Mechanical response of aluminum foam sandwich structure under impact load

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Abstract
This study investigates the mechanical response of aluminum foam sandwich panels, sandwich cylindrical shells, and sandwich shallow shells under impact loads. First, a finite element model of the sandwich panel was established, and an impact load was applied. The numerical results were compared with theoretical and experimental results to verify the model’s effectiveness. Second, the energy absorption efficiency and overall deformation of sandwich panels, sandwich cylindrical shells, and sandwich shallow shells under the same impact load were studied. The research shows that the energy absorption performance of the sandwich shells is better than that of the sandwich panels, and the overall deformation is less than that of the sandwich panels. The effect of increasing panel thickness on the two types of sandwich shell studies is based on this basis. The conclusions describe that increasing the panel thickness will significantly reduce the structure’s energy absorption efficiency and deformation. Finally, the effect of single- and double-layer structure on the impact resistance of sandwich shells was studied when the total thickness of the sandwich structure was unchanged. The results show that compared with the single-layer structure, the energy absorption efficiency, overall deformation, and contact force between the projectile and structure of the double-layer structure will be reduced.

1. Introduction
As a composite material, the aluminum foam sandwich panel has good impact resistance and energy absorption owing to the energy absorption of aluminum foam and the high strength of steel, which is widely used in many protective structures in the aerospace and automobile industry [1–3]. Moreover, it has attracted many scholars to simulate and study its quasi-static and dynamic mechanical properties [4–9].

Radford et al [10] conducted impact tests and numerical simulations of aluminum foam sandwich panels. The research shows that adding aluminum foam can increase energy absorption and reduce structural deformation. Zhang et al [11] conducted experimental and mesoscopic research on double-layer aluminum foam under an impact load. First, aluminum foam’s static and dynamic mechanical response is studied experimentally, and the mechanical properties of single-layer and double-layer structures were analyzed. Then, the dynamic response of aluminum foam was studied through the mesoscopic model of x-ray computerized tomography images, and the deformation of the double-layer structure under high-velocity impact was analyzed. Results description density distribution is significant for crushing. Ren et al [12] conducted an experimental study on the quasi-static compression properties of a multilayer aluminum foam sandwich structure and discussed the influence of density, stacking number, and interlayer board on the multilayer sandwich structure. The research shows that, compared with monolithic aluminum foam, the mechanical properties of the multilayer foam core structure were slightly reduced, while the compressive performance of the multilayer sandwich structure was significantly improved. Damghani et al [13] studied the aluminum foam sandwich structure’s energy absorption under dynamic load through numerical simulation. The effects of foam
cores with different relative densities and projectiles with different speeds and qualities on the sandwich structure’s deformation and energy absorption were acquired. The results are in good agreement with the experimental. Xia et al [14] analyzed the impact resistance of aluminum foam sandwich panels through experiments, theories, and numerical simulations. The research shows that the sandwich panel’s impact resistance mainly relies on increasing the deformation of the aluminum foam core to dissipate energy. The thicker the core layer, the more significant the proportion of energy absorption of the aluminum foam, the smaller the overall deformation of the sandwich panel, and the greater the impact resistance. Wang et al [15] studied aluminum foam sandwich panels’ deformation and failure modes under explosive loads through experiments. The research shows that the aluminum foam presents a ‘gradual’ compression deformation, and the deformation deflection at the center point of the back panel of the aluminum foam sandwich panel and the explosive impulse is approximately in a quadratic relationship. Liu et al [16] used the numerical simulation to prove that a hollow cylindrical shells sandwich structure with a gradient metal foam core has a better blast resistance than hollow cylindrical shells without a gradient foam core. Through experiments and numerical simulations, Jing et al [17–20] studied the effect of geometric structure (i.e., panel thickness, the relative density of core layer, and sample curvature) on the energy absorption and destruction of cylindrical metal shells under dynamic loads. Pan et al [21] conducted a finite element analysis on the mechanical properties of the double-layer aluminum foam sandwich curved panels. The above studies involved the study of sandwich panels and sandwich cylindrical shells. However, they did not compare the mechanical properties of sandwich panels and sandwich cylindrical shells under impact loads, and there is no research on the mechanical properties of sandwich shallow shells under impact loads.

Based on the above, this study uses ANSYS/LS-DYNA to study the mechanical response of aluminum foam sandwich panels, sandwich cylindrical shells, and sandwich shallow shells under impact loads. The effects of different impact loads were simulated by varying the incident velocities of the aluminum foam projectiles. The effects of panel thickness and delamination on the mechanical properties of sandwich cylindrical and shallow shells were further studied.

2. Model validation

Compared with sandwich cylindrical shells and shallow shells, sandwich panels have an uncomplicated preparation and are relatively easy to obtain. In addition, the mechanical response of aluminum foam sandwich panels under impact loads has a relatively complete theoretical system and a large number of experimental results. Therefore, this study used aluminum foam sandwich panels to verify the finite element model.

2.1. Material properties
The aluminum foam sandwich structure consists of a front panel, an aluminum foam core, and a back panel. The two panels are made of aluminum alloy with a thickness of 0.5 mm. The material properties are as follows: density: \( \rho = 2780 \text{ kg m}^{-3} \), elastic modulus: \( E = 68 \text{ GPa} \), Poisson’s ratio: \( \mu = 0.33 \), yield strength: \( \sigma_y = 310 \text{ MPa} \), shear modulus: \( G = 28 \text{ GPa} \). The middle core layer was filled with aluminum foam with different relative densities (relative density \( \rho = 11\%, 15\%, \) and \( 18\% \)), and the thickness is 10 mm. The materials stress-strain curves are given in figure 1. The properties of these materials are listed in table 1.

2.2. Finite element model
The entire model was divided into four parts: projectile, front panel, aluminum foam, and back panel. The projectile is a cylinder with a diameter of 36.5 mm and length of 80 mm. For sandwich cylindrical and shallow shells, the radius of curvature \( R = 500 \text{ mm} \), and the central angle is \( \theta = 28.6^\circ \). The cylindrical shell arc length \( L_1 \) was calculated according to the arc length formula \( L = \theta n R / 180^\circ \), and the width \( L_2 \) is equal to the arc length. The length and width of the shallow shell were obtained using the arc length formula \( L = \theta n R / 180^\circ \). The overall dimensions of the three aluminum foam sandwich structures are 250 mm \( \times \) 250 mm \( \times \) 10 mm. The model was established and solved using the ANSYS/LS-DYNA software. The projectile was described by "MAT_HONEYCOMB and 3D Solid 164 elements, the aluminum alloy panel was described by "MAT_PLASTIC_KINEMATIC and Thin Shell 163 elements, and the aluminum foam core was described by "MAT_CRUSHABLE_FOAM and 3D Solid 164 elements. The panel and aluminum foam were connected to a common node. Moreover, failure criteria were set for the panel and aluminum foam. The panel adopts failure strain \( FS = 0.12 \) of the set material model, and the aluminum foam adopts maximum shear strain of the plastic motion constitutive model MSS = 0.4. When the strain generated by the element exceeded the set value, it was deleted. The projectile uses surface-to-surface erosion contact with the entire aluminum foam sandwich structure. Both the projectile and aluminum foam core use automatic single-surface contact, and the contact between the panel and aluminum foam core uses automatic surface-to-surface contact. Because the aluminum...
foam sandwich structure is mainly fixed on the structure in actual engineering, the boundary conditions can be approximated as fixed boundary conditions. In the simulation process, fixed boundary conditions were simulated by constraining all degrees of freedom of all nodes on the four sides of the model. Owing to the symmetry of the structure, the 1/4 model was adopted, and symmetric boundary conditions were set on the Z-Y and Z-X surfaces of the sandwich panels. Symmetric boundary conditions were set on the X-Z and X-Y surfaces of the sandwich cylindrical shells and sandwich shallow shells. The finite element models of the three structures are shown in figure 2.

2.3. Model validation

To test the validity of the numerical model, the numerical results of the aluminum foam sandwich panel (the relative density of the aluminum foam core is $\rho = 11\%$) established in this study are compared with the theoretical and experimental. The impact load is defined by the loading impulse $I$, $I = m \cdot \dot{v}$, where $m$ is the projectile’s mass, and $\dot{v}$ is the projectile’s velocity. The loading impulse corresponding to the experiment was achieved in the simulation process by fixing the projectile mass and changing the projectile incident velocity. The deformation and the final length of the projectile after impact are described using the Hawkyard energy method [22], and the equation of the projectile’s initial velocity $v_0$ and the projectile’s strain $\varepsilon_0$ is

$$\frac{1}{2} \rho_0 v_0^2 = \sigma_y \ln \left( \frac{1}{1 - \varepsilon_0} \right) - \varepsilon_0$$

(1)

where $\rho_0$ is the projectile’s density and $\sigma_y$ is the projectile’s yield strength. After the impact, the length $X$ of the undeformed part of the projectile is $X = L_p (1 - \varepsilon_0)$, where $L_p$ is the projectile’s initial length. The length of the final deformed part of the projectile is

$$H = L_p (1 - \varepsilon_0) \ln \left( \frac{1}{1 - \varepsilon_0} \right)$$

(2)

The total length of the projectile after the impact is $L_f = X + H$. The theoretical and numerical simulation lengths of the projectile after impact are shown in figure 3.

![Figure 1. Stress-strain curve of aluminum foam for simulation.](image-url)

![Figure 2. Finite element models of the three structures.](image-url)

![Figure 3. Comparison of theoretical and numerical simulation lengths of the projectile.](image-url)

| Materials          | Density (kg m$^{-3}$) | Young’s modulus (GPa) | Poisson ratio | Yield stress (MPa) |
|--------------------|-----------------------|-----------------------|---------------|--------------------|
| Aluminum foam (11%)| 297                   | 0.6                   | 0.2           | 5.3                |
| Aluminum foam (15%)| 405                   | 1.0                   | 0.2           | 5.49               |
| Aluminum foam (18%)| 485                   | 1.0                   | 0.2           | 7.11               |
| Foam projectile    | 600                   | 1.0                   | 0.285         | 7.0                |

Table 1. Material properties.
The projectile impact the deformation of the front panel after the sandwich panel can be described by the following formula proposed in the literature [14]:

$$\delta_1 = v \sqrt{\frac{m}{2} \left( \frac{1}{13.2\sigma_y h} + \frac{2l}{\pi^2 b (2h\sigma_y + c\sigma_p)} \right)}$$

where $\delta_1$ is the deformation value of the center point of the front panel, $v$ is the projectile’s initial velocity, $m$ is the projectile’s mass, $\sigma_y$ is the panel’s yield strength, $\sigma_p$ is the aluminum foam’s yield strength, $h$ is the panel’s thickness, and $c$ is the aluminum foam’s thickness, $b$ is the sandwich panel’s width, and $l$ is the sandwich panel’s calculated span. The theoretical and simulated deformation values at the center point of the front panel are shown in figure 4. The simulated deformation value of the center point of the back panel and the experimental values in the literature [23] are shown in figure 5. According to figures 3–5, the simulated values were in good agreement with the theoretical and experimental values, indicating that the finite element model established in this study was reliable.
3. Effect of shape on aluminum foam sandwich structure

This section discusses the mechanical response of aluminum foam sandwich panels, sandwich cylindrical shells, and sandwich shallow shells under impact loads. Figure 6 shows the deformation diagram of the three structures under impulse $I = 5.014 Ns$, and figure 7 shows the velocity-time history curve of each of the three structures under the corresponding impulse. The slope of the three structures in the velocity increase section indicates that the front panel is larger than the aluminum foam, and the aluminum foam is larger than the back panel. After the impact stabilized, the velocities of the three parts tended to the same stable value. This shows that when the sandwich structure is impacted, the front panel is first squeezed, then the aluminum foam is squeezed, and finally, the back panel is squeezed. After a short time, the velocities of the three parts tended to be consistent, and the deformation of the entire sandwich structure reached a stable state.

Figure 8 shows the energy absorption of the three structures under an impact load. We can know from the figure that the energy absorption of the three relative density sandwich structures is consistent. With an increase in impulse, the energy absorption of the three structures increases, but under the same impact load, the energy absorption from low to high is the sandwich panel, sandwich cylindrical shell, and sandwich shallow shells.
Moreover, when the impulse reaches its maximum value, in the three figures (a), (b), (c), the energy absorbed by the sandwich cylindrical shell is 23%, 27%, and 20% higher than that of the sandwich panel; the energy absorbed by the sandwich shallow shell is 46%, 54%, and 40% higher than that of the sandwich panel. It shows that the energy absorption of the sandwich shell is significantly better than that of the sandwich panel.

Figure 9 shows the overall deformation of the three aluminum foam sandwich structures under an impact load. As shown in the figure, the overall deformation of the three sandwich structures increases with impact load. However, under the same impact load, the overall deformation of the sandwich panel was greater than that of the sandwich shell, and the overall deformation in descending order was the sandwich panel, sandwich cylindrical shell, and sandwich shallow shell. Moreover, when the impulse reaches its maximum value, in the three figures (a), (b), (c), the overall deformation of the sandwich cylindrical shell is 34%, 18%, and 21% smaller than that of the sandwich panel; the overall deformation of the sandwich shallow shell is 45%, 30%, and 37% smaller than that of the sandwich panel.

Figure 10 shows the velocity-time history curves of the three aluminum foam sandwich structures under impact loads. It can be seen from the figure that under the three relative densities, when the impact stabilizes, the structural velocities from high to low are the sandwich panel, sandwich cylindrical shell, and sandwich flat shell.

As shown in figures 8–10, the sandwich shell is superior to the sandwich panel in terms of structural energy absorption, overall deformation, and velocity after impact stabilization. Therefore, converting the aluminum foam sandwich structure into a curved structure can effectively improve energy absorption, reduce overall deformation, and reduce the velocity of the structure after impact.

4. Effect of panel thickness on the mechanical properties of sandwich structure

From the previous section, we know that converting the aluminum foam sandwich structure into a curved structure can effectively improve energy absorption, reduce overall deformation, and reduce the velocity of the structure after impact. Therefore, this section mainly focuses on the influence of the panel thickness on the mechanical properties of sandwich cylindrical shells and sandwich shallow shells. The thickness of the front and back panels is increased from h = 0.5 mm to h = 0.9 mm, and other conditions remain unchanged. Figure 11 shows the energy absorptions of the two sandwich shells. It can be seen from the figure that the energy absorption of the two sandwich shells decreases as the thickness of the panel increases. However, the energy absorption of the sandwich shallow shell with the same thickness was still higher than that of the sandwich cylindrical shell, which is consistent with the conclusion shown in figure 8.

Figure 12 shows the overall deformation of the two sandwich shells. It can be observed from the figure that when the thickness of the panel increases, the overall deformation of the two sandwich shells decreases. Moreover, the overall deformation of the sandwich shallow shell of the same thickness is still smaller than that of the sandwich cylindrical shell, which is consistent with the conclusion shown in figure 9.
Figure 7. Velocity time history curves of each part of the three structures ($\rho = 11\%$, $I = 5.014N\cdot ms$).

(a) Aluminum foam sandwich panel.

(b) Aluminum foam sandwich cylindrical shell.

(c) Aluminum foam sandwich shallow shell.
As shown in figures 11 and 12, increasing the panel thickness will reduce the energy absorption and overall deformation of the sandwich shell. This is because increasing the shell thickness improves the structure’s...
Figure 9. Overall deformation of aluminum foam sandwich structures with different shapes.

(a) Aluminum foam core's relative density is 11% $(\rho=11\%)$.

(b) Aluminum foam core's relative density is 15% $(\rho=15\%)$.

(c) Aluminum foam core's relative density is 18% $(\rho=18\%)$.
stiffness, enhancing the structure’s ability to resist deformation while reducing the plastic deformation of the aluminum foam, thus reducing the energy absorption of the structure.

Figure 10. Velocity time history curves of three structures under impact load.

(a) Aluminum foam core's relative density is 11% 
\[ I = 5.014Ns \].

(b) Aluminum foam core's relative density is 15% 
\[ I = 3.7605Ns \].

(c) Aluminum foam core's relative density is 18% 
\[ I = 2.507Ns \].
Figure 11. The energy absorbed by sandwich structures with diverse panel thicknesses.

(a) Aluminum foam core's relative density is 11%.

(b) Aluminum foam core's relative density is 15%.

(c) Aluminum foam core's relative density is 18%.
(a) Aluminum foam core's relative density is 11%.

(b) Aluminum foam core's relative density is 15%.

(c) Aluminum foam core's relative density is 18%.

Figure 12. Overall deformation of the sandwich structures.
5. Comparison of mechanical properties of single-and double-layer sandwich structures

This section mainly studies the effect of single-and double-layer structures on the mechanical properties of aluminum foam sandwich shells. When the total thickness of the structure remained unchanged, the two sandwich shells changed from single-layer to double-layer. The single-layer structure consists of the front panel, the back panel, and the aluminum foam. The thickness of the two panels is 0.9 mm, and the thickness of the aluminum foam is 10 mm; The double-layer structure consists of five parts: the front panel, the upper aluminum foam, the middle panel, the lower aluminum foam, and the back panel. The thickness of the three panels is 0.6 mm, and the thickness of the two aluminum foam cores is 5 mm. The two sandwich shells' single-layer finite element models are shown in figures 2(b) and (c), and the double-layer finite element model are shown in figure 13.

Figure 14 shows the energy absorption of two sandwich shell single-layer and double-layer structures. It can be seen from the figure that when the impulse is small, there is almost no difference in the energy absorption between the single-layer and double-layer structures of the two sandwich shells. However, with the increase of impulse, the energy absorption of the double-layer structure of sandwich cylindrical and shallow shells gradually becomes less than that of the single-layer structure. When the impulse reaches its maximum value, the energy absorption of the sandwich cylindrical shell double-layer structure is reduced by 16%, and the sandwich shallow shell double-layer structure is reduced by 6%.

Figure 15 shows the energy absorption of the upper and lower aluminum foams of the two sandwich shell double-layer structures. It can be seen from the figure that whether it is a sandwich cylindrical shell or a
sandwich shallow shell, the energy absorption of the upper aluminum foam is higher than that of the lower aluminum foam. Figure 16 shows the overall deformation of the single-layer and double-layer structures of the two sandwich shells under an impact load. It can be seen from the figure that the overall deformation of the two sandwich shells' double-layer structures is smaller than that of the single-layer structures. When the sandwich structure is impacted, the front panel is first squeezed, then the aluminum foam is squeezed, and finally, the back panel is squeezed. The energy transmission path is the front panel-aluminum foam-back panel. When it is a double-layer structure, the thickness of the front panel decreases due to the middle panel’s addition. When the projectile impacts, the energy transmission path is the front panel, upper aluminum foam, middle panel, lower aluminum foam, and back panel. Due to the greater stiffness of the middle panel, the plastic deformation of the lower aluminum foam is restricted, thereby reducing the energy absorption of the lower aluminum foam. In addition, owing to the high stiffness of the middle panel, it can effectively resist deformation and reduce the impact of the lower aluminum foam and back panel; thus, the overall deformation of the structure can be effectively reduced.
Figure 17 shows the contact force curves between the projectile and the entire structure under impulse $I = 4.5126N\cdot s$ for the single-layer and double-layer structures of the two sandwich shells. Figure 18 shows the peak contact force between the projectile and the entire structure under different impact loads of the single-layer and double-layer structures of the two types of sandwich shells. It can be seen from figure 18 that whether it is a sandwich cylindrical shell or a sandwich shallow shell, the contact force of the projectile with the entire structure under the double-layer structure is smaller than the corresponding contact force of the single-layer structure.

In summary, whether it is the sandwich cylindrical shell or sandwich shallow shell, the structure changes from single-layer to double-layer under the condition that the total thickness remains unchanged. Although the energy absorption efficiency is reduced, it can reduce the deformation of the structure under an impact load, reduce the contact force between the projectile and the entire structure, and improve the impact resistance of the structure.

6. Conclusions

This study investigated the mechanical responses of aluminum foam sandwich panels, sandwich cylindrical shells, and sandwich shallow shells under impact loads. The sandwich shells were found to have a better energy absorption efficiency than the sandwich panels. Subsequently, the effect of the thickness of the panel on the
mechanical properties of the sandwich shells was studied. Finally, the effect of the single-layer and double-layer structure on the mechanical properties of the aluminum foam sandwich shells was studied under the condition that the overall thickness of the sandwich shell remains unchanged. The main conclusions are as follows.

(1) Under the same impact load, the energy absorption of the three sandwich structures in descending order is as follows: sandwich shallow shell, sandwich cylindrical shell, and sandwich panel. The overall deformation from high to low is sandwich panel, sandwich cylindrical shell, and sandwich shallow shell. Moreover, the overall velocity of the structure after the impact stabilizes is also that the sandwich shallow shell is smaller than the sandwich cylindrical shell, and the sandwich cylindrical shell is smaller than the sandwich panel.

(2) When impulse $I = 6.2675 \text{Ns}$ and the relative density of 11% in the aluminum foam sandwich structure, the energy absorbed by the sandwich cylindrical shell and the sandwich shallow shell is 23% and 46% higher than that of the sandwich panel; the overall deformation is 34% and 45% smaller than that of the sandwich panel. When the aluminum foam's relative density is 15%, the energy absorbed by the sandwich cylindrical shell and the sandwich shallow shell is 27% and 54% higher than that of the sandwich panel; the overall deformation is 18% and 30% smaller than that of the sandwich panel. When the aluminum foam's relative density is 18%, the energy absorbed by the sandwich cylindrical shell and the sandwich shallow shell is 20% and 40% higher than that of the sandwich panel; the overall deformation is 21% and 37% smaller than that of the sandwich panel.

(3) Increasing the thickness of the panel will reduce the energy absorption and overall deformation of the sandwich shell. However, under the same impact load, the energy absorption of the sandwich shallow shell is still higher than that of the sandwich cylindrical shell, and the overall deformation is smaller than that of the sandwich cylindrical shell.

(4) Under the condition that the overall thickness of the sandwich shell remains unchanged, compared with the single-layer structure, the double-layer structure has a reduced energy absorption efficiency. However, it can reduce the deformation of the structure under an impact load, reduce the contact force of the projectile and the entire structure, and improve the impact resistance of the structure.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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References

[1] Guo Q Y et al 2017 Research status and preparation of aluminum foam composite structure Light Metal Material 251–7
[2] Tian K N et al 2015 Status and prospect of finite element simulation of aluminum foam sandwich structure mechanical property Foundry Equipment and Technology 48–52
[3] Cheng P et al 2018 Structure performance optimization of double-layer aluminum foam sandwich panels under rockfalls impact Journal of Vibration and Shock 37 85–91
[4] Ruan D, Lu G X and Wong Y C 2010 Quasi-static indentation tests on aluminum foam sandwich panels Compos. Struct. 92 2039–46
[5] Wang N Z et al 2016 Three-point bending performance of a new aluminum foam composite structure Transactions of Nonferrous Metals Society of China 26 359–68
[6] Tang E L, Zhang X Q and Han Y F 2019 Experimental research on damage characteristics of CFRP/aluminum foam sandwich structure subjected to high velocity impact J. Mater. Res. Technol. 8 4620–30
[7] Guo K L et al 2019 Numerical study on mechanical behavior of foam core sandwich plates under repeated impact loadings Compos. Struct. 224 111030
[8] Tang E L et al 2020 Simulation of CFRP/aluminum foam sandwich structure under high velocity impact Journal of Materials Research and Technology 9 7273–87
[9] Zhao Y et al 2021 Mechanical properties and energy absorption capabilities of aluminum foam sandwich structure subjected to low-velocity impact[J] Constr. Build. Mater. 273 121996
[10] Radford D D et al 2006 The response of clamped sandwich plates with metallic foam cores to simulated blast loading Int. J. Solids Struct. 43 2243–59
[11] Zhang J H et al 2020 Experimental and mesoscopic investigation of double-layer aluminum foam under impact loading Compos. Struct. 241 110859
[12] Cheng X R et al 2019 Experimental study on the quasi-static compression behavior of multilayer aluminum foam sandwich structure J. Alloys Compd. 810 151860
[13] Damghani M N and Gonabadi A M 2019 Numerical study of energy absorption in aluminum foam sandwich panel structures using drop hammer test J. Sandwich Struct. Mater. 21 3–18
[14] Xia Z C et al 2017 Analysis on impact resistance of aluminum foam sandwich panels Engineering Mechanics 34 207–16
[15] Wang T et al 2016 Experimental investigation into deformation and damage patterns of sandwich plates with aluminum foam core subjected to blast loading Acta Armamentarii 37 1456–63
[16] Liu X R et al 2012 Blast resistance of sandwich-walled hollow cylinders with graded metallic foam cores Compos. Struct. 94 2485–93
[17] Jing L et al 2013 Blast resistance of clamped cylindrical sandwich shells with metallic foam cores Key Eng. Mater. 535–536 461–4
[18] Jing L et al 2013 Dynamic response of cylindrical sandwich shells with metallic foam cores under blast loading—numerical simulations Compos. Struct. 99 213–23
[19] Jing L et al 2013 A numerical simulation of metallic cylindrical sandwich shells subjected to air blast loading Latin American Journal of Solids and Structures 10 631–45
[20] Jing L et al 2013 Energy absorption and failure mechanism of metallic cylindrical sandwich shells under impact loading Mater. Des. 52 470–80
[21] Pan X and Zhang J Y 2019 Numerical study on impact resistance of double-layer aluminum foam curved sandwich plates Mater. Res. Express 6 046556
[22] Ren H L and Ning J G 2013 Shock Dynamics of Solid (Beijing: National Defense Industry Press) 221–2
[23] Song Y Z 2009 Investigation on plastic dynamic response of sandwich plates with cellular metallic materials subjected to foam aluminium projectile impacting Taiyuan University of Technology 34–9