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Bending energy dissipation mechanism of glass fiber/resin composite foam sandwich panel

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Abstract: [**Objectives**] In order to understand the energy absorption mechanism of glass fiber/resin composite foam sandwich panels under bending load, the numerical simulation analysis and experimental study were carried out from the angle of energy dissipation. [**Methods**] The finite element analysis model for glass fiber/resin composite foam sandwich panels was established based on finite element software ABAQUS to simulate and analyze the typical failure mode and energy absorption mechanism under three-point bending and compare the numerical simulation results with test results. Furthermore, the influence of the thickness of the panel and the core on the bearing capacity and energy absorption capacity was further analyzed based on the analysis of the validity of the numerical model. [**Results**] The results show that an increased thickness of composite face sheet can provide higher energy absorption mechanism of glass fiber/resin composite foam sandwich panels. [**Conclusions**] The study in this paper can provide reference for the engineering protection application design of glass fiber/resin composite foam sandwich structure, which has certain theoretical significance and engineering application value.

Key words: composite material; foam sandwich panel; failure mode; energy dissipation

CLC number: U661.43; U663.9+9

0 Introduction

With continuous enhancement of requirements on structural design for impact protection, structures with excellent impact resistance are expected in engineering to meet different impact protection requirements. Composite sandwich structures have light weight, high specific strength, high specific stiffness, good energy absorption, and designable mechanical properties. Therefore, they have been widely used in aerospace, transportation, and ship and ocean engineering for impact protection [1].

For the most widely used glass fiber/resin composite foam sandwich panels, bending is their most common load-bearing and energy-absorbing state under low-speed impact loads. Li et al. [2] pointed out that research on the bending of composite sandwich panels under low-speed impact loads had become the focus in engineering, due to the fact that up to 90% of the structural failure is caused by bending. Xiong et al. [3-5] studied quasi-static and dynamic bending responses of sandwich panels with different material systems. Fan et al. [6] summarized the research progress of lightweight high-strength lattice materials and their mechanical properties. At present, research on the impact resistance of glass fiber/resin composite foam sandwich panels mainly focuses on impact strength, impact stiffness, and post-impact residual strength of overall structures [7-9]. However, little attention has been paid to energy dissipation and

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synergistic energy-absorption compatibility of different material components of structures under impact loads. Thus, it is difficult to provide a method of engineering application value for the design and optimization of impact resistance of sandwich panels.

In this paper, a numerical analysis model of glass fiber/resin composite foam sandwich panel was established based on the finite-element software ABAQUS [10-12]. Then, typical failure modes and energy dissipation mechanisms of such sandwich panels under three-point bending loads were analyzed through simulation. On this basis, the effects of structural sizes of composite faces and cores on energy dissipation of overall structures were analyzed. Thus, it provides a reference basis for the design and optimization of impact resistance of composite sandwich panels.

1 Test verification scheme

1.1 Specimen preparation

Three raw materials were used for preparing specimens of glass fiber/resin composite foam sandwich panel: EWT400 alkali-free glass-fiber twill from Jiangsu Jiuding New Material Co., Ltd. and 510C epoxy vinyl resin from Ashland Group for composite faces, and HP130 foam from DIAB for cores. Fig. 1 shows a specimen. Specifically, a composite face plate had a thickness of 4 mm, consisting of 13 layers of fiber cloth with a laying direction of $[0]_{13}$ and a single-layer thickness of 0.308 mm. The foam had a thickness of 40 mm. The specimen had an overall size (length × width × thickness) of 360 mm × 50 mm × 48 mm.

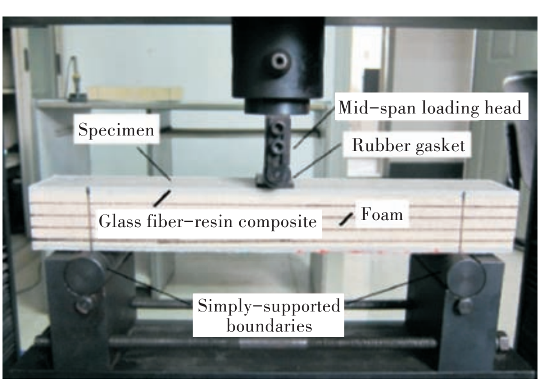


Fig.1 Test plan of three point bending

1.2 Test principle

The quasi-static three-point bending test of the sandwich-panel specimen is a displacement-controlled test, with its process being controlled by artificially-set compression displacement. During the three-point bending test, the compression rate of the mid-span loading head remains stable. This is not exactly the same as the fact that the compression rate of an impact body continuously decreases until zero in an actual impact process. However, for low-speed impact with a rate less than 10 m/s, bending characteristics of a specimen under quasi-static compression are similar to those during the low-speed impact. In addition, it is easier to observe detailed dynamic deformation evolution under quasi-static compression conditions than under normal impact test conditions. Especially, in the case of testing whether a new structure has excellent mechanical load-bearing properties and energy dissipation, quasi-static test research is generally carried out for verification.

The main equipment of the three-point bending test was a 10 t electric-servo universal material testing machine from Xi'an LETRY. In the test, three-point loading was adopted for bending, and simply-supported boundaries were set at the bottom, with a span of 275 mm. Both the mid-span loading head and the bottom simply-supporting tooling were cylinders with a diameter of 20 mm. The mid-span loading head continuously applied a load through displacement, with a loading rate of 2 mm/min, until unloading or obvious structural failure of the specimen. Thus, a complete load-displacement curve was obtained. Fig. 1 shows the loading scheme for the test.

2 Numerical-analysis model

2.1 Model establishment

A numerical-analysis model of the composite sandwich-panel specimen under three-point bending was established by ABAQUS/Explicit. Specifically, the upper and lower composite faces were simulated by continuum shell elements SC8R; the foam core was simulated by three-dimensional solid elements C3D8R; the interfaces between the composite faces and the foam core were simulated by cohesive elements COH3D8. In the model, steel supporting cylinders on both sides of the bottom were of fixed-end boundaries, while the top mid-span loading head had sliding constraints, applying an axial displacement load through the MPC action point. Compared with the composite sandwich-panel specimen, the bottom simply-supporting tooling and the mid-span loading head are of higher stiffness. Therefore, their deformation was ignored in the numerical simulation, and they were defined as discrete rigid bodies. Contact between the loading head as well as the steel supporting cylinders on both sides and the specimen can be defined by the universal contact algorithm in explicit solution analysis. Hard contact was adopted in the normal direction, and the tangential friction coefficient was set to 0.3. Fig. 2 shows the finite-element analysis model of the composite sandwich-panel specimen.

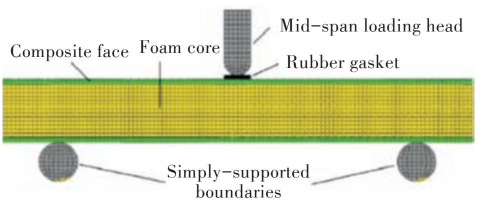


Fig.2 Finite element model of three point bending

2.2 Constitutive models of materials

Two-dimensional Hashin failure criteria were adopted for failure analysis of the surface composite of glass fiber/resin composite foam sandwich panels. Such criteria are based on the degradation of mechanical properties of materials under maximum stress. Table 1 lists test parameters of mechanical properties of the surface composite laminates. Traction-separation bilinear constitutive relation described by the cohesion model in ABAQUS was adopted for interfaces between the composite faces and the foam core. Both stress and strain criteria can be used for failure analysis of glue films, and the quadratic stress criterion was adopted in this paper.

$$D_{\text{init}} = \left[\frac{\langle \sigma_{\text{n}} \rangle}{N_{\max}}\right]^2 + \left[\frac{\sigma_{\text{t}}}{T_{\max}}\right]^2 + \left[\frac{\sigma_{\text{s}}}{S_{\max}}\right]^2 \tag{1}$$

$$\langle \sigma_{\text{n}} \rangle = \begin{cases} \sigma_{\text{n}}, & \sigma_{\text{n}} > 0 \\ 0, & \sigma_{\text{n}} < 0 \end{cases} \tag{2}$$

where σ_{n}, σ_{s} and σ_{t} are interlaminar normal stress and shear stress in two directions, respectively. $N_{\max}$, $T_{\max}$, and $S_{\max}$ correspond to the peak strength of interlaminar tension and shear. The damage started to occur when the initial damage variable D_{init} was equal to 1. Parameters of interfacial mechanical properties are shown in Table 2.

The elastic modulus and Poisson's ratio of the foam core were 170 MPa and 0.36, respectively. As an elastoplastic material, the foam core provides structural stiffness. Therefore, the Crushing-foam constitutive model was selected as the damage failure criterion of the foam core, with its compressive yield-stress ratio of k = 1.73 and plastic Poisson's ratio of v = 0. Table 3 lists plastic stress-strain relationship obtained based on uniaxial quasi-static compression tests of the foam core.

Table 1 Material properties of composite laminate

Attribute	Value
Longitudinal stiffness E_{11}/GPa	25.8
Transverse stiffness E_{22}/GPa	21.8
Out-of-plane stiffness E_{33}/GPa	10
Poisson's ratio v_{12}	0.115
Poisson's ratio v_{13}, v_{23}	0.26
Shear modulus G_{12}/GPa	3.85
Shear modulus G_{13}, G_{23}/GPa	1
Longitudinal tensile strength X_{t}/MPa	489
Longitudinal compressive strength X_{c}/MPa	309
Transverse tensile strength Y_{t}/MPa	276
Transverse compressive strength Y_{c}/MPa	183
Out-of-plane tensile strength Z_{t}/MPa	64.4
Shear strength S_{12}, S_{23}, S_{13}/MPa	33.9
Density ρ/(kg·m^{-3})	1 900

Table 2 Mechanical parameters of glue film

Attribute	Value
Longitudinal stiffness E_{11}/MPa	3 000
Shear modulus G_{13}/MPa	1 160
Shear modulus G_{23}/MPa	1 160
Normal stress σ_{n} /MPa	20 000
Shear stress σ_{s} /MPa	20 000
Shear stress σ_{t} /MPa	20 000
Primary fracture energy G_{IC}/(J·mm^{-1})	0.252
Secondary fracture energy G_{IIC}/(J·mm^{-1})	0.665

Table 3 Elastic-plastic data of the foam core

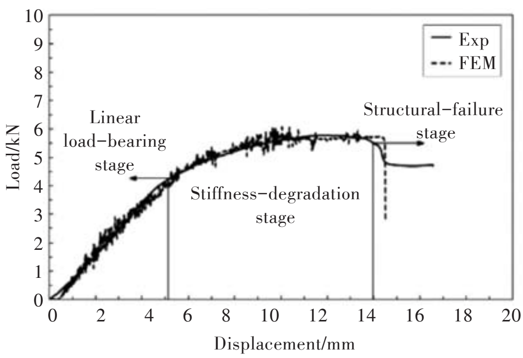
Yield stress/MPa	Plastic strain
1.393	0
1.631	0.003
1.799	0.011
1.854	0.020
1.744	0.032
1.649	0.046
1.671	0.068
1.704	0.126
1.730	0.205

3 Comparative analysis of results

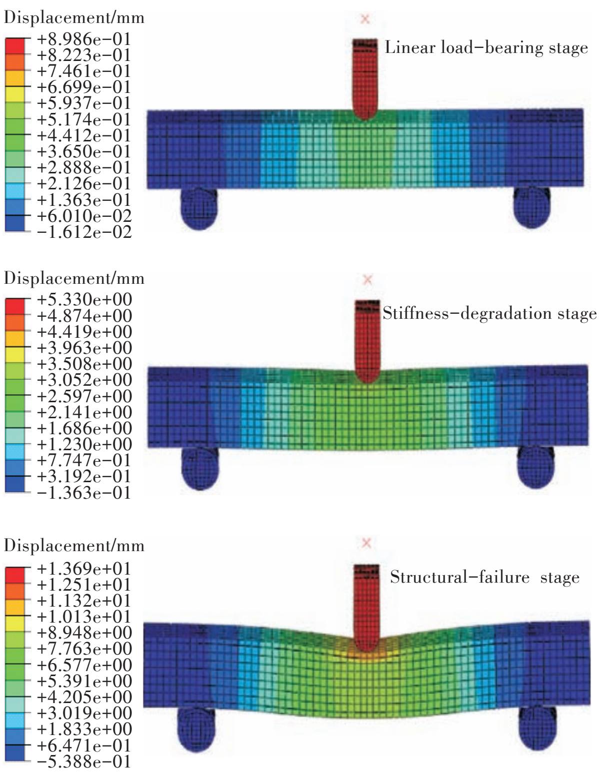
3.1 Effectiveness verification of numerical model

3.1.1 Comparative analysis of bending response characteristics

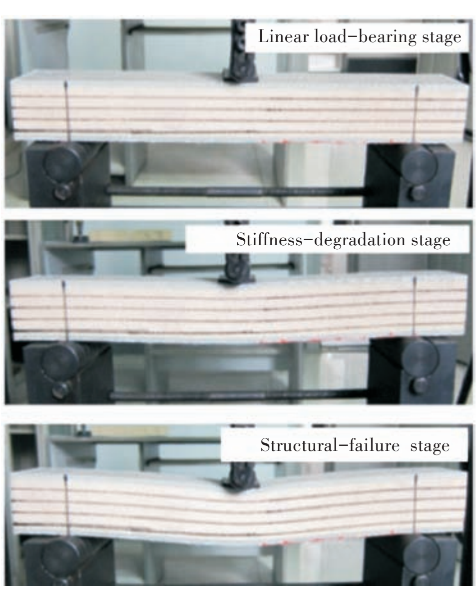
In this section, FEM-calculation and experimental (Exp) results of response characteristics of the composite sandwich-panel specimen under quasi-static three-point bending were comparatively analyzed firstly. On this basis, the effectiveness of the numerical model was verified, and mechanical load-bearing properties and energy dissipation of the composite sandwich-panel specimen were evaluated, as shown in Fig. 3.



(a) Comparison of load-displacement curves



(b) Simulation results



(c) Experimental results

Fig.3 Comparison of experimental and simulation results under three-point bending

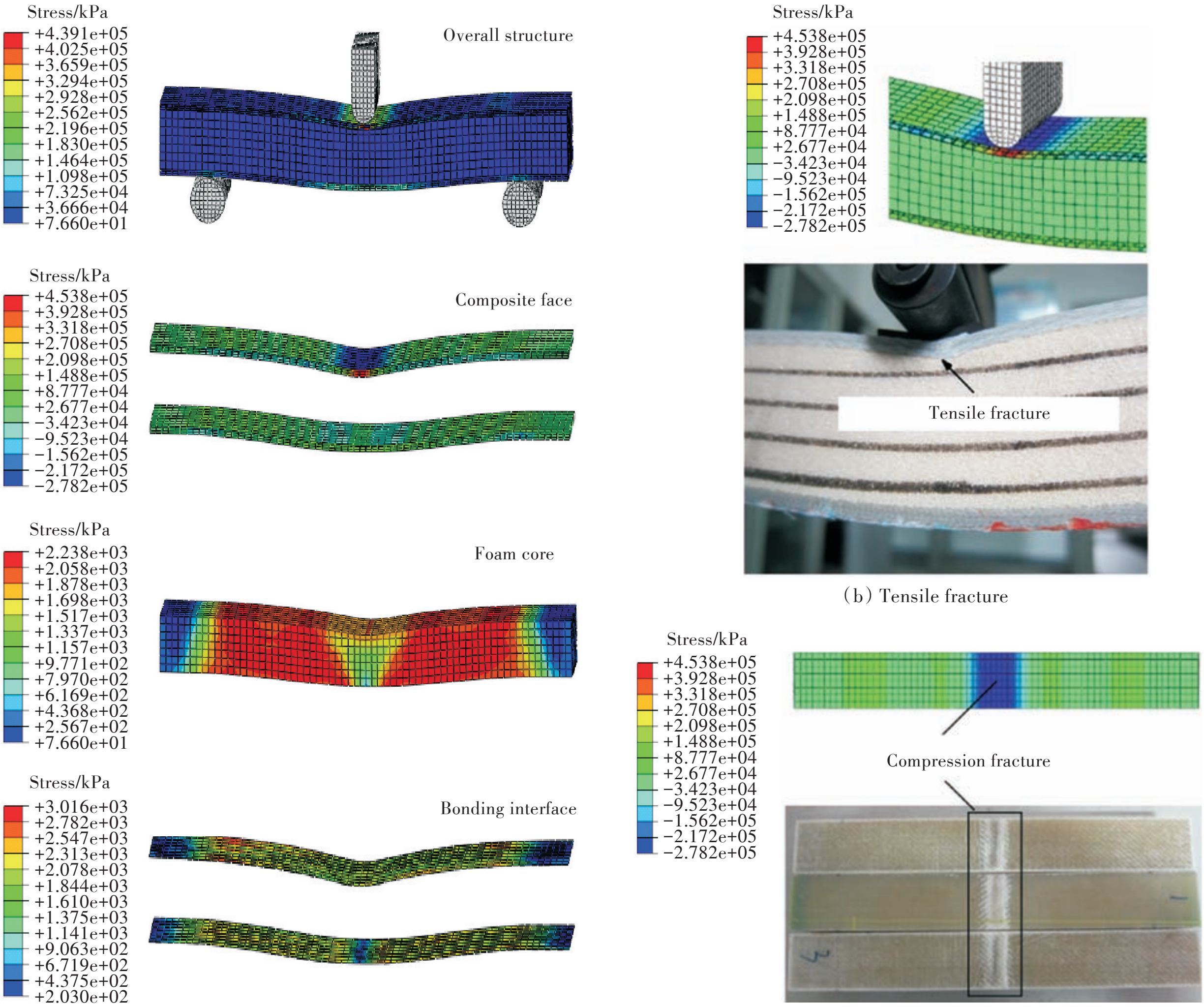
According to the comparative analysis of load-response characteristic curves, the response of the composite sandwich-panel specimen is obviously divided into three stages: a linear-elastic load-bearing stage, a stiffness-degradation stage, and a structural-failure stage. In the initial stage of linear elastic bending, the compression load of the mid-span loading head tends to rise linearly. In the case of the compression load reaching 3.99 kN, structural stiffness is degraded, and the specimen starts to enter the stiffness-degradation stage. However, the load-bearing capacity of the structure still tends to rise, and the compression load is relatively stable in a long compression range. In the case of the compression load reaching 5.76 kN, stiffness degradation of the structure ends, and the load of the mid-span loading head drops greatly. Hence, the specimen enters the structural-failure stage. From Fig. 3 (a), it can be seen that simulation results are in good agreement with experimental ones.

The three-point bending of the composite sandwich-panel specimen can be divided into two stages. In the initial linear-elastic load-bearing stage, the specimen bends as a whole. With the increase in the loading displacement of the mid-span loading head, the stress in the contact area between the loading head and the specimen continuously rises. In the transition from stiffness degradation to structural failure of the specimen, with the continuous enlargement of local indentation, the specimen shows the coexistence of local indentation and overall bending. Simulation results are in good agreement with experimental ones, as shown in Figs. 3 (b) and 3 (c).

3.1.2 Comparative analysis of bending failure modes

In this paper, the damage evolution of the composite sandwich-panel specimen under three-point bending was comparatively analyzed through numerical simulation and high-speed photography. Fig. 4 shows stress contours and final failure modes of different material components of the specimen under ultimate loads.

In the initial stage of quasi-static three-point bending, the specimen is in a linear-elastic bending state. Specifically, the foam core and the composite faces are all in a linear elastic state, jointly bearing the mid-span compression load. When the mid-span compression load increases to 3.99 kN, compression-induced plastic damage occurs in the foam core, which is macroscopically manifested as a reduc-



(a) Stress state of composite material (c) Compression fracture

Fig.4 Bending failure modes of composite foam sandwich panel specimens

tion in structural stiffness of the specimen. In combination with the analysis of the numerical model, it is known that average stress in the foam core within the contact area between the mid-span loading head and the upper face of the specimen is higher than 1.39 MPa. This indicates that the foam core has a large area of plastic damage, resulting in degradation of the structural stiffness of the composite sandwich-panel specimen. At this time, peak tensile stress and peak compressive stress of the upper composite face plate along the span direction in the contact area are only 109.8 and 166.7 MPa, much less than its thresholds of tensile and compressive strength in this direction. Therefore, the upper face plate is still in a linear elastic load-bearing state. After the specimen enters the stiffness-degradation stage, different from the metal structure, this structure undergoes internal stress redistribution and still has a high load-bearing capacity. With the increase in the mid-span compression load and compression deformation, the stress in the composite face plates continuously increases. In the case of the mid-span compression load reaching 5.76 kN, peak tensile stress and peak compressive stress of the upper composite face plate along the span direction in the contact area are up to 453.8 and 278.2 MPa, close to the thresholds of tensile and compressive strength of the composite face plate in this direction. With a further increase in the compression of the mid-span loading head, the specimen will enter the structural-failure stage. Hence, the upper composite face plate undergoes local compression damage to its top and tensile fracture at the interface between its bottom and the foam core. At this time, peak stress in the interface between the composite face plate and the foam core is only 3.02 MPa, much less than the ultimate strength of 20 MPa of the bonding interface. Therefore, no interfacial damage of any form is observed. This is in good agreement with experimental results, indicating a good interface treatment of the specimen. According to the comprehensive analysis, the numerical simulation can yield results consistent with experimental ones, effectively simulating damage failure processes and typical failure modes of glass fiber/resin composite foam sandwich panels.

3.1.3 Comparative analysis of energy dissipation

In combination with the results of ABAQUS numerical simulation, this paper quantitatively analyzed energy dissipation of different material components in the three-point bending of the composite sandwich-panel specimen. In addition, it comparatively analyzed the FEM-calculation results and experimental results (Exp), as shown in Fig. 5. In the figure, E_w is work done by an external load.

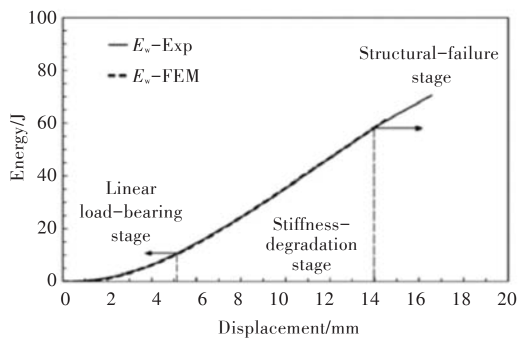


Fig.5 Comparison of experimental and simulation results of total energy

It can be seen from Fig. 5 that E_w curves from the test results (Exp) and the FEM-calculation results are in good agreement with each other.

Overall energy balance of the numerical-analysis model for three-point bending can be expressed as

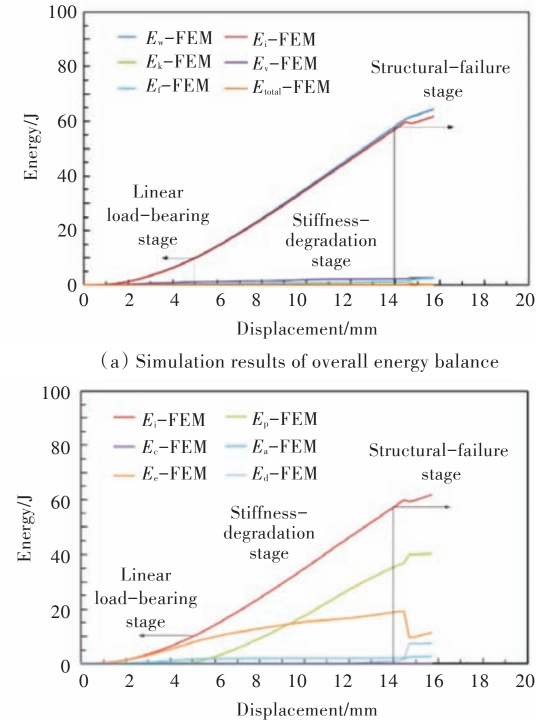
$$E_i + E_v + E_f + E_k - E_w = E_{total} \tag{3}$$

where E_i is internal energy; E_v is viscosity-dissipated energy; E_f is friction-dissipated energy; E_k is kinetic energy; E_{total} is the sum total of these energy components and must be constant, usually with an error of less than 1% in a numerical-analysis model.

$$E_i = E_e + E_p + E_c + E_d + E_a \tag{4}$$

In Formula (4), internal energy represents the sum of energy, including recoverable elastic strain energy E_e, plasticity-dissipated energy E_p, viscoelasticity- or creep-dissipated energy E_c, damage-dissipated energy E_d of composites and interfaces, and artificial strain energy E_a. The artificial strain energy includes energy stored in hourglass resistance and in transverse shear of beam and shell elements. The artificial strain energy E_a is usually less than 5%, and excessive artificial strain energy indicates necessary mesh refinement or modification.

Fig. 6 shows the energy dissipation of the numerical-analysis model for three-point bending.



(a) Simulation results of overall energy balance

(b) Simulation results of internal energy balance

Fig.6 Energy absorption process of model

As can be seen from Fig. 6, most of the work done by the external load on the composite sandwich-panel specimen in the whole loading process is converted into the internal energy of the specimen. Moreover, most of the internal energy is converted into inelastic irrecoverable damage-dissipated energy, as well as recoverable elastic strain energy stored in the structure. Energy is mainly dissipated in the stiffness-degradation stage. In the inelastic irrecoverable damage-dissipated energy, absorbed energy in plastic damage to the foam core accounts for 85%, and absorbed energy in fracture of the composite face plates accounts for only 15%. Table 4 lists the specific distribution of energy dissipation.

Table 4 Energy absorption distribution of model

Energy type	Value/J		
	Overall	Face	Core
Total energy	66	–	–
Friction-dissipated energy	2.6	–	–
Viscosity-dissipated energy	2.8	–	–
Kinetic energy	0.1	–	–
Internal energy	61	–	–
Damage-dissipated energy	7.4	7.4	0
Plasticity-dissipated energy	40.3	0	40.3
Creep-dissipated energy	0	–	–
Linear-elastic strain energy	11.3	8.2	3.1
Artificial strain energy	2.7	–	–

3.2 Effects of structural size on energy dissipation

On the basis of verifying the effectiveness of the numerical-analysis model, this paper further analyzed glass fiber/resin composite foam sandwich panels through numerical simulation. Thus, effects of designed structural sizes on energy dissipation were analyzed, providing a reference for optimal design of impact resistance of composite sandwich panels. Different thicknesses of glass fiber/resin composite foam sandwich panels were briefly recorded as a+b+a. Specifically, a represents the thickness of a composite face plate, which was set to 2-6 mm in the calculation model, and b represents the thickness of a foam core, which was set to 20-60 mm in the calculation model. Numerical simulation results were compared with the calculation results of the 4 + 40 + 4 sandwich-panel specimen described in Section 1.1, as shown in Fig. 7.

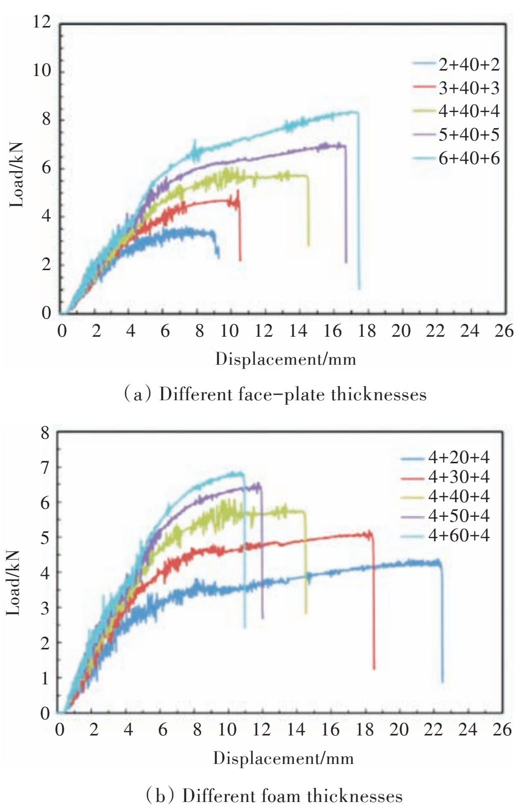


Fig.7 Load-displacement results of composite foam sandwich panels with different dimensions

Fig. 7 (a) shows calculated load-displacement curves of the models with the same thickness of foam cores and different thicknesses of composite face plates. According to the analysis, given a constant foam thickness of 40 mm, in the case of face-plate thicknesses gradually increasing from 2 mm to 6 mm, the initial loading stiffness and yield loads of the load-displacement curves tend to increase gradually. In addition, effective compression of the structures is greatly increased. Thus, overall energy dissipation is effectively enhanced. Fig. 7 (b) shows the load-displacement curves of the models with the same thickness of face plates and different thicknesses of foam cores. According to the analysis, given a constant face-plate thickness of 4 mm, in the case of foam thickness gradually increasing from 20 mm to 60 mm, the initial loading stiffness and yield loads of the load-displacement curves also tend to increase gradually. However, effective compression of the structures is greatly decreased, resulting in degradation of overall energy dissipation of the structures.

In order to quantitatively measure the effects of changes in thicknesses of composite face plates and foam cores on overall energy dissipation of structures, Fig. 8 shows variation curves of specific energy absorption of sandwich panels with different thicknesses of glass fiber-resin composite faces and foam cores. Here, specific energy absorption is defined as the energy absorbed per unit mass of a specimen in a

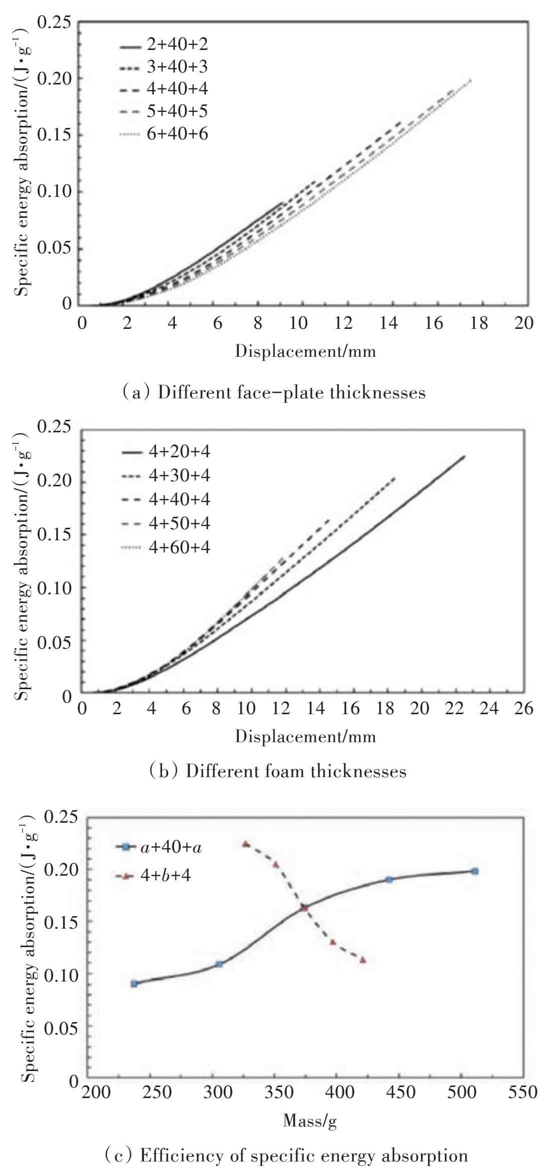


Fig.8 Energy absorption results of composite foam sandwich panels with different dimensions

three-point bending test.

According to Fig. 8, for glass fiber/resin composite foam sandwich panels under three-point bending loads, given a fixed thickness of foam cores, increasing thicknesses of face plates can improve loading stiffness in linear stages of the sandwich panels, initial yield loads, and energy dissipation efficiency in effective loading deformation. Further analysis shows that thickness increasing of composite face plates expands effective loading-deformation ranges of whole structures. As a result, foam cores undergo more sufficient plastic damage in the effective loading-deformation ranges. Thus, the energy dissipation of the whole structure is greatly improved. As shown in Fig. 8 (c), given a foam-core thickness of 40 mm, in the case of thicknesses of upper and lower face plates increasing from 4 mm to 6 mm, i.e., the thickness ratio of the upper or lower face plate to the core of a specimen increasing from 1∶10 to 1∶6.7, specific energy absorption is greatly improved. In the case of a fixed face-plate thickness, increasing foam thicknesses of sandwich panels also improves loading stiffness in linear stages and initial yield loads of the sandwich panels under three-point bending loads. However, the excessive bending stiffness of foam cores can convert deformation of upper composite face plates of specimens from deformation dominated by overall bending to that dominated by local indentation. In addition, the premature appearance of compression-induced fracture of upper composite face plates leads to a decrease in effective loading-deformation ranges of sandwich panels. As a result, the foam cores fail to have sufficient plastic damage. Therefore, specific energy absorption of sandwich panels in such a case tends to decrease with the increase in foam-core thicknesses. As shown in Fig. 8 (c), given a face-plate thickness of 4 mm, in the case of foam-core thicknesses increasing from 20 mm to 40 mm, i.e., the thickness ratio of the upper or lower face plate to the core of a specimen decreasing from 1∶5 to 1∶10, specific energy absorption is greatly reduced. In practical engineering applications, glass fiber/resin composite foam sandwich panels must meet design requirements on structural strength and stiffness. On this premise, reasonably increasing thicknesses and mechanical properties of their composite face plates can effectively improve mechanical load-bearing capacity and energy dissipation of the whole structures.

4 Conclusions

A numerical-analysis model of glass fiber/resin composite foam sandwich panels was established based on the finite-element software ABAQUS. The model can effectively simulate typical failure modes and energy-dissipation mechanisms in three-point bending tests, with numerical simulation results being in good agreement with experimental ones. This provides a basis for impact-resistance design of glass fiber/resin composite foam sandwich panels, showing certain engineering value.

According to the research results, on the premise that weight-based design requirements of protective structures are satisfied, properly increasing thicknesses and mechanical properties of face plates can greatly improve mechanical load-bearing capacity and energy dissipation of glass fiber/resin composite foam sandwich panels. Specifically, a reasonable thickness ratio of the upper or lower face plate to the core is between 1∶8 and 1∶5, which can lead to high energy-absorption efficiency.

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玻璃纤维/树脂复合材料泡沫夹层板弯曲能量耗散机制

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摘　要：[**目的**] 为了解玻璃纤维/树脂复合材料夹层板在弯曲载荷作用下的能量耗散机制，从能量耗散角度开展数值模拟分析和试验研究。[**方法**] 基于有限元软件ABAQUS建立玻璃纤维/树脂复合材料泡沫夹层板的有限元分析模型，对三点弯曲试验中典型的破坏模式和能量耗散机制进行模拟分析，将数值模拟结果与试验结果进行对比。在数值模型有效性分析的基础上，进一步分析面板和夹芯层厚度对玻璃纤维/树脂复合材料泡沫夹层板力学承载性能和能量耗散机制的影响。[**结果**] 结果表明，增加表层复合材料面板厚度能够更大程度地提高玻璃纤维/树脂复合材料泡沫夹层板的比吸能效率。[**结论**] 研究成果可为玻璃纤维/树脂复合材料泡沫夹层结构的工程防护应用设计提供参考，具有一定的理论意义和工程应用价值。

关键词：复合材料；泡沫夹层板；破坏模式；能量耗散