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Dynamic response of sandwich spherical shell with graded metallic foam cores subjected to blast loading

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ABSTRACT

Finite element simulations were conducted to investigate the dynamic responses of metallic sandwich spherical shells with graded aluminum foam cores under inner blast loading. The deformation of spherical shells, the energy absorption of each core layer, and the propagation characteristic of stress waves in the foam core layers were analyzed and discussed. The spherical shells exhibited an overall inflation–deformation mode as the foam cores were compressed gradually. The arrangement of the core layers with different relative densities had significant effects on the dynamic plastic responses of the spherical shells. The core layer arrangements of 15%–20%–10% and 20%–15%–10% (relative densities) from inside to outside demonstrate the optimal resistance to blast loading.

1. Introduction

Metallic sandwich structures are widely used in the aviation industry as well as in ship and railway engineering because of their low density, high specific strength, and effective energy absorption. The cores of these sandwich structures are commonly made of foams [1–4], honeycombs [5,6], or truss lattices [7,8]. Xue [1,2], Hutchinson and Xue [3] and Vaziri and Hutchinson [4] compared the impact resistance of metallic sandwich plates with that of solid plates of the same weight and found that the sandwich plates demonstrate superior mechanical behavior under impact loading. Fleck and Deshpande [9] and Qiu et al. [10,11] developed analytical models to analyze the response of clamped sandwich beams and plates subjected to shock loading; the authors divided the response into three phases: fluid–structure interaction phase, core crushing phase, and beam or plate bending and stretching phase.

Adopting a hierarchical structure is an alternative way to enhance the mechanical properties of light-weight materials and structures [12]. Several studies on hierarchical cores are mainly focused on the development of multiscale theoretical models of hierarchical materials [13,14], the design of hierarchical composite structures [15,16], and the mechanical properties of sandwich structures with hierarchical cores [17–20]. Functionally graded foams are typical materials that feature a hierarchical structure [21]. Bruck [22] presented a “one-dimensional model” to analyze stress wave propagation in FGMs. The results indicated that the benefit of the FGM over the sharp interface is to introduce a time delay to the reflected wave propagation, and this delay leads to greater dynamic energy absorption. Cui [23] illustrated that functionally graded foams are superior to uniform foams in terms of energy absorption, and that functionally graded foams with convex gradients perform better than those with concave gradients. The performance of functionally graded foams can be improved further with the enlargement of the density difference. Liu et al. [24] investigated the dynamic responses and blast resistance of all-metallic sandwich-walled hollow cylinders with graded aluminum foam cores and compared them with those of conventional ungraded ones. When graded cylinders and ungraded cylinders are subjected to identical air blast loadings, the radial deflection of the former is smaller than that of the latter, whereas the blast resistance of the former is stronger than that of the latter. This result can be improved further by optimizing the arrangement of foam cores. Jing [25] set up an experiment to study the response of sandwich shells with graded metallic foam cores under blast loading, and analyzed the effects of the different combinations of cores on the blast resistance of the structure.

Unlike the internal stress in cylinder shells, the stress of in spherical shells is distributed homogeneously because of central symmetry of their geometries and loadings. Under the same wall thickness, spherical shells show excellent bearing capacity. At present, spherical shells are mainly applied in the storage of all kinds of gas and liquefied gas for the gas supply systems of cities and in the petrolic, chemical, and metallurgical industries. The response of monolithic spherical shells to shock type dynamic

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loadings has been investigated extensively over the past 70 years; other investigated issues include the bifurcation problem [26], the buckling problem [27,28], the elasto-plastic stress propagation and distribution [29,30], and the tensile plastic instability [31] under internal or external pressure [32].

However, experimental or computational investigations on the dynamic responses of sandwich spherical shells have yet to be reported. Therefore, the present work addresses this gap in the literature by exploring the aforementioned topic. Commercially available finite element (FE) code LS-DYNA 971 was employed to investigate the dynamic responses of metallic sandwich spherical shells with graded aluminum foam cores. To validate the numerical approach, the numerical results were compared with those of the experimental measurements carried out for sandwich shells with homogeneous aluminum foam cores [25] (Section 2). The deformation process of spherical shells, the energy absorption of each core layer, and the propagation behavior of stress waves in the foam core layers were discussed. Details are presented in the following sections.

2. Geometry model and material properties

2.1. Geometry modeling

Only 1/8 of the spherical shells with graded metallic foam cores were modeled because of the symmetry of their structures and loadings (Fig. 1a). The inner and outer radii of the sandwich shell are 200 and 230 mm, respectively. Six different graded groups (groups “a” to “f”) were considered by arranging the three foam core layers (Table 1). For instance, the core arrangement of group “a” was 10%–15%–20% (low/middle/high relative densities) from inside to outside; that of group “f” was 20%–15%–10% (high/middle/low relative densities). The thickness of each core layer was 10 mm, and the thicknesses of both the Inner-face-sheet (IFS) and the Out-face-sheet (OFS) was 1 mm. The interfaces between foam layers were defined as interface 1 (if1) and interface 2 (if2). The explosive used in the simulation had a spherical shape. Unless otherwise specified, the mass of the TNT was 350 g. The explosive was detonated at the inner center of the structure.

Eight-node solid elements with reduced integration were used for the cores, and Belytschko-Tasy shell elements were used for the face-sheets. The average element length was 2 mm. The numbers of shell elements and solid elements were 33750 and 253125, respectively. Mesh sensitivity studies revealed that further refinement does not significantly improve the accuracy of the calculations. The meshed model is shown in Fig. 1b. Four representative nodes located separately on the IFS (node 152), OFS (node 17253), and the interfaces between foam layers (node 35108 and node 137563) were selected to measure the radial velocity and displacement (Fig. 1b).

Table 1
Core arrangement groups of the graded sandwich spherical shells.

Groups	*a* (%)	*b* (%)	*c* (%)	*d* (%)	*e* (%)	*f* (%)
Foam#1	10	10	15	15	20	20
Foam#2	15	20	10	20	10	15
Foam#3	20	15	20	10	15	10

2.2. Material properties

The foam cores were modeled as a compressible continuum using the metal foam constitutive model of Deshpande and Fleck [33]. In the FE calculations, the foam was modeled by LS-DYNA Material Type 63. The quasi-static uniaxial compressive stress versus the strain curves of the foam measured experimentally for three different relative densities (10%, 15%, and 20%) are plotted in Fig. 2. The data on foam cores were obtained by standard quasi-static tests. Therefore the plateau stress of foam cores resulting from possible strain rate sensitivity may slightly be underestimated. The IFS and OFS were both made of aluminum alloy and simulated by isotropic and kinematic hardening plasticity model in LS-DYNA code. The strain rate was accounted for using the Cowper and Symonds model, which scales yield stress with the following factor:

$$1 + \left(\frac{\bar{\varepsilon}}{C}\right)^{1/P} \tag{1}$$

where $\bar{\varepsilon}$ is the strain rate. The density of the face sheets was $\rho = 2.7\ \mathrm{g/cm^3}$, the yield stress was $\sigma_{0.2} = 67$ MPa, Young's modulus was $E = 72$ GPa, Poisson's ratio was $\lambda = 0.33$, $C = 6500\ \mathrm{s^{-1}}$, and $P = 4$ [34].

3. Validation of numerical approach

3.1. Validation of deformation mode and parameters

Sandwich shells with aluminum foam-cores tested by Jing et al. [25] under air blast loading were simulated to validate the

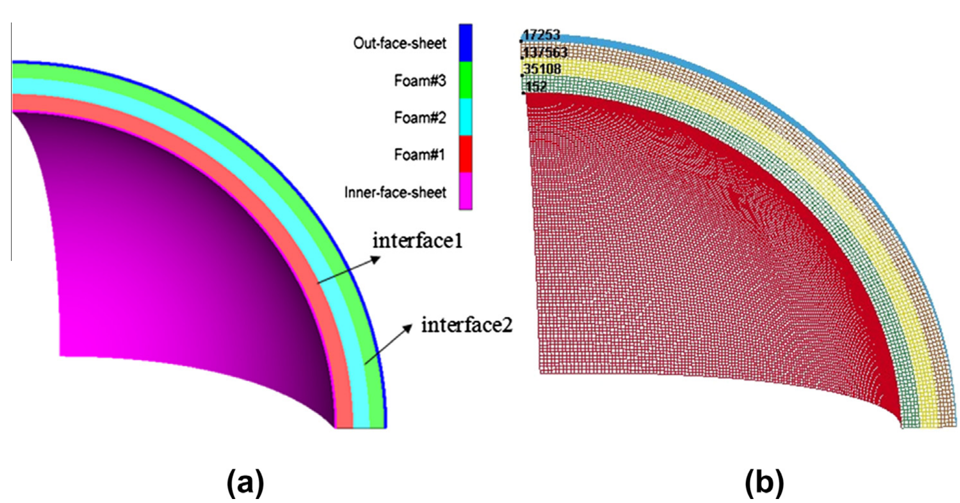

Fig. 1. Graded sandwich hollow spherical shell: (a) geometry model; (b) FE model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)