Mechanical Response of Square Honeycomb Sandwich Plate with Asymmetric Face Sheet Subjected to Blast Loading

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Abstract

Sandwich structures are widely used in many important engineering to resist the blast loading. In order to improve the capacity of energy absorption, topology of core structure, e.g. foam, folded plate, square and hexagonal honeycombs, and pyramidal truss is studied. However, very few investigations have been carried out to study the dynamic mechanical response and energy absorption of sandwich plate with asymmetric face sheet. In this paper, the dynamic mechanical response of sandwich plate with asymmetric face sheet is numerically analyzed using LS-DYNA code. For the sandwich plate with asymmetric face sheet, the thickness of core, the thickness of wall, the cell size and the mass of sandwich plate are fixed in analysis. We take the thickness ratio \( \delta \) of the upper face sheet to the lower face sheet to be \( \frac{2}{5}, \frac{3}{4}, 1, \frac{4}{3} \) and \( \frac{5}{2} \), respectively. The maximum deflection and energy absorption of the sandwich plate subjected to blast loading are investigated for different \( \delta \). And the performance of the sandwich plate is compared to that of the solid plate with the same mass and the same material. The efficiency of energy absorption and the performance of resistance to blast are also obtained for the five structures under the same mass of TNT charge. The effect of \( \delta \) on the dynamic response of square honeycomb is discussed. The results can be used for optimizing design of sandwich plate with enough resistance to blast.

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1. Introduction

Blast protection is important in engineering, such as some critical structures, buildings, devices, etc.

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Sandwich structures are widely used in production engineering due to the excellent performance of ultra-light, higher stiffness and strength to weight ratios, and energy absorption capability. In order to improve the capacity of energy absorption, different topology of core structures are studied, e.g. foam, folded plate, square and hexagonal honeycombs, and pyramidal truss, etc.

More recently, the static and dynamic responses of sandwich structures are widely investigated by Qin et al. [1-5], Dharmasena et al. [6] and Wang et al. [7,8]. In these structures, the thicknesses of both face sheets are identical. Few researchers focused on the dynamic response of sandwich structure with different thickness of face sheet. In this paper, the dynamic mechanical response of the square honeycomb sandwich plate with the different thickness ratio $\delta$, which is defined as the thickness ratio of the upper face sheet to that of the lower face sheet, as $2/5$, $3/4$, $1$, $4/3$ and $5/2$ subjected to blast loading is studied. As a comparative study, the dynamic mechanical response of a solid monolith plate is also done.

2. Models of Numerical Simulation

2.1. Geometrical Models

In this paper, the sandwich plate and the solid monolith plate with the area of 500mm×500mm and the same mass are studied. For both plates, the materials are homogeneous and isotropic. And both are full clamped in four edges. According to the symmetry, a quarter of the square plate with 250mm×250mm is modeled. The thickness of the square honeycomb core is 25mm. And the length of the cell is also 25mm and the wall thickness is 0.5mm. For different $\delta$, the mesh figures are shown in Fig.1. All the six structures have the same mass and the sandwich plates have the same core.

2.2. Material Models

The material of face sheets and core of square honeycomb sandwich panel are both aluminum alloy, the former is Al2024 and the latter is Al3104. In the simulation, the mechanical behavior of aluminum alloy is modeled by isotropic and kinematic hardening plasticity, which is labeled as *MAT_PLASTIC_KINEMATIC in LS-DYNA code. For aluminum alloy, the strain ratio effect is ignored in this paper. For Al2024, the mass density is 2.68g/cm³, Young’s modulus is 72GPa, Poisson’s ratio is 0.33, Yield stress is
75.8 MPa and Tangent modulus is 737 MPa. For Al3104, the mass density is 2.72 g/cm³, Young’s modulus is 69 GPa, Poisson’s ratio is 0.34, Yield stress is 262 MPa and Tangent modulus is 690 MPa. For hardening parameter $\beta=0.5$, it shows that kinematic hardening and isotropic hardening are both action and quits.

2.3. Blast Loading

In this paper, the structures are applied the blast loading by virtue of the keywords of *LOAD_BLAST and *LOAD_SEGMENT_SET in LS-DYNA code. The keyword *LOAD_BLAST defines an air blast function for the application of pressure loading due to explosives in conventional weapons. In this paper, the pressure loading on the structure is determined by the ConWep function which is an exponential decay of the incident and reflected pressure with time,

$$P(t)=P_{so}\left[1-(t-T_a)/T_0\right]\exp\left[-A\times(t-T_a)/T_0\right]$$

where, $P(t)$ is the pressure at time $t$ (kPa), $P_{so}$ is the peak incident pressure (kPa), $T_0$ is the positive phase duration (msec), $A$ is the decay coefficient (dimensionless), and $T_a$ is the arrival time (msec) [9].

The loading adds to the upper face sheet using the keyword *LOAD_SEGMENT_SET. With the interaction of blast loading and the structure, a large deformation including plastic bending, stretching and bulking occurs. We define the contact type as *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE between the upper face sheet, the core and the lower face sheet to prevent the penetration of materials.

3. Results and Discussion

3.1. Deformation of Sandwich Plate and Solid Plate

For different sandwich plate, the dynamic response is different at the same mass of TNT charge. Fig. 2 shows the different mechanical response of five sandwich plates and a solid plate with the action of shock wave caused by 800 g TNT explosive charge.

![Mechanical response of six structures subjected to blast loading of 800 g TNT charge](image)

Fig. 2. Mechanical response of six structures subjected to blast loading of 800 g TNT charge (a) $\delta=2/5$, (b) $\delta=3/4$, (c) $\delta=1$, (d) $\delta=4/3$, (e) $\delta=5/2$ and (f) solid plate

As can be seen from Fig. 2(a), when the thickness ratio $\delta$ equals to $2/5$, the main deformation patterns of sandwich plate include the local dent of the upper face sheet, the core buckling and densification...
besides the overall stretching and bending of sandwich plate. With the increase of \( \delta \), the local dent of the upper face sheet weakens. For a larger \( \delta \), especially \( \delta = 5/2 \), the deformation pattern changes to the buckling of the lower face sheet. For the blast loading of 800g TNT charge, the core of four structures except (e) is densified as a progressive type from the top to the bottom. But the deformation pattern of the solid plate is overall stretching and bending. At the same time, the rear surface of the solid plate is in tensile with the action of the reflected rarefaction wave. And the intensity of the reflected rarefaction wave of the solid plate is higher than that of sandwich plate.

According to the analytical model\([10]\), the whole deformation procedure of clamped circular sandwich plate subjected to shock loading can be split into three phases:

Phase I: The blast impulse is transmitted to the upper face sheet of the sandwich structure, and the upper face sheet is assumed to have a velocity \( V_0 \) while the rest of the structure is stationary.

Phase II: The core is compressed while the lower face sheet is stationary.

Phase III: The lower face sheet starts to deform and finally the structure is brought to rest by plastic bending and stretching.

Comparing the response of this model to that of the sandwich plate with asymmetrical face sheet, we can see that this model is available for a less \( \delta \). But for the sandwich plate with \( \delta = 5/2 \), the deformation of the lower face sheet is earlier than that of the core. So the analytical model is not adapted to large thickness ratio. This new deformation pattern needs to be verified in the next experiment.

3.2. Energy Absorption

When shock wave arrives at the upper face sheet, a reflected shock wave generates. And at the same time, the structure deforms to absorb the energy from shock wave. Fig.3 gives the internal energy (IE) absorption of six structures varies with the mass of TNT explosive charge. And the IE absorption increment ratio of the sandwich plate to monolithic solid plate is shown in Fig.4.

Fig.3 shows that IE absorption of structure increases with the increase of the mass of TNT explosive charge. And IE absorption of all sandwich plates is larger than that of monolithic solid plate. At less mass of TNT explosive charge, such as 50g, IE absorption of four sandwich plate except sandwich plate with \( \delta = 2/5 \) is close to that of monolith solid plate, the increment is less that 20\%, as Fig.4 shows. It indicates that IE absorption of sandwich plate is not obvious increase than that of monolithic solid plate in lower blast loading.

![Fig.3. Internal energy absorbed by six structures in different mass of TNT explosive charge](image1)

![Fig.4. Internal energy absorbed increment ratio of sandwich plate to solid plate in different mass of TNT explosive charge](image2)
With the same mass of TNT explosive charge, that’s to say the same blast loading, IE absorption of the sandwich plate and its increment ratio both increase with the decrease of $\delta$. For example, IE absorption of the sandwich plate with the thickness ratio $\delta$ as $2/5$, $3/4$, $1$, $4/3$ and $5/2$ separately equals to $3.7742 \times 10^3 J$, $4.5397 \times 10^3 J$, $5.1852 \times 10^3 J$, $5.9097 \times 10^3 J$ and $8.0848 \times 10^3 J$ for 500g TNT explosive charge. And the IE absorption increment ratio of the sandwich plate to the solid plate is 19.06%, 43.21%, 63.58%, 86.43% and 155.05% separately.

Furthermore, Fig.4 also shows that IE absorption increment ratio has a different rule for different $\delta$. When $\delta$ equals to 5/2, the IE absorption increment ratio changes with the mass of TNT explosive charge as a linear regulation nearly. But for other four structures, the curves of IE absorption increment ratio and the mass of TNT explosive charge are all raised upwards. Especially for $\delta = 2/5$, the curve reaches a peak at 500g TNT explosive charge. It denotes that sandwich plate has the maximum energy absorption efficiency relative to the solid plate at the same blast loading. When the mass of TNT explosive charge larger than 500g, the IE absorption increment ratio decreases with the increase of the mass of TNT explosive charge. It denotes the different deformation pattern of the sandwich plate. When the mass of TNT explosive charge is larger than 500g, the local dent of the upper face sheet and the core densification occur rapidly, while the overall deformation of the lower face sheet is weak. So the upper face sheet, the densified core and the lower face sheet were compressed together and forms a solid plate nearly.

3.3. The Maximum Deflection

With the action of shock wave, the sandwich plate deforms with the local dent, the core buckling or densification and overall stretch and bending. For overall stretch and bending, the plate has a perpetual deformation. Then the maximum deflection is defined as the deflection at the cent point of the rear surface of the lower face sheet. Fig.5 gives the curves of the maximum deflection and the mass of TNT explosive charge. It exhibits that the maximum deflection of the sandwich plate is less than that of the solid plate. It indicates that the sandwich plate has a more excellent blast-resistance than that of the solid plate. For five sandwich plates, the maximum deflection is close at the same mass of TNT explosive charge. Fig.6 gives the deflection ratio of the sandwich plate to the solid plate.

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Fig.5. The maximum deflection of six structures at different mass of TNT explosive charge

Fig.6. The deflection ratio of the sandwich plate to the solid plate at different mass of TNT explosive charge
At the mass of TNT explosive charge less than 100g, the maximum deflection of the sandwich plate is about 50% of that of solid plate, just as Fig.6 shows. When the mass of TNT explosive charge increases, the maximum deflection ratio also adds. And at larger mass of TNT explosive charge, such as 800g, the maximum deflection ratio is close to 90%. It also verifies that the sandwich plate is densified just as a solid plate.

For the sandwich plate with $\delta = 2/5$, the curve of the maximum deflection ratio is above the others when the mass of TNT explosive charge is less than 500g. This phenomenon can be explained by the deformation of the sandwich plate. When shock wave arrive at the upper face sheet of the sandwich plate, local dent of the upper face sheet and the core buckling occur but the degree of deformation is limited for less mass of TNT explosive charge. Nearly at the same time, the lower face sheet begins to move and the overall stretch and bending takes place. On the contrary, for the sandwich plate with larger $\delta$, the local dent of the upper face sheet is also limited and the core buckling and partial densification are main deformation pattern. So the core partial densification decreases the overall stretch and bending and causes the maximum deflection to reduce.

4. Summary

In this paper, mechanical response of sandwich plate with asymmetry face sheet is simulated. The internal energy absorption and the maximum deflection are acquired. The results indicate:

i) The deformation pattern of the sandwich plate with asymmetry face sheet is different from that with symmetry face sheet. The local dent of the upper face sheet is obvious for less $\delta$ while the buckling of lower face sheet is apparent for larger $\delta$. For the sandwich plate with symmetry face sheet, both phenomena occur but are not obvious.

ii) The efficiency of energy absorption changes with $\delta$ at the same blast loading. The efficiency of energy absorption increases with the decrease of $\delta$.

iii) The maximum deflection doesn’t change obviously with $\delta$. At larger mass of TNT explosive charge, the maximum deflection of the sandwich plate is close to that of the solid plate. It indicates that the capacity of blast-resistance has a peak.

So the sandwich plate with asymmetry face sheet can be designed for various purposes. For a certain blast loading and the same mass of structure, the capacity of energy absorption can be optimized by changing the ratio of upper face sheet to lower face sheet.

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