Composite Structures 107 (2014) 36–47

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Response of metallic cylindrical sandwich shells subjected to projectile impact—Experimental investigations

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ARTICLE INFO

Article history:
Available online 15 July 2013

Keywords:
Sandwich shell
Metallic foam
Dynamic response
Deformation/failure mode

ABSTRACT

The dynamic response of peripherally clamped cylindrical sandwich shells with two aluminum face-sheets and an aluminum foam core has been experimentally investigated using an improved loading technique. The resistance to impact loading is assessed by using the permanent transverse deflection at central point of back face-sheet of the sandwich shell. The comprehensive deformation and failure modes of specimens were classified and analyzed in term of face-sheets and core, and then the failure mode map of specimens was presented. Effects of impulse, face-sheet thickness, core thickness and relative density of core on the resistance to impact loading were discussed in detail. Deformation mechanism of sandwich shells subjected to projectile impact was explored based on the results of strain gauges adhered on the face-sheets. Results indicate that both the deformation/failure modes and back face-sheet deflection of sandwich shells are sensitive to impulse and their geometrical configurations, and the curved sandwich structures have an evident advantage on the resistance to deform, to the flatted sandwich panels. The experimental results have important reference value to the further study and engineering application of metallic sandwich structures.

1. Introduction

With an increasing application of novel protective materials/structures in the military facilities and other blast/impact resistance constructions, metallic sandwich structures consisting of two thin face-sheets and a softer cellular metal core, have showed their good blast/impact resistance performance and energy absorption capability [1–3]. Therefore, the structural response of these sandwich structures has become the focus of the related research scientists. Considerable studies on sandwich structures with cellular metal cores such as foams or honeycombs were conducted, and the typical deformation/failure modes, load-bearing capacity and energy dissipation mechanism have been examined experimentally, theoretically and numerically. Fleck and co-workers [4–7] proposed a three-stage analytical model to predict the dynamic response of the sandwich beam and plate under impulsive loading. In these models, the whole response is divided into three sequential stages: (I) fluid–structure interaction phase; (II) core compression phase; and (III) the overall bending and stretching phase. To validate their analytical models, the corresponding finite element analyses were also conducted and a good agreement has been obtained [8,9]. Based on the three-stage framework, extensive studies on impulsive resistance of sandwich structures were performed by other researchers. By employing the membrane factor method and a new yield criterion, Qin et al. [10–12] derived the analytical solutions for large deflections and time responses of sandwich beam with a metallic foam core. Zhu et al. [13] adopted an energy dissipation rate balance approach and incorporated a newly developed yield condition in the theoretical analysis, to predict the blast response of peripherally clamped square metallic sandwich panels with either honeycomb or aluminum foam core. The analysis has been shown to compare well with the corresponding experimental investigations [14,15] and numerical simulation [16]. Experimentally, Nurick et al. [17] investigated the inelastic response of blast-loaded sandwich panels, comprising mild steel face-sheets and aluminum alloy honeycomb cores. Three phases of interaction were identified based upon deformation, contact, crushing and tearing responses of the sandwich components. Villanueva and Cantwell [18] undertook the high velocity impact tests of a range of novel aluminum foam sandwich structures using a nitrogen gas gun. Typical failure modes, ballistic limit and energy absorbing characteristics of the specimens were presented and discussed. Similarly, the dynamic response of sandwich beams with metallic foam cores [19–21], aluminum honeycomb cores [21], or Y-frame and corrugated cores [22], and sandwich panels with different cores [14,15,23–25] was widely investigated. However, all of these studies only focus on the flatted sandwich structures,

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0263-8223/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.compstruct.2013.07.011

although a large number of curved structures are employed in the practical applications.

Consequently, some exploratory studies on the dynamic response of curved sandwich structures under blast loading were conducted. Shen et al. [26,27] examined the plastic large deformation response of curved sandwich panels and short sandwich tubes with aluminum foam cores under air blast loading. Using the computer modeling method, Liu et al. [28] investigated the blast response of metallic sandwich-walled hollow cylinders with graded aluminum foam cores. Recently, Hoo-Fatt et al. [29] derived a theoretical formula for the early time response of a blast-loaded composite cylindrical sandwich shell. Based on these studies, Jing et al. [30,31] conducted the experimental investigation and numerical simulation on the dynamic response of metallic cylindrical sandwich shells with aluminum foam cores under blast loading. Nevertheless, there is still no comprehensive report on the dynamic response of metallic sandwich shells, especially under impact loading over a wide range of velocities.

In order to test prototypes at the laboratory scale, there has been a long-standing need to develop a simple, economical and safe experimental technique to dynamically load a structure, to replace the high explosives. In a study by Radford et al. [32], a convenient experimental technique was developed to simulate blast loading by using metallic foam projectile impact, which impulse per unit area $I_0 = \rho l_0 v_0$ can be adjusted by changing the density ρ, length l_0 and velocity v_0 of the projectile. But 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 or density of foam projectiles. For example, increasing the projectile length cannot improve signally the impulse, due to the nearly constant compressive value, for a given impact velocity. On the other hand, changing the density of projectile easily tends to two extreme modes, i.e. ricochet of fully densified projectile and perforation of projectile with slight compression. Therefore, it is significant to develop a loading technique to enhance markedly shock pressure for a given velocity range. It is well known that, due to the different impedances, the impact pressure produced by low density materials is lower than that of high density materials, and the pressure of low density materials can be enhanced with the help of the high density materials. Based on this theory, an improved loading technique by using metallic foam projectile adhered with Nylon cylinder was employed in the paper, to explore the impact response of the cylindrical sandwich shells with aluminum foam cores.

2. Experimental procedure

2.1. Specimen

Cylindrical sandwich shells, which were made up of two thin face-sheets adhered to a light core by a commercially available acrylate, with length of 310 mm and arc length also of 310 mm were used in the tests. Drawing of a sandwich shell is shown in Fig. 1. The face-sheet was made from LY-12 aluminum alloy, and its mechanical properties are listed in Table 1. The core material was the closed-cell aluminum foam (Zhaosheng aluminum foam Co., Ltd., Jiangsu, China), and the typical uniaxial compressive stress–strain curve of foam core with different relative densities were obtained from the standard quasi-static test and shown in Fig. 2. Two radii of curvature (250 mm and 500 mm), three face-sheet thicknesses (0.5 mm, 0.8 mm and 1.0 mm) and three core relative densities (10%, 15% and 20%) were utilized in the test.

Table 1
The mechanical properties of face-sheet material.

Material	Density (kg/m^3)	Young's modulus (GPa)	Shear modulus (GPa)	Poisson ratio	Yield stress (MPa)
LY-12	2780	68	28	0.33	310

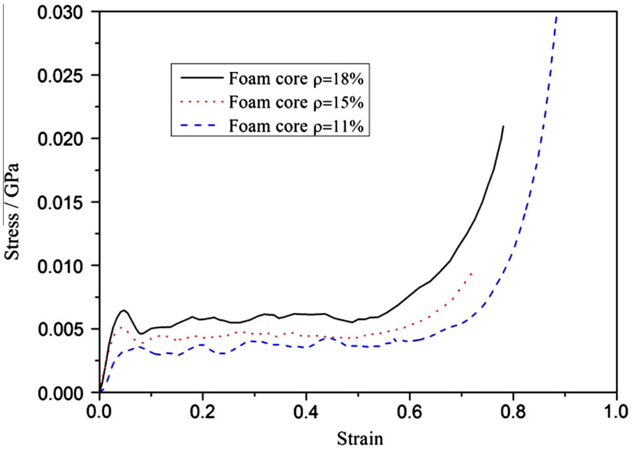

Fig. 2. Quasi-static compressive stress–strain curve of aluminum foam cores.

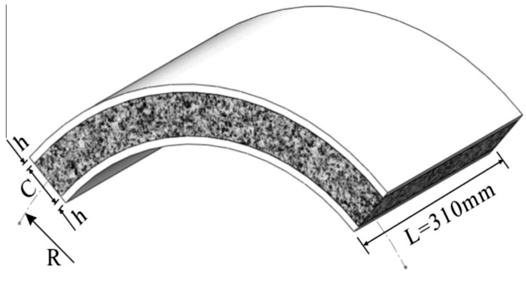

Fig. 1. Sketch of the sandwich shell with aluminum foam core.

A total of 38 specimens were manufactured and arranged into three groups as indicated in Tables 2–4, where R, H, C and m_C are the radius of curvature, face-sheet thickness, core thickness and core mass of sandwich shell specimen; l_f and m_f are the length and mass of metallic foam projectile; m_N is the mass of Nylon cylinder; v_0 is the velocity of projectile; and I and W are the impulse and deflection, respectively. Each group was designed to investigate the effect of one or two particular parameters on the dynamic response of the sandwich shells. To understand better the deformation/failure mechanism of the metallic sandwich shell under impact loading, the strain response at the key points on the face-sheets of specimens was measured by strain gauges, as shown in Fig. 3. These strain gauges (BE-120-3AA, zemic.com, China) with ultimate strain of 2.0%, nominal resistance of 119.1 ± 0.1 Ω and gauge factor of 2.21, were adhered along the central circumferential and longitudinal directions, being marked in different symbols.

2.2. Experimental set-up

Impact tests were conducted on a dynamic loading device using a special designed fixture to clamp the sandwich shells, as shown in Fig. 4. The overall experimental device includes air gas, clamped frame, laser displacement transducer and data recorder. A sketch of the experimental set-up is drafted in Fig. 5. A laser displacement transducer (LD 1625-200, με.com, Germany) was employed to measure the deflection–time response of the central point of back face-sheet of the sandwich shells, while a digital oscilloscope