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Energy absorption and failure mechanism of metallic cylindrical sandwich shells under impact loading

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ABSTRACT

The dynamic response, energy absorption capability, and deformation and failure of clamped aluminum face-sheet cylindrical sandwich shells with closed-cell aluminum foam cores were investigated numerically by impacting the shells at central area with metallic foam projectiles in this paper. Typical deformation/failure modes and deflection response of sandwich shells, obtained from the experiments, were employed here to validate the numerical simulation. Numerical results indicate that the shock resistance of sandwich shells could be enhanced significantly by optimizing their geometrical configurations; the thickness of back face-sheet has a greater contribution than that of front face-sheet. Increasing of impact velocity and decreasing of face-sheet thickness, core relative density and curvature radius can enhance the energy absorption capability of sandwich shells. The initial curvature of sandwich shells may induce easily tearing failure along their circumferential directions. These findings can guide well the theoretical study and optimal design of metallic sandwich structures subjected to impulsive loading.

1. Introduction

Sandwich structures, which consist of two thin and stiff face-sheets and a softer cellular metal core such as foams, honeycombs or lattices, have attracted increasingly wide research interests due to their excellent shock-resistance performance and energy absorption capability under blast/impact loading [1–3]. A large number of studies have been conducted, and the typical deformation/failure modes, deflection response and failure mechanism of sandwich beams and panels have been investigated experimentally [4–6], while the corresponding predictions have been examined theoretically and numerically [7–10]. Especially, an analytical model developed by Fleck and Deshpande [7,8] has become a theoretical frame of studying the dynamic response of sandwich structures. In the model, the whole response of the sandwich structure was divided into three sequential stages: (I) fluid–structure interaction; (II) core compression; and (III) overall bending and stretching. However, all of these researches are limited into the flat sandwich structures, although extensive curved structures are used in the practical engineering applications. Shen et al. [11] conducted the exploratory experiments to investigate the response of curved sandwich panels with aluminum foam cores under air blast loading. Using the finite element method, Liu et al. [12] demonstrated the superior blast resistance of sandwich-walled hollow cylinders with graded metallic foam cores than that of ungraded ones. Hoo-Fatt et al. [13] developed an analytical model to predict the early time response of a composite cylindrical sandwich shell under blast loading. Recently, Jing et al. [14–16] examined experimentally and numerically the effects of geometrical configurations (i.e. face-sheet thickness, core relative density and specimen curvature) and blast impulse on the deformation/failure of cylindrical sandwich shells with aluminum foam cores subjected to air blast loading. However, these studies did not involve in the dynamic response, energy absorption and failure mechanism of sandwich shell structures under projectile impact over a wide range of velocities.

It is well-known that the high performance explosives are not the economical and safe experimental techniques to test prototypes at the laboratory scale. Hence, Radford et al. [17] developed a convenient loading technique to simulate the blast pressure pulse by using metallic foam projectile impact. The magnitude and duration of the pressure pulse can be controlled by suitable adjustment of the velocity, length and density of the foam projectile. Nonetheless, for a specific impact test occasion where the velocity is limited into a certain range, the impulse requirement cannot be met only by changing the length and density of foam projectiles [18]. An improved loading technique by using foam projectile adhered with Nylon cylinder was employed to explore the impact response of the cylindrical sandwich shells [18].

The primary objective of the present research is to study the energy absorption capability and failure mechanism of sandwich

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shells with aluminum foam cores under Nylon-foam projectile impact. Typical deformation/failure modes and deflection response of specimens obtained from the experiments were used to validate this finite element mode. Effects of impact velocity, specimen curvature, face-sheet thickness and core relative density on the energy absorption capability of sandwich shells were discussed and analyzed. Finally, the failure mechanism of impact-loaded sandwich shells was also examined.

2. Experimental details

In the experiments, a total of 38 cylindrical sandwich shell specimens, which were made up of two thin aluminum alloy face-sheets and a metallic foam core, with arc length of 310 mm and length also of 310 mm were tested. Two radii of curvature R (250 mm and 500 mm), three face-sheet thicknesses H (0.5 mm, 0.8 mm and 1.0 mm) and three core relative densities $\bar{\rho}$ (10%, 15% and 20%) were utilized. Impact tests were conducted on a dynamic loading device using a special designed fixture to clamp the sandwich shells, as shown in Fig. 1. The specimens were peripherally clamped only leaving a curved exposed area of 250 mm × 250 mm. An improved loading technique by using metallic foam projectile with diameter of 36.5 mm and length of 80 mm adhered with the same diameter Nylon 6 cylinder with length of 35 mm was employed to explore the impact response of sandwich shells. In the tests, the foam core was made from the closed-cell aluminum foam slab (Zhaosheng aluminum foam Co., LTD., Jiangsu, China) while circular cylindrical foam projectiles were electro-discharge machined from aluminum foam block (Luoyang Ship material research institute, CSIC, China).

From the tested results, deformation and failure of sandwich shells can be characterized by indentation, penetration and perforation failure of front face-sheet; compression and shear failure of core; the large inelastic deformation, transverse tearing and petal-like tearing of back face-sheet; and the interfacial failure between face-sheets and core. Some typical failure modes were presented compared with those of simulation results in Section 4.2. The quantitative test results including impulse and the permanent central point deflection of back face-sheet are given in Table 1.

3. Computational model

The dynamic response of sandwich shells subjected to projectile impact was numerically simulated using LS-DYNA 970 finite element software. Considering the symmetry of specimens, only a quarter of the shell was modeled, as shown in Fig. 2. The entire model comprises 93463 nodes and 97953 elements. The LY-12

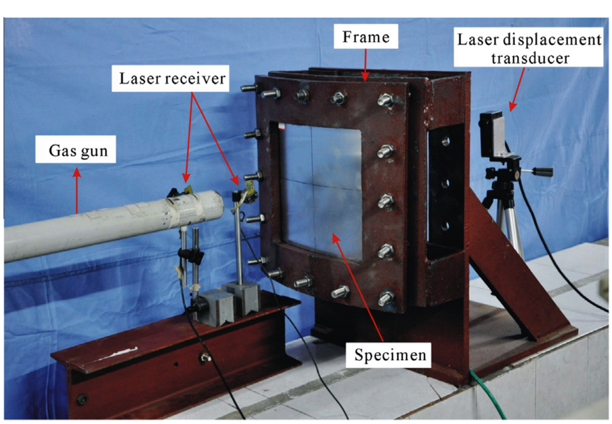

Fig. 1. Experimental set-up.

face-sheets were modeled by Belytschko-Tasy shell element, while the metallic foam core was modeled by the default brick element.

The mechanical properties of LY-12 aluminum alloy was simulated by a plastic kinematic constitutive model (*MAT_PLASTIC_KINEMATIC), which can account for the strain rate effect using the Cowper–Symonds model, i.e.,

$$\frac{\sigma_d}{\sigma_0} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}} \quad (1)$$

where σ_d and σ_0 are dynamic and static yield stress, $\dot{\varepsilon}$ is the strain rate, C, P is the constant, respectively. Since the weak strain rate-sensitive of aluminum alloy, the effect was ignored in this simulation. The aluminum foam core was modeled by using a simple material model (*MAT_CRUSHALBE_FOAM), which is dedicated to modeling crushable foam with optional damping and tension cutoff. The models *MAT_HONEYCOMB and *MAT_RIGID were used to described the large deformation of metallic foam projectile and nearly undeformed Nylon projectile, respectively. It is noted that the major use of this model *MAT_HONEYCOMB is usually for honeycomb and foam materials with real anisotropic behavior. However, since it is better to avoid the computational difficulties caused by mesh distortion in large deformation analysis, it was simplified here to describe the large uniaxial compressive deformation of foam projectile. The quasi-static uniaxial compressive stress versus strain curves of aluminum foam cores with different relative densities and foam projectile are shown in Fig. 3. To obtain the similar failure modes with that of experiment, the material erosion capability of LS-DYNA was used. Maximum shear strain (MSS), and failure strain (FS) of the plastic kinematic constitutive model were used to defined the failure criteria of foam core and face-sheets, respectively. Here, it is taken that MSS = 0.4 and FS = 0.12. The mechanical properties of face-sheets, aluminum foams and Nylon projectile are listed in Table 2. It must be emphasized that the plastic Poisson ratios of all the metallic foams were considered to be zero in the simulations.

The boundary and initial conditions in numerical simulations retain the same as that of experiments. The bolts used in the tests to clamp the shells to the fixture were represented by nodal constraints in the numerical model. Symmetric boundary conditions about x–z and y–z planes were imposed. Automatic, surface-to-surface contact options were generally used for sandwich shell, while the automatic single surface contact option was used for aluminum foam core.

4. Simulation results and discussion

The simulation results of sandwich shells under projectile impact loading mainly include five aspects: (1) structural response process of sandwich shells; (2) deformation/failure modes; (3) back face-sheet deflection; (4) energy absorption capability; and (5) deformation and failure mechanism. These are individually described in sub Sections 4.1–4.5.

4.1. Structural response process of sandwich shells

Fig. 4 indicates the deformation process of sandwich shells with metallic foam cores subjected to projectile impact. When the projectile impacted the sandwich shell specimen, the impulse is transmitted immediately to the central area of the front face-sheet, and then the core is compacted gradually resulting in compression deformation of the specimen. During this stage, the front face-sheet, core and back face-sheet obtain finally a common velocity while a large amount of energy is dissipated by the large deformation of front face-sheet and core compression. The deformation profile has the shape of a uniform dome, moving out from the