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Single-Curvature Sandwich Panels with Aluminum Foam Cores under Impulsive Loading

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Abstract

Single-curvature sandwich panels combine the advantages of the shell and sandwich structure and are therefore envisaged to possess good potential to resist blast and shock or impact loads. This study presents a comprehensive report on the dynamic response and shock resistance of single-curvature sandwich panels, comprising two aluminum alloy face-sheets and an aluminum foam core, subjected to air-blast loading, in terms of the experimental investigation and numerical simulation. The deformation modes, shock resistance capability, and energy absorption performance are studied, and the influences of specimen curvature, blast impulse, and geometrical configuration are discussed. Results indicate that the deformation/failure, deflection response, and energy absorption of curved sandwich panels are sensitive to the loading intensity and geometric configuration. These results are significant to guide the engineering applications of sandwich structures with metallic foam cores subjected to air-blast loading.

Keywords: metallic foam, sandwich structure, single curvature, blast loading, shock resistance, energy absorption, deformation mode

1. Introduction

Light-weight cellular metallic foams possess good multifunctional combinations of mechanical, physical, and electromagnetic properties including the high specific stiffness, high specific strength, and superior energy dissipation capacity by plastic deformation of their cellular microstructures [1–3]. Since they can undergo the large plastic deformation at a constant nominal stress, resulting in a relatively long plateau stress in their stress versus strain response history curves shown in **Figure 1**, metallic foams are continually used in energy absorbers for the protective purpose [3]. More commonly, the metallic foams are extensively used as the cores of

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Figure 1. Stress versus strain response curve of the aluminum foam with 11% relative density.

sandwich structures to enhance the blast/shock resistance performance. The sandwich structure typically consists of two thinner but stiffer face-sheets and a softer crushable core, which is a special topology form comprising a combination of different materials that are bonded to each other so as to utilize the properties of each component for the structural advantage of the whole assembly. The face-sheets resist nearly all of the applied in-plane loads and bending moments, while the core sustains the transverse and shear loads mainly. The employment of flatted sandwich structures (i.e., the beam and panel) to resist blast/shock loadings still remains academic and engineering interests, and the responses of these sandwich structures to various loading cases have been widely investigated [4–12]. Some representative failure modes (e.g., face-sheet yielding and core compression or shear) have been experimentally observed [5, 7, 9–11], while the load-carrying capability and mechanisms of plastic failure and energy absorption have been predicted in theory and simulation [4, 6, 8, 12].

Curved sandwich panels, which better combine the advantages of shell and sandwich structures, are envisaged to possess good potential in withstanding blast or impact [13–15]. However, studies on curved metallic sandwich structures appear quite limited to date. Consequently, a comprehensive study on blast-loaded single-curvature sandwich panels with aluminum foam cores is conducted in experiment and simulation.

2. Air-blast experiments

2.1. Experimental procedure

2.1.1. Specimens

Single-curvature sandwich panel specimens, 310 mm long, with an arc length also of 310 mm, were fabricated from two thin LY-12 aluminum alloy face-sheets bonded to an aluminum foam

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Figure 2. Photograph of specimens with the two radii of curvature.

core using commercially available adhesive. **Figure 2** shows the picture of single-curvature sandwich panels with two radii of curvature, that is, 250 and 500 mm. Three face-sheet thicknesses (i.e., 0.5, 0.8, and 1.0 mm) and three core relative densities (i.e., 11, 15, and 18%) were examined. The quasi-static mechanical properties of LY-12 aluminum alloy face-sheets with the density $\rho = 2780 \text{ kg/m}^3$ are Young's modulus E = 68 GPa, Poisson's ratio $\nu = 0.33$, yield stress $\sigma_{fY} = 310 \text{ MPa}$, and shear modulus G = 28 GPa.

The core material was closed-cell aluminum foam, and the typical quasi-static uniaxial compressive stress-strain responses for three different relative foam densities are shown in **Figure 3**. Here, an energy efficiency-based approach is proposed to calculate the plateau stress and densification strain. Energy absorption efficiency η (ε_a) is defined as the energy absorbed up to a given nominal strain ε_a normalized by the corresponding stress value σ_c (ε) [16]:

$$\eta(\varepsilon_a) = \frac{\int_{\varepsilon_{cr}}^{\varepsilon_a} \sigma(\varepsilon) d\varepsilon}{\sigma(\varepsilon)_{\varepsilon = \varepsilon_a}}$$
(1)

where ε_{cr} is the strain at the yield point corresponding to commencement of the plateau regime. The densification strain ε_D is the strain value corresponding to the stationary point in the efficiency-strain curve, that is, where the efficiency is a global maximum:

$$\left. \frac{d\eta(\varepsilon)}{d\varepsilon} \right|_{\varepsilon = \varepsilon_D} = 0 \tag{2}$$

The energy absorption efficiency curves of the aluminum foams are also depicted in **Figure 3**, and the plateau stress is obtained from



Figure 3. Stress versus strain response and energy absorption efficiency versus strain curves of aluminum foam cores.

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$$\sigma_{pl} = \frac{\int_{\varepsilon_{cr}}^{\varepsilon_{D}} \sigma_{c}(\varepsilon) d\varepsilon}{\varepsilon_{D} - \varepsilon_{cr}}$$
(3)

By calculating, the plateau stress σ_{pl} and densification strain ϵ_D of aluminum foams with three various relative densities are $\sigma_{pl} = 5.30$ MPa and $\epsilon_D = 0.62$ (for 11% relative density), $\sigma_{pl} = 5.49$ MPa and $\epsilon_D = 0.55$ (for 15% relative density), and $\sigma_{pl} = 7.11$ MPa and $\epsilon_D = 0.54$ (for 18% relative density), respectively.

A total of 48 specimens were fabricated, and for each blast condition, two nominally identical specimens were tested. All specimens were uniquely labeled – the label R500-H0.5-C10- ρ 15%-f1 represents the specimen with a 500 mm radius of curvature, 0.5 mm face-sheet thickness, 10 mm core thickness, and 15% core relative density, which is the first specimen used for exploring the influence of face-sheet thickness on the dynamic response. The specimens were arranged into four groups; each group was designated for examining the effect of one or two parameters on the structural response.

2.1.2. TNT charge

Blast loading was applied to the specimens by detonating a cylindrical TNT charge with a density of 1.55 g/cm³; a photograph is shown in **Figure 4**. Seven various mass charges (i.e., 10, 15, 20, 25, 30, 35, and 40 g) with an approximate height-to-diameter ratio of 1 were fabricated by changing the diameter and height of the charges.

2.1.3. Ballistic pendulum system

The specimen-frame assembly was attached to a four-cable ballistic pendulum system, which was employed to measure the impulse imparted to the front face of the specimen, as shown in **Figure 5**. The charges were mounted in front of the center of specimens, at various standoff



Figure 4. Picture of cylindrical TNT charge.



Figure 5. Photograph of the overall experimental setup.

distances. The movement of the pendulum was measured by a laser displacement transducer. Each single-curvature sandwich panel was clamped peripherally by steel frames, leaving an effective exposed curved area of 250×250 mm.

When the TNT charge is detonated, the impulsive load produced causes the pendulum to move, and its motion corresponds to that of a simple pendulum, described by the following equation:

$$M\frac{d^2x}{dt^2} + C\frac{dx}{dt} + \frac{Mg}{R}x = 0$$
(4)

where *M* is the total mass, *x* the horizontal displacement, *C* the damping coefficient, and *R* is the cable length. Suppose $2\beta = C/M$ and $\omega_n^2 = g/R$, then Eq. (4) is simplified by

$$\ddot{x} + 2\beta \dot{x} + \omega_n^2 x = 0 \tag{5}$$

Introducing the damping ratio $\xi = \beta / \omega_n$, the solution of Eq. (5) is given by

$$x = Ae^{-\beta t}\sin(\omega t + \varphi)$$
(6)
where $\omega = \sqrt{\omega_n^2 - \beta^2}$, $A = \sqrt{x_0^2 + \frac{(\dot{x}_0 + \beta x_0^2)}{\omega^2}}$, and $\tan \varphi = \frac{x_0 \omega}{\dot{x}_0 + \beta x_0}$.

With the initial condition $x_0 = 0$, Eq. (5) can be written as

$$x = \frac{\dot{x}_0}{\omega} e^{-\beta t} \sin \omega t \tag{7}$$

The period of the oscillation of the pendulum $T = 2\pi/\omega$; if x_1 is the displacement of the pendulum for a period of t = T/4 and x_2 for a period of t = 3 T/4, then

$$x_1 = \frac{T}{2\pi} e^{-\frac{\beta T}{4}} \dot{x}_0 \tag{8}$$

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$$x_2 = \frac{T}{2\pi} e^{-\frac{3\beta T}{4}} \dot{x}_0$$
 (9)

$$\beta = \frac{2\ln\left(x_1/x_2\right)}{T} \tag{10}$$

If the values of β , x_1 , and x_2 are known, then the initial velocity of the pendulum is given by

The impulse imparted into the pendulum is generally given by

$$I = M \cdot \dot{x}_0 \tag{12}$$

(11)

where *M* is the total mass of the pendulum. By introducing (11) into Eq. (12), given by

 $\dot{x}_0 = \frac{2\pi}{T} e^{\frac{\beta T}{4}} x_1$

$$I = Mx_1 \frac{2\pi}{T} e^{\frac{\beta T}{4}} \tag{13}$$

In the present tests, $\beta = 0.031$, M = 151.3 kg, T = 3.12 s, and R = 2.69 m. Generally, the rotation angle (θ) should be less than 5°; in this study, θ is approximately 2.1°, which is acceptable.

2.2. Experimental results and discussion

The blast impulse is calculated by Eq. (13), according to the ballistic pendulum movement measured by the laser displacement transducer, as shown in **Figure 6**. The permanent deflection of the center of the back face-sheet was also examined by the posttest measurements. Here, the experimental results are classified and presented in the following subsections, in terms of typical deformation/failure modes and influences of some key parameters on the final permanent deflection (since the resistance to blast loading is quantified by the permanent deflection of the central point of the back face-sheet).

2.2.1. Deformation modes

The deformation and failure modes of the single-curvature sandwich panels can be classified into that of the front face-sheet, core, and back face-sheet, respectively, although all the sandwich panels present the evident global deformation with the various local failures.

The front face-sheet of single-curvature sandwich panels subjected to blast loading mainly fails in the local indentation, transverse tearing, and petal-like tearing, as shown in **Figure 7**. Indentation failure shown in **Figure 7(a)** is the localized severe deformation without rupture, and the indentation depth is related with the load magnitude. When deformation of the face-sheet exceeds its ductility at larger loads, failure is dominated by tearing. The transverse tearing may occur for a certain range of blast loads, as shown in **Figure 7(b)**. With the increase of blast loading, the petal-like tearing mode shown in **Figure 7(c)** will be caused.



Figure 6. Typical displacement-time response of ballistic pendulum in a blast test.





Figure 8 illustrates the typical cross-sectional profiles of blast-loaded sandwich specimens with two radii of curvature. Each specimen can be split into three regions (i.e., core crushing region, shear failure region, and an uncompressed region) from the mid-span to the clamped end, according to the deformation degree of the core. Core crushing is considered as the generation of a hole in the specimen central zone, as shown in **Figure 8(a)**. The fracture of core in the central zone may be observed for some specimens as shown in **Figure 8(b)**. The core also can be failed by core shear under the transverse shear force. Moreover, the delamination between the crushed core and face-sheets can be found in the core shear region. In those regions far away from the loading area, the cores are generally uncompressed.

The deformation/failure of the back face-sheet corresponds to Mode I (gross inelastic deformation), Mode II (gross inelastic deformation with tensile tearing at the edges), and tearing. The deformation profile of the back face-sheet for the typical Mode I response is dome-shaped at the center, and with obvious plastic hinges extending from the plate corner to the base of the Single-Curvature Sandwich Panels with Aluminum Foam Cores under Impulsive Loading 127 http://dx.doi.org/10.5772/intechopen.70531



Figure 8. Collapse patterns of the foam core: (a) progressive compression with shear failure in central area and (b) fracture of central core.

dome, as shown in **Figure 9(a)**. **Figure 9(b)** shows significant inelastic deformation with tensile tearing at the clamped edges of the curved sandwich panel. For the thinner specimen subjected to a larger impulse, tearing of the back face-sheet was observed, as shown in **Figure 9(c)**.

2.2.2. Influence of blast impulse on the shock resistance

The maximum center-point deflection of curved sandwich panels (H = 0.8 mm, C = 10 mm, relative density = 15%) and curved monolithic plates of equivalent mass (H = 3.0 mm) are plotted in **Figure 10**, as a function of impulse for different blast distances and six charge masses (10, 15, 20, 25, 30, and 35 g). As expected, the central deflection increases with impulse for all test configurations. By applying a linear fit to the data, the relationship between the central deflection and the blast impulse can be written as

$$W = kI + b \tag{14}$$

where *W* and *I* are, respectively, the central deflection in mm and impulse in Ns; *k* and *b* are the two constants with the values of 1.22 mm/Ns and -9.03 mm for *R* = 500 mm curved sandwich panels and 1.85 mm/Ns and -10.66 mm for *R* = 250 mm sandwich specimens, respectively.



Figure 9. The deformation/failure of the back face-sheet: (a) Mode I (gross inelastic deformation), (b) Mode II (gross inelastic deformation with tensile tearing), and (c) tearing failure.



Figure 10. Relationship between central deflection and blast impulse.

A comparison of the blast resistance between curved sandwich panels and monolithic plates of equivalent mass is also shown in **Figure 10**. Those R = 500 mm sandwich panel specimens show the better resistance to blast loading compared to the solid shells with the equivalent mass. However, the central deflection of R = 250 mm curved sandwich panels were larger than that of solid counterparts. This may be explained that the deformation of the smaller radius of curvature specimens is governed by the local failure, which may decrease the energy absorption capability of the foam cores; however, the deformation of the solid shell counterparts is dominated by the global bending.

2.2.3. Influence of face-sheet thickness on the shock resistance

The dependence of the central deflection of the back face-sheet on face-sheet thickness is shown in **Figure 11**, where additional data corresponding to the same conditions are included to show the possible general trend. The central point deflection decreases with the increased face-sheet thickness, as expected. For R = 250 mm curved sandwich panels, those specimens with 0.8-mm- and 1.0-mm-thick face-sheets show the smaller deflections than curved panels with the 0.5 mm face-sheets, by 28.3 and 56.3%, respectively. This is also the case for the R = 500 mm specimens, whereby the deflections are, respectively, 48.5 and 68.8% smaller.

2.2.4. Influence of core relative density on the shock resistance

The central point deflection of specimens is plotted in **Figure 12** as a function of core relative density. For both curvatures, the specimens with the larger core relative density results in the smaller deflections. Taking the core relative density of 11% as a reference, R = 250 mm

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Figure 11. Effect of face-sheet thickness on central deflection of curved sandwich panels.



Figure 12. Effect of core relative density on central deflection of curved sandwich panels.

sandwich panels with higher relative densities (15 and 18%) can decrease the average deflection, by 46.6 and 55.9%, respectively. However, for R = 500 mm sandwich panels, it is difficult to quantify the effect of core relative density on the structural response of specimens, due to the large variability in both impulse and deflection.

2.2.5. Influence of specimen curvature on the shock resistance

The influence of curvature is deduced primarily from **Figure 10**. Two major influences can be identified: (i) the blast resistance of single-curvature sandwich panels with the larger radius of curvature is better, and (ii) a comparison between the response of the curved sandwich panels and the solid shell counterparts with the same mass is made, as stated in Section 2.2.2. Obviously, the deformation of curved sandwich panels with the smaller radius of curvature is governed by local penetration failure, while the deformation of the larger radius of curvature specimens is the global deformation with bending and stretching dominants. The larger deformation zone of the latter appears to contribute the greater plastic energy absorption and thus enhances the resistance to blast loading.

3. Finite element simulations

Based on the experiments, corresponding finite element (FE) simulations have been undertaken by employing the nonlinear, explicit finite element code LS-DYNA 970.

3.1. FE model

Since the curved sandwich panel is symmetric about x-z and y-z planes, only a quarter of the curved panel was modeled, as shown in **Figure 13**. The entire model comprises 53,166 nodes and 61,257 elements. The LY-12 face-sheets were modeled by Belytschko-Tsay shell element,



Figure 13. FE model of the 1/4 curved sandwich panel and charge.

while the foam core was modeled by the default brick element. Similarly, one quarter of the charge was modeled shown in **Figure 13**, and eight-node brick elements with arbitrary Lagrange-Eulerian (ALE) formulation were adopted.

The mechanical behavior of face-sheets were represented by material model 3 of LS-DYNA (*MAT_PLASTIC_KINEMATIC), while the aluminum foam core was modeled by material model 63 of LS-DYNA (*MAT_CRUSHALBE_FOAM). A high-explosive material model (*MAT_HIGH_EXPLOSIVE_BURN) incorporating the JWL equation of state (EOS_JWL) was used to describe the material property of the TNT charge:

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}$$
(15)

where *p* is the blast pressure, *E* is the internal energy per initial volume, *V* is the initial relative volume, and ω , *A*, *B*, *R*₁, and *R*₂ are the material constants, respectively. The material parameters of the curved sandwich panel and TNT charge are kept the same as experimental ones.

The bolts used in the tests to clamp the curved panels to the fixture were represented by nodal constraints in the numerical model. Symmetric boundary conditions about *x*-*z* and *y*-*z* planes were imposed. The blast load imparted on the front face-sheet of curved sandwich panel was defined with algorithm of *CONTACT_ERODING_SURFACE_TO_SURFACE. Automatic, surface-to-surface contact options were generally used for curved sandwich panels.

3.2. Simulation results and discussion

3.2.1. Explosion and structural response process

The whole response can be divided into three stages: Stage I (expansion of the explosive), Stage II (explosive product interacts with the curved sandwich panel), and Stage III (plastic deformation of the curved sandwich panel under the inertia).

3.2.1.1. Stage I: expansion of the explosive

The expansion of the explosive starts at the point of detonation (central point of the top surface of charge), as shown in **Figure 14**. The detonation of a high-performance explosive is achieved by compressing and heating of its constituents, resulting that a chemical reaction is triggered and then it is supersonically propagated through the explosive at the Chapman-Jouguet velocity. Whereafter, a strong shock wave, generated by the violent expansion of the gaseous products, propagates into the ambient medium. Since the sound speed increases with the increased temperature in the compressible flow, shock waves are generated. The detonation wave generated by the cylindrical charge presents an obvious directionality and a cross distribution shape. The axial propagation speed is larger than the radial propagation speed, so the axial pressure is also greater than that of radial direction due to the proportional relationship between the wave speed and intensity in air medium.



Figure 14. A typical process of the charge detonation.

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Figure 15. A typical process of explosive product-structure interaction.

3.2.1.2. Stage II: explosive product-curved panel interaction

The expansion of the explosive begins to interact with the front face-sheet of curved sandwich panel at this stage. It is seen from **Figure 15** that the explosive product-curved panel interaction lasts over a time period of approximately $32 \ \mu$ s, from approximately $t = 28 \ \mu$ s to $t = 60 \ \mu$ s, corresponding the duration of the contact force between the explosive product and target structure almost becomes to zero. **Figure 15** shows the interaction of the explosive product with the curved panel, accompanied with the upward distortion as a result of the reflection from the curved target panel. Indentation deformation is first occurred in the central region of



Figure 16. A typical process of curved sandwich panel deformation.

front face-sheet of the specimen, and then it extends both outward and downward with the transfer of blast impulse. Back face-sheet of the specimen has little deformation at this stage. Once the coupling interaction is completed (i.e., the contact force becomes to zero at $t = 60 \ \mu$ s), the high-explosive model should be manually deleted from the finite element code.

3.2.1.3. Stage III: deformation of curved sandwich panel under its own inertia

In this stage, there is no coupling effect between the explosive product and the structure, and the curved sandwich panel remained to deform under the inertia, as shown in **Figure 16**. The central indentation failure of the front face-sheet is formed by gradually compressing the foam core, and the deformation extends outward until to the external clamped boundaries by traveling plastic hinges. The deformation of the curved sandwich panel structure is mainly governed by the plastic bending and stretching, accompanied with the slight oscillation. The whole curved sandwich panel finally presents a global dishing shape, and the maximum deflection of the back face-sheet occurs at the central point of the specimen.

3.2.2. Deflection response of the back face-sheet

Figure 17 compares the experimental and simulated permanent deflection at the central point of the back face-sheet. It is shown that all data points are close to the line of perfect match, which represents that the simulated data are agreed well with the experimental results. In order to better understand the deformation mechanism of curved sandwich panel, the progressions of deflections at several key nodes (as shown in **Figure 18**) along the central



Figure 17. Comparison of experimental and numerical back-face deflection.

circumferential and longitudinal directions are presented in **Figure 19**. Both circumferential and longitudinal nodes for the front and back face-sheets have the similar deformation trend. At ~300 μ s, all the nodes, except the node C5, have the maximum transient deflections, and then the deflection of these nodes decreases obviously due to the rebound of the elastic



Figure 18. Locations of the circumferential and longitudinal nodes on the face-sheets.



Figure 19. Deflection variation of key points on the face-sheets of the curved sandwich panel. (a) Circumferential (front face-sheet), (b) circumferential (back face-sheet), (c) longitudinal (front face-sheet), and (d) longitudinal (back face-sheet).

deformation until the whole deformation process is finished. The deformation of the back facesheet obviously lags behind that of the front face-sheet, and the central point deflection of back face-sheet is also smaller than that of front face-sheet due to the foam core compression.

3.2.3. Energy absorption capability

Figure 20 shows the histories of plastic dissipation of the components of a curved sandwich panel (R250-h0.8-C10- ρ 15%-B3) subjected to blast loading. In the early stage of the response, the front face-sheet compresses the aluminum foam core, resulting in core crushing and significant energy dissipation. It can be found from **Figure 20** that most of energy is dissipated by the large deformation of front face-sheet and core compression and core constitutes a major contribution, which is about 60% of total dissipation.

Effects of the impulse level and geometric configuration on the energy absorption of the components of the curved sandwich panels were indicated in a stack bar diagram in **Figure 21**. The partition of energy absorption of specimens is compared and analyzed in terms of the impulse level (specimen nos. 1–3), face-sheet thickness (specimen nos. 4–6), and core relative density (specimen nos. 7–9). The increase of impulse leads to a rise of total plastic energy dissipation in the specimens. Most of energy dissipation is attributed to large plastic deformation of front face-sheet and core compression. The energy absorption does not present a monotonic relationship with the face-sheet thickness. The specimen with 0.8-mm-thick face-sheets has the best energy absorption performance, followed by that of 0.5-mm-thick face-sheet, and the worst is that of 1.0-mm-thick face-sheet. This can be explained as follows: the



Figure 20. History of plastic dissipation of sandwich specimen during plastic deformation.



Figure 21. Plastic energy dissipation by the components of curved sandwich panels.

curved sandwich panel with thicker face-sheets deforms smaller due to the relatively larger structural stiffness; however, the severe damage may occur at the thinner front face-sheet under the large blast loading. Moreover, the total energy absorption amount of the curved sandwich panels decreases with the increased core relative density. Compared to the sandwich panels with the 10% core relative density, those specimens with 15 and 20% core density display relatively smaller energy absorption values, by 3.95 and 8.3%, respectively. This is attributed that the core compression values decrease with the increased core relative density, and the dominant deformation/failure mode of curved sandwich specimens is converted from the local core compression to global bending deformation, resulting in a weaker energy absorption capability.

4. Conclusions

Single-curvature sandwich panels with closed-cell aluminum foam cores, which include two radii of curvature (i.e., 250 and 500 mm), three face-sheet thicknesses (i.e., 0.5, 0.8, and 1.0 mm), and six different arrangements of foam core layers, were tested under air-blast loadings of various magnitudes. A total of 48 curved sandwich panels were examined, and the typical deformation and failure modes and the quantitative blast impulse and specimen deflection results were obtained and discussed. Based on the experiments, the corresponding finite element simulations were conducted using LS-DYNA software. The explosion and structural

response process, back face-sheet deflection response, and energy absorption capability were explored. Experimental results show that permanent central point deflection linearly increases with blast impulse for all the specimen configurations and blast resistance of specimens can be enhanced by increasing the face-sheet thickness or the core density. The weaker blast resistance of R = 250 mm curved sandwich panels, compared to monolithic plates with the same mass, and the R = 500 mm sandwich panels, which are attributed to the different dominant deformation mechanisms. Simulation results present that the deformation modes, deflection responses, and energy absorption capability of curved sandwich panels are related with the loading intensity and geometric configuration. Energy absorption capability of curved sandwich specimens is monotonically increasing with the increased blast impulse and decreasing with the increase of core relative density. However, it does not monotonically change with the face-sheet thickness.

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