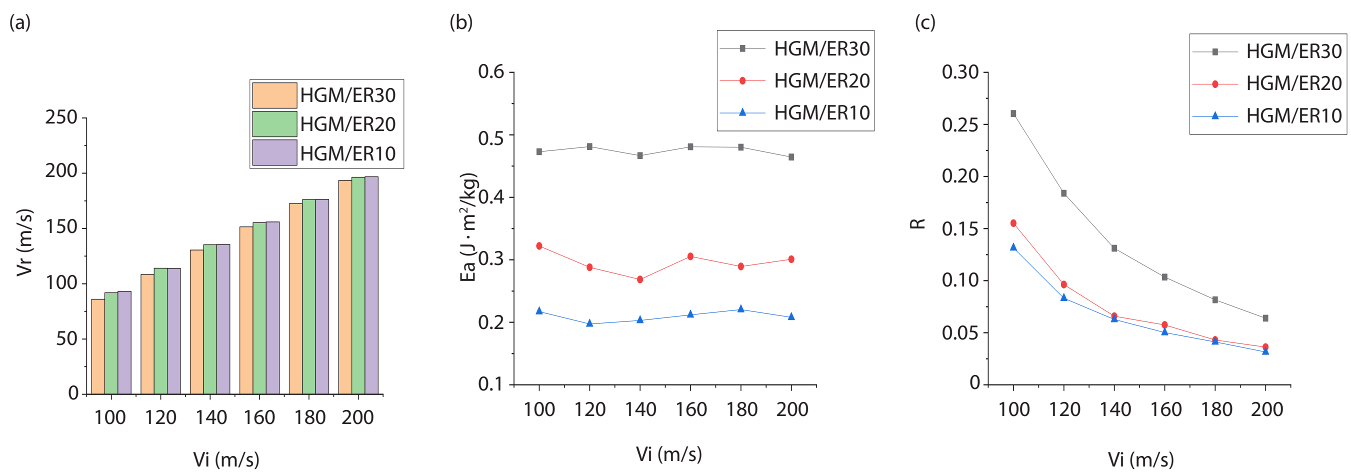

Figure 6 Energy absorption effect of HGM/ER foam core material at different microbead mass filling rates

the energy. With the increase of the filling rate of a certain microbead mass, the energy absorption rate of the foam material will also increase. However, with the increase of the initial impact velocity, the effect becomes no longer significant. The reason may be that the energy absorption of composite foam sandwich structure under high-speed impact is mainly completed by the panel with higher strength, and the core material has little influence on the energy absorption under high-speed impact. The main role of the foam core is that because it usually has a low density, it can greatly reduce the overall weight of the sandwich structure while ensuring structural performance.

Influence of Core Layer Thickness on High-Speed Impact Response of HGM/ER Floating Material Sandwich Structure

The impact of three core layer thicknesses on the impact response of composite foam sandwich structures with a 30% microbead mass filling rate is explored. The three evaluation indexes of residual velocity, surface density energy absorption rate and energy absorption rate are also used for evaluation, and six groups of initial impact velocities are used to explore. As shown in Figure 7a, increasing a certain core layer thickness can reduce the residual velocity of the composite foam sandwich structure and improve the energy absorption effect. However, such an increase in core layer thickness has little impact on the reduction of the residual velocity under high-speed impact. In the six groups of initial impact velocities, except for the initial velocity of 180 m/s, the surface density energy absorption of the core layer with the initial velocity decreases gradually with the increase of the core layer thickness. In the larger velocity range, the core layer's surface density energy absorption value with the larger core layer thickness is lower, indicating that in the case of higher lightweight requirements, the core layer's surface density energy absorption value is lower. Arbitrarily increasing the thickness of the core layer is not desirable to improve the energy absorption performance of the HGM/ER composite foam sandwich structure. The slope of the energy absorption-initial impact velocity curve decreases with the increase of initial impact velocity, which may be because the energy absorption performance of the foam material itself is limited at high speed. The increase of core layer thickness has little effect on the energy absorption rate of the sandwich structure of HGM/ER composite foam material at high speed.

Influence of Panel Thickness on High-Speed Impact Response of HGM/ER Floating Material Sandwich Structure

In order to investigate the influence of panel thickness on the high-speed impact response of HGM/ER composite foam sandwich structure in detail, two working conditions were examined: the influence of equal thickness panel on the high-speed impact response of HGM/ER composite foam sandwich structure and the influence of non-equal thickness panel on the high-speed impact response of HGM/ER composite foam sandwich structure. A panel of equal thickness refers to a panel of equal thickness between the front and back panels, and a panel of non-equal thickness refers to a panel of unequal thickness between the front and back panels. In order to investigate the influence of the thickness of the

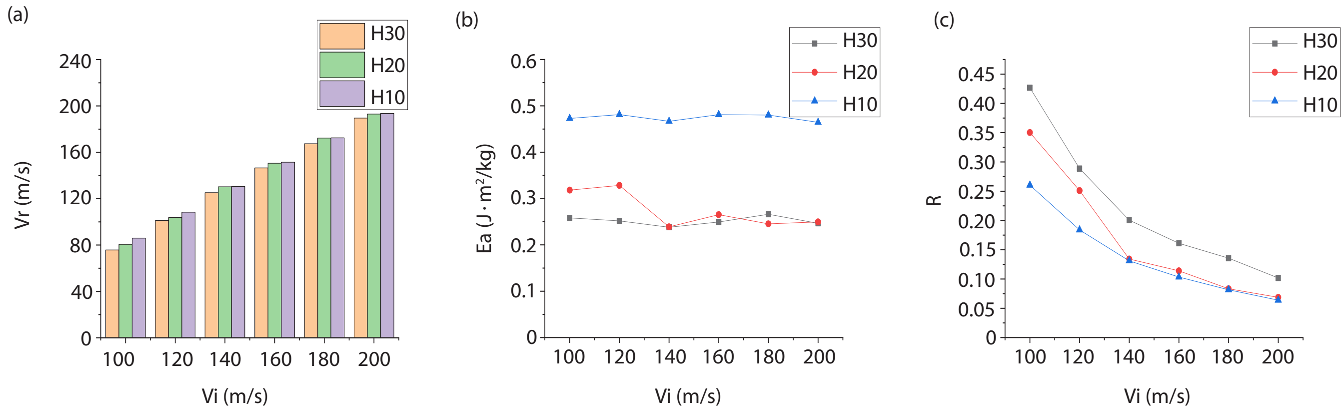

Figure 7 Energy absorption effect of HGM/ER foam core material with different core thickness

panel with equal thickness on the high-speed impact damage characteristics of the HGM/ER composite foam sandwich structure, three working conditions were set, with the thickness of the front panel 1.5 mm and the rear panel 1.5 mm, the front panel 1mm and the rear panel 1mm, and the front panel 0.5 mm and the rear panel 0.5 mm. Table 3 shows the thickness parameters of the sandwich structure's front panel, back panel, rubber layer and core layer under three different working conditions.

Table 3 Thickness parameters of each part of the sandwich structure

	Front plate thickness (mm)	Back plate thickness (mm)	Core thickness (mm)	Thickness of rubber layer (mm)
Condition 1	1.5	1.5	20	0.1
Condition 2	1	1	20	0.1
Condition 3	0.5	0.5	20	0.1

As shown in Figure 8a, within the velocity range studied, the larger the thickness of the panel, the smaller the residual velocity of the sandwich structure, and the value of the reduction does not change significantly with the increase of the initial impact velocity, which means that increasing the thickness of the panel can effectively improve the absorption capacity of the sandwich structure to the impact material within a larger velocity range. As shown in Figure 8b, the surface density energy absorption value also gradually increases with the increase of the initial impact velocity, indicating that when the structure is fully penetrated, the impact of the surface density energy absorption with the increase of panel thickness is positive. Figure 8c describes the changes in energy absorption rate with panel thickness under different initial impact velocities. Overall, the energy absorption rate is positively correlated with the panel thickness of the sandwich structure under the studied velocity range and when the sandwich structure is fully penetrated. However, it is evident that such gain will gradually decrease with the increase of initial impact velocity. At the initial impact velocity of 180 m/s, the maximum difference in energy

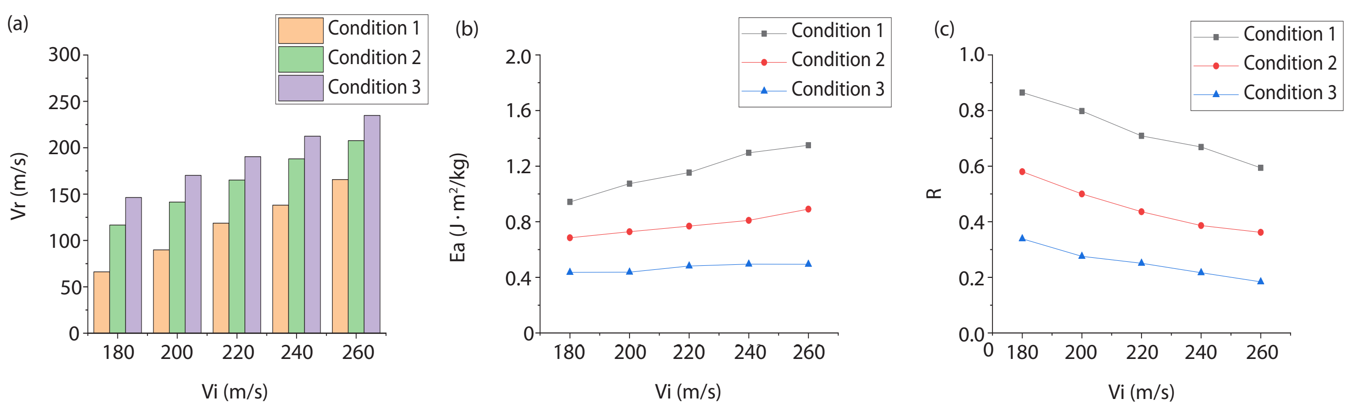

Figure 8 Energy absorption effect of HGM/ER composite foam sandwich structure under equal thickness panel

absorption rate of sandwich structures with different panel thicknesses is 0.5261, while at the initial impact velocity of 260 m/s, this difference decreases to 0.41.

Figure 9 shows the damage morphology of the front and rear panels of the composite foam sandwich structure under different impact velocities. It is found from the five groups of working conditions that the damage morphology of the front and rear panels of the composite foam sandwich structure presents a relatively regular circular fracture, and the fracture area of the rear panel is relatively larger than that of the front panel.

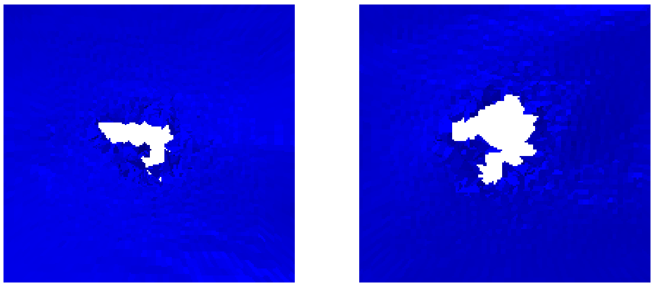

Figure 9 Damage morphology of front and rear panels of composite foam sandwich structure; (a) is the front panel, (b) is the rear panel

In exploring the influence of panel thickness distribution of non-uniform thickness panels on high-speed impact damage characteristics of HGM/ER composite foam sandwich structures, under the condition that the total panel thickness remains unchanged, three working conditions are set: a) front panel thickness 1.5 mm, rear panel thickness 1.5 mm, b) front panel thickness 1 mm, rear panel thickness 2 mm, and c) front panel thickness 2 mm, rear panel thickness 1 mm.

Table 4 shows the thickness parameters of the front panel, back panel, rubber layer and core layer of the sandwich structure under three different working conditions.

Table 4 Thickness parameters of each part of the sandwich structure

	Front plate thickness (mm)	Back plate thickness (mm)	Core thickness (mm)	Thickness of rubber layer (mm)
Condition 4	1.5	1.5	20	0.1
Condition 5	1	2	20	0.1
Condition 6	2	1	20	0.1

As can be seen from the residual velocity curves of three different working conditions in Figure 10, changing the thickness configuration of the front and rear panels has a significant impact on the high-speed impact resistance of the sandwich structure. It can be seen from the curves that the sandwich structure with a front panel thickness of 2 mm and a rear panel thickness of 1 mm has the greatest kinetic energy loss. However, this influence will gradually decrease with the increase of the initial impact velocity. Under the condition that the total panel thickness is unchanged, the density energy absorption and energy absorption rate increase with the increase of the thickness of the upper panel. That is, the ballistic limit velocity gradually decreases with the increase of the thickness of the upper panel.

Five sets of data from the initial velocity of 180 m/s-260 m/s are investigated. In the overall response trend of the sandwich structure, the residual velocity is relatively low when the front plate is thicker. In the initial stage of impact, if the front plate is thin, the deformation of

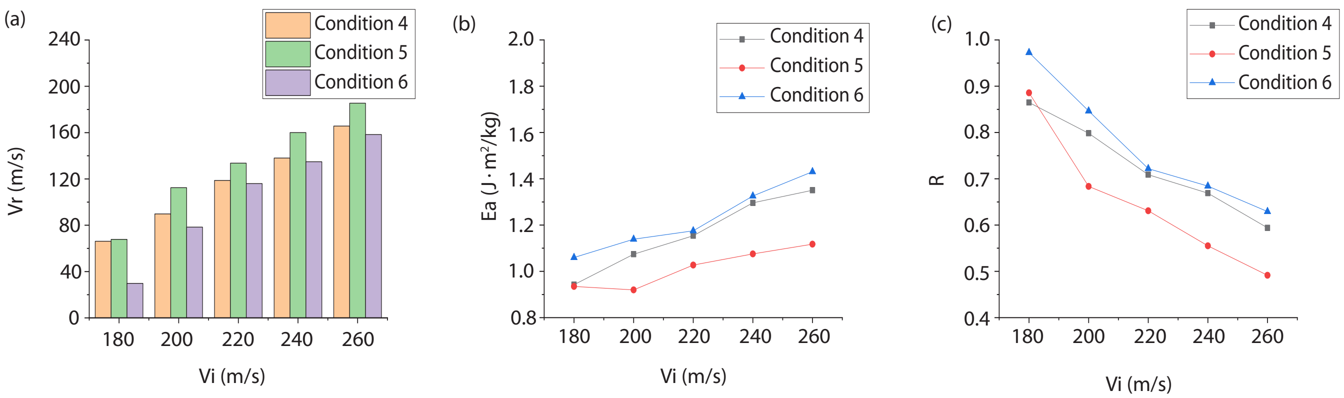

Figure 10 Energy absorption effect of HGM/ER composite foam sandwich structure under non-equal thickness panel

the front plate will occur in advance due to the rapid transmission of compressive stress waves to the back plate. With the fracture of the front plate, the projectile penetrates the composite material of the rubber layer and core layer at high speed. It rapidly impacts the rear plate, which limits the expansion of the plastic deformation zone and thus reduces the overall energy absorption. On the contrary, if the front plate is thicker and the rear plate is thinner, the residual velocity of the projectile after penetrating the front plate is significantly reduced, which is not enough to completely penetrate the rear plate, resulting in large plastic deformation of the rear plate, thus enhancing the energy absorption capacity of the structure. Therefore, under the above three working conditions, the sandwich structure with a front panel thickness of 2 mm and a rear panel thickness of 1 mm has stronger energy absorption capacity and better impact resistance. From this analysis, it can be seen that when designing the sandwich structure, the thickness of the front panel should be larger than that of the back panel so that the energy absorption capacity of the sandwich structure under the same side density can be optimised.

CONCLUSION

This article used ABAQUS nonlinear finite element software to present a progressive damage model for hollow glass microspheres/epoxy resin (HGM/ER) composite foam sandwich structures. The model employed the three-dimensional Hashin failure criterion for damage initiation and integrates a cohesive zone model to capture interlayer damage. Experimental results validate the model's accuracy in predicting material damage behaviour. The study examines how the mass filling rate of microbeads, core layer thickness, and panel thickness affect the damage characteristics under high-speed impact. Key findings include: increasing the filling rate of microbeads enhances impact resistance slightly, but the foam core is not the primary energy absorber; thicker core layers absorb less energy per unit area, and energy absorption decreases with higher impact velocities, suggesting that simply thickening the core is ineffective for lightweight design; conversely, increasing panel thickness improves impact resistance, as the panel serves as the main energy-absorbing component. Thicker front panels enhance energy absorption, highlighting important design considerations for optimising the impact resistance of composite foam sandwich structures.

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