AN EXPERIMENTAL AND NUMERICAL STUDY ON THE BLAST RESISTANCE OF SINGLE-CURVATURE SANDWICH PANELS WITH LAYERED-GRADIENT METALLIC FOAM CORES

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ABSTRACT

The shock resistance of single-curvature sandwich panels with two aluminium alloy face-sheets and a layered-gradient closed-cell aluminium foam core, under air-blast loading, was investigated experimentally and numerically in this study. Two radii of curvature and six various layered-gradient core configurations were examined. Both experimental and simulated results indicate that varying the core-layer arrangement can attribute to improve the shock resistance of LGMFC sandwich panels to blast loading, and the LGMFC sandwich panels with a smaller radius of curvature have a better shock resistance performance. Besides, the specimens with larger radius of curvature can absorb a greater amount of energy due to their global deformation associated with bending and stretching dominates. These findings are beneficial for guiding the design and assessment of layered-gradient sandwich structures in engineering protective applications.

1 INTRODUCTION

Sandwich structures, consisting of two thinner stiff face-sheets bonded to a thicker low-density core, have been extensively used as energy absorbers and blast/shock/impact-resistant structures in a wide range of protective applications, due to their desirable specific strength/stiffness, energy absorption capability, as well as thermal and acoustical insulation performance [1-3]. Traditionally, various types of foams, honeycombs and trusses are available to be as core materials of sandwich structures. Since the Functionally Graded Materials (FGMs) have increasingly become to be of much current research interests, many attempts of inserting a FGM core into the sandwich structure have been increasingly made, expecting to reduce the interfacial shear stress at face-sheet/core interfaces caused by the stiffness discontinuity, and to avoid the interfacial failure so as to improve the load-carrying capability [4, 5].

Compared to the continuous FGM core, the layered FGM core is generally preferred to be employed for sandwich structures due to the ease of fabrication. Thus, numerous studies on the dynamic response of sandwich structures with layered FGM cores, subjected to blast, impact and penetration loadings, have been conducted [6-8]. These sandwich structures with layered FGM cores have been demonstrated to be able to improve the resistance to blast and impact loadings, by endowing an optimized core-layer arrangement; however, they seem to be failure to enhance the penetration and perforation resistance [8]. Nevertheless, the resistance capability of layered FGM core sandwich structures is specifically affected by many geometrical parameters such as the number of layers, thickness of each layer, variation of core density and interfacial conjunction of layers, so how the layered FGM core sandwich structures respond to blast/impact loadings still remains to need to be fully understood.
Consequently, the shock resistance of single-curvature sandwich panels with Layered-gradient Metallic Foam Cores (LGMFC), under air-blast loading, was investigated experimentally and numerically in this study. Two radii of curvature and six various layered-gradient core configurations were examined.

2 EXPERIMENTS

The air-blast tests on single-curvature LGMFC sandwich panels have been briefly reported in the previous study [9] together with those results of ungraded monolithic core specimens. The corresponding experimental procedure and results were reviewed and discussed here.

2.1 Specimen and experimental set-up

Single-curvature LGMFC sandwich panel specimens, with the equivalent longitudinal and arc length of 310 mm, were fabricated by two 0.8mm LY-12 aluminum alloy face-sheets put together with three 10mm-thick but density-different closed-cell aluminum foam cores. Three core relative densities – 11%, 15% and 18% – were utilized to constitute six different core-layer arrangements. Two radii of curvature, i.e., 250 mm and 500 mm, were studied. Schematic diagrams of the single-curvature LGMFC sandwich panel and core-layer arrangements were shown in Figs. 1 and 2, respectively. It is noted that three core-layers were just put together without any conjunction.

Fig. 1 Schematic diagram of the single-curvature LGMFC sandwich panel

The cylindrical TNT charge, with the density of 1.55 g/cm³ and a height-to-diameter ratio of 1, was used to provide the blast loading to the specimens. A four-cable ballistic pendulum set-up, as shown in Fig. 3, was employed to measure the blast impulse. The specimens were put into a self-designed steel frame with peripheral clamping, leaving a curved exposed area of 250 mm × 250 mm; and the specimen-frame assembly was mounted to the front end of the ballistic pendulum.
2.2 Experimental results

The blast impulse is estimated by the recorded displacement-time response curves of the ballistic pendulum via the following equation

\[ I = M x_1 \frac{2 \pi e^{\frac{\beta}{4}}}{T} \]  

(1)

where \( \beta = C/2M = [2 \ln(x_1/x_2)/T] \), and \( x_1 \) and \( x_2 \) are the horizontal displacements at \( t_1 = T/4 \) and \( t_2 = 3T/4 \), respectively; for the present case, \( \beta = 0.031, M = 151.3 \text{kg}, T = 3.12 \text{s}, R = 2.69 \text{m} \). The central point deflections of the back face-sheets of single-curvature LGMFC sandwich panel specimens were obtained by post-test measurements. The normalized transverse permanent deflections of specimens with two curvature radii and six different core-layer arrangements are plotted in Fig. 4 as a function of the normalized impulse, where the deflection and impulse are normalized to the dimensionless form as

\[ \bar{W} = \frac{W}{L} \]  

(2)

\[ \bar{I} = \frac{I}{A_0 M \sqrt{\sigma_f / \rho_f}} \]  

(3)

where \( \bar{I} \) and \( \bar{W} \) are the normalized impulse and deflection; \( I, A_0, \sigma_f \) and \( L \) are the measured impulse, loading area, mass per unit area and longitudinal half-length of specimens; \( \sigma_f \) and \( \rho_f \) are respectively, the yield strength and density of the face-sheets.

It can be found from Fig. 4 that varying the core-layer arrangement can attribute to improve the shock resistance of LGMFC sandwich panels to blast loading, for both two radii of curvature cases. The maximum difference is 13% for 500 mm radius of curvature specimens, and 16.5% for those 250 mm radius of curvature specimens. However, it is hard to deduce the order of the resistance performance from the limited post-test measured data, due to the experimental errors and scatter.
caused by the following factors: i) the imperfect uniformity of density of foam materials; ii) the sliding of the specimen from the clamped ends; and iii) the inevitable test and measure errors. Therefore, the corresponding finite element simulation remains to be conducted to clarify the influence of the core-layer arrangement on specimen deformation.

3 FINITE ELEMENT MODELING

3.1 Model information

One quarter of the LGMFC sandwich panel, imposed the corresponding symmetrical boundary conditions, was built using LS-DYNA 971, as shown in Fig. 5. The sandwich panel was meshed to 2mm × 2mm, and the entire model comprises 116688 elements and 126558 nodes for 250 mm radius of curvature specimens while 95625 elements and 115520 nodes for 500 mm radius of curvature specimens. The face-sheets were represented by shell element and were described by the material model *MAT_PLASTIC_KINEMATIC, while the core-layers were modeled by eight-node solid element and were described by the material model *MAT_CRUSHABLE_FOAM. The mechanical parameters of face-sheets are as follows: Density $\rho_f = 2780$ kg/m$^3$; Young's Modulus $E = 68$ GPa; Poisson's ratio $\nu = 0.33$; and Yield stress $\sigma_Y = 310$ MPa. The quasi-static compressive stress versus strain response curves of aluminum foams with three various relative densities were shown in Fig. 6.

The clamped boundary conditions were represented by nodal constraints in the simulation. Automatic surface-to-surface contact options were generally used for the LGMFC sandwich shell. The blast loading was simulated by the option *LOAD_BLAST, which defines an air-blast function for the application of pressure loads due to explosives. The mass damp option *DAMPING_GLOBAL with a damping constant of 0.002 was selected to damp low-frequency structural modes.

3.2 Validation of the simulation approach

The finite element model and simulation approach were validated with the experimental data of the central point deflection of specimens, as shown in Fig. 7. It is found that a reasonable agreement of simulation data with experimental measurements is obtained for R500 specimens, although the
simulation results may slightly underestimate the specimen deflections. However, this difference becomes abnormally large for R250 specimens. The corresponding possible reasons can be explained as follows: i) the larger errors during the post-test measurement cause the unreal specimen deformation; ii) the failure behaviour of materials is not taken into account in the simulations, and the deformation of R250 specimens is governed by local failure, unlike to the R500 specimens, which are mainly failure by the large global deformation. Although a relatively large gap between experimental data and simulation results exists, the present simulation approach is still valid to qualitatively study the influence of core-layer arrangement on specimen deformation.

4 RESULTS AND DISCUSSION

4.1 Influence of core-layer arrangements

The normalized maximum transverse deflections of LGMFC sandwich panels with six various core-layer arrangements under air-blast loading are presented in Fig.8. For R500 specimens, the deflections of specimens with the highest-density bottom cores seem to be smaller, and that with G1 configuration has the smallest deflection. That is to say, the blast resistance performance of R500 specimen with G1 configuration is the best. However, the deflections of R250 specimens vary slightly under the small-weight TNT blast loading. From these slight differences, the best blast resistance configuration, G5, still can be identified.

![Fig. 8 Effect of core-layer arrangements on normalized deflection of specimens](image)

Here, the Specific Energy Absorption (SEA) index is used to discuss the energy absorption of core foams for various core-layer arrangement LGMFC sandwich panels, which is defined as

\[ SEA = \frac{E_a}{\rho AL_0} \]
where $E_a$ is the absorbed energy; $\rho$, $A$ and $L_0$ are the material density, cross section area and length of the structure, respectively. Fig. 9 shows the specific energy absorption versus time curves of core foams for various configuration sandwich panels. It is found from Fig. 9 (a) that the R500 specimens with the highest-density bottom cores have larger values of specific energy absorption, which may be attributed to the the large global deformation mode of specimens. However, from Fig. 9 (b), the blast resistance configuration, G5, has the lowest SEA value; this is because the failure of R250 specimens is governed by local deformation.

4.2 Influence of specimen curvature

As described above, specimens with two radii of curvature (i.e., R500 and R250) were studied. The influence of specimen curvature is discussed via blast resistance and energy absorption capability, by taking the G1 configuration as an example. Fig. 10 shows the normalized deflection versus time response curves of G1 configuration specimens with two radii of curvature. It is shown that the blast resistance of LGMFC sandwich panels with a smaller radius of curvature is better.

Fig. 10 The normalized deflection-time curves

Fig. 11 SEA versus time curves

Fig. 11 presents the specific energy absorption versus time curves of G1 configuration specimens with two radii of curvature. It is seen that the specific energy absorption value of the G1 configuration R250 specimen is much lower than that of R500 specimen. This may be attributed that the failure in specimens with a smaller radius of curvature is dominated by localized deformation, while in less curved specimens, global deformation associated with bending and stretching dominate. The larger area of deformation of the latter seems to indicate a greater amount of energy absorbed.

5 CONCLUSIONS

The blast resistance of single-curvature sandwich panels with radii of curvature and six various layered-gradient core configurations under air-blast loading, was investigated experimentally and numerically in this study. The blast resistance and energy absorption capability of specimens are examined, and the influences of core-layer arrangements and specimen curvature are discussed. Some conclusions can be drawn as follows: i) the optimal core-layer arrangements can improve the shock resistance and energy absorption of specimens; ii) the LGMFC sandwich panels with a smaller radius of curvature have a better shock resistance performance; and iii) the specimens with larger radius of curvature can absorb a greater amount of energy due to their global deformation associated with bending and stretching dominate.

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