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Sandwich panels with layered graded aluminum honeycomb cores under blast loading

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Sandwich panels with triple layered graded honeycomb cores were tested under blast loading. The structural response was analyzed by using finite element software LS-DYNA after validation against the experiments. The structural deformation modes were classified into three types and the core layer deformation was divided into three regions. For the same value of impulse, a localized impulse led to severely localized deformation mode. A relatively evenly distributed impulse resulted in largely global bending deformation. Under the same loading, graded panels with the core of the largest relative density placed near the impact face suffered a smaller deflection than the panels with uniform core. Furthermore, for the same deformation mode the normalized back face sheet deflection increased linearly with impulse.

1. Introduction

Sandwich structures with crushable material cores and high strength face sheets are often used as blast resistant components. The cores can be honeycombs [1,2], foams [3], corrugated [4,5] or latticed cores [6,7]. Due to the cellular constructions of the cores, they have low density, high stiffness/weight ratio, high strength/weight ratio and effective energy absorption capabilities. Under shock loading, studies have been made for their deformation process [8] and deformation modes [9–12]. The deformation process was divided into three steps by Fleck et al. [8]: the fluid-structure interaction stage; core crushing with the velocities of the faces and core becoming equalized by momentum sharing; and the retardation phase.

In the recent years, stepwise graded materials, where the material properties vary gradually or layer-by-layer within the material itself, were utilized as core materials in sandwich beams and plates. Energy absorption of graded beams subject to low velocity impact and quasi-static loading has been studied. Etemadi et al. [13] analyzed the effects of projectile initial velocity, kinetic energy and the beam's dimensions on the impact behavior of sandwich beams with a functionally graded (FG) core by using the finite element (FE) simulation code LS-DYNA. The graded properties of the beams were obtained by changing the Young's modulus of FG core. It was concluded from their observations that for sandwich beams with a core of which the property varies from the strongest near the impact face to the weakest, the maximum contact force increases and the maximum strain decreases, compared with that of sandwich beams with a homogenous core. Cui et al. [14] proposed a FG polymeric foam model and analyzed its energy absorbing ability using the FE method. In the model, the densities of the foam are varied through the thickness. Their results indicated that the functionally graded foam is superior in energy absorption to the uniform foam. The performance of such foams can be improved further if the density difference is enlarged. Gardner et al. [15] analyzed the performance of FG sandwich composite beams under shock wave loading. The foam core was monotonically graded based on increasing acoustic wave impedance. The blast resistance of the sandwich beams increased with the number of core layers.

The dynamic and blast responses of graded beams have been studied by finite element analysis. Liu et al. [16,17] investigated the dynamic responses and blast resistance of all-metallic sandwich-walled hollow cylinders and panels with graded aluminum foam cores and compared them with those of conventional ungraded ones. When graded specimens and ungraded ones were subjected to identical air blast loadings, the blast resistance of the graded composite was better than that of the ungraded ones,

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and the core of largest relative density near the impact face had advantage over the others. Li et al. [18] and Apetre et al. [19] numerically investigated the dynamic responses of metallic sandwich structures with FG cores. The particular core design can exhibit better energy absorption and mitigate or completely prevent impact damage on the sandwich structures. Zhang et al. [20] analyzed the dynamic response of sandwich steel panels with three kinds of corrugated core arrangements consisting of identical core density, subjected to dynamic air pressure loading. It was found that the sandwich plate with relatively smoothly graded core outperforms the other two arrangements.

The blast resistance of sandwich shells with layered foam cores and tubular cores was investigated previously by the authors [21,22], by employing FE simulation. It was concluded that monotonically decreasing the relative density of foams [21] or the wall thickness of the tubes [22] allowed a stepwise compression of the core layers and thus reduced the deflection of the back face sheet.

All of the previous studies on graded metallic sandwich structures were based on finite element analysis. In the present investigation, blast experiments with graded sandwich panels are reported. The specimens comprised aluminum alloy face sheets and triple-layered graded honeycomb cores. The experimental results are compared with those of conventional ungraded sandwich panels under the same loading condition. Finite element analysis has been also performed to further reveal the details of the deformation process.

2. Materials and geometry

2.1. Honeycomb

Hexagonal honeycombs manufactured from AA-5052-H32 aluminum alloy, with an expanding angle (θ) of 30° were used and the geometrical parameters of the honeycombs are shown in Fig. 1. The side length of cell a is 2.5 mm, 2.0 mm and 1.5 mm respectively. The cell wall thickness (τ) is measured to be nominally 0.04 mm, and the double thick wall measured 0.095 mm (more than double the single foil thickness due to the bonding). The density of the honeycomb core is given as [23]:

$$\rho^* = \frac{2\tau/a}{(1+\sin\theta)\cos\theta}\rho_s \tag{1}$$

where ρ_s = 2.7 g/cm^3 is the density of the foil material. The relative density of the three honeycombs are $(\rho^*)_{2.5} = 2.46\%\rho_s$, $(\rho^*)_{2.0} = 3.08\%\rho_s$ and $(\rho^*)_{1.5} = 4.11\%\rho_s$, respectively. The subscript denotes the value of side length of the cell. From the measurement there were some variations in cell size and expanding angle within the honeycomb core. The overall effect of this variation on the final deflection was, however, assumed to be negligible, although the peak load might be affected slightly [11].

Quasi-static compression tests were performed to characterize the core material. The square honeycomb specimens were of side length 300 mm, large enough to minimise any possible size effect of the bulk honeycomb core [24].

The compressive stress-strain curves of honeycombs with three different relative densities, in the X3 direction, are shown in Fig. 2. There are four stages on the curve. (1) Stage 1: elastic compression zone. (2) Stage2: plastic yield zone. The peak stress, or plastic yield point, occurs in this zone; and due to the non-uniform compression and progressive buckling of cell walls, there is much undulation on the curve. (3) Stage 3: plastic plateau zone. There is a stable and long plateau stress (σ_{pl}) region, and most of the energy was absorbed in this zone. (4) Stage 4: densification zone. In this zone, the honeycomb is being fully compressed and the stress increases sharply within a small range of strain.

The plateau stress of the bulk honeycomb core increases when the cell side length decreases, but the densification strain (ε_l) decreases, which is 0.80, 0.78 and 0.76 respectively.

2.2. Face sheet

The front/back face sheets and the interface sheets were manufactured from AA2024-O aluminum alloy (the two interface sheets were placed between the core layers, as shown in Fig. 4, in order to prevent the core from intruding each other). Tensile tests were performed in a servo hydraulic test machine (Instron 8874) at a strain rate of 10^{-4}/s. The axial strain was measured using both strain gauges and a laser extensometer, for comparison, while the transverse strain was also measured with a strain gauge. The dimensions of dog-bone samples following the Tensile Testing of Metallic Material Standard (ISO 6892-1:2009) and the measured stress versus strain response are shown in Fig. 3. The value of Young's modulus is E = 72 GPa, and the Poisson ratio is ν = 0.3. The aluminum alloy has a 0.2% offset yield strength of 76 MPa,

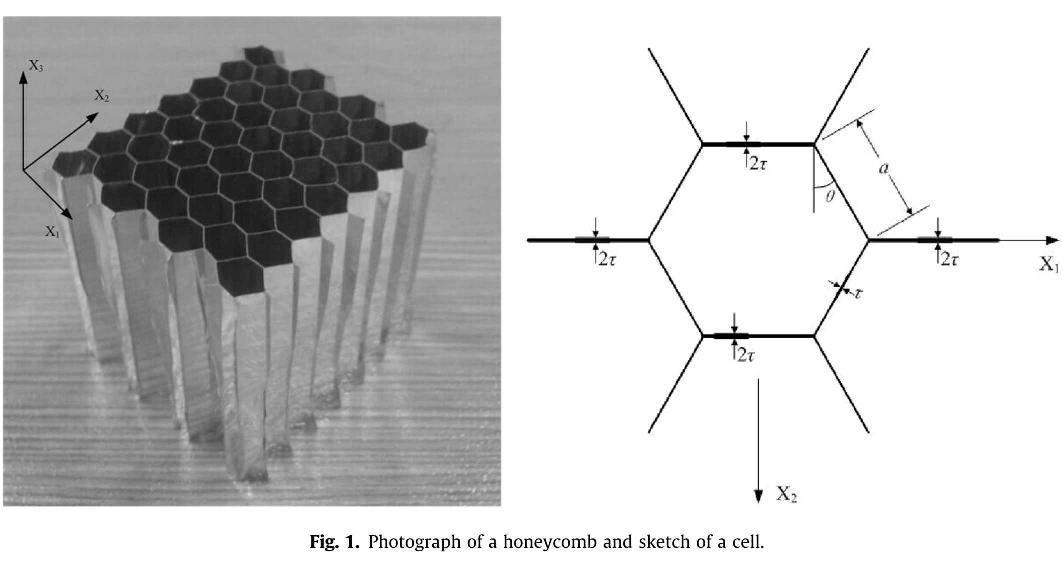

Fig. 1. Photograph of a honeycomb and sketch of a cell.