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The dynamic response of sandwich panels with cellular metal cores to localized impulsive loading

Lin Jing [a,*], Zhihua Wang [b], Longmao Zhao [b]

[a] State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China
[b] Institute of Applied Mechanics and Biomedical Engineering, Taiyuan University of Technology, Taiyuan 030024, China

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ABSTRACT

The deformation/failure modes and dynamic response of peripherally clamped square monolithic and sandwich panels of localized impulsive loading were investigated experimentally by metallic foam projectile impact. The sandwich panels comprise three different types of cellular metallic cores, i.e., closed-cell aluminum foam core, open-cell aluminum foam core and aluminum honeycomb core. Experimental results show that all the sandwich panels present mainly large global inelastic deformation with obvious local compressive failure in the central area, except for those open-cell foam core sandwich panels. The dynamic response of sandwich panels is sensitive to the applied impulse and their geometrical configurations. Based on the experimental investigation, a theoretical analysis was developed to predict the dynamic response of sandwich panels by employing a comprehensive yield locus and a modified classic monolithic panel theory. A comparison of experimental results and theoretic predictions was made, and a good agreement was then found. These findings are very useful to guide the engineering applications of metallic sandwich structures for the protection purpose.

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1. Introduction

The employment of sandwich structure, which is a special form comprising a combination of two thin stiff metallic/composite skins and a softer low-density cellular metallic core, continues to be of much academic and industrial interests [1–3]. These sandwich structures have the favorable ability to undergo large plastic deformation at a relatively long low plateau stress, attributing to the devisable microstructure of cellular metallic cores, resulting in a wide use in many protective engineering as shock-resistance components and energy absorbers to resist in blast, shock or impact loads [2–4]. With the development of using a metallic foam projectile to simulate shock loading on a structure [5], which is safe and simple to conduct in a laboratory setting, corresponding studies on the dynamic response of such sandwich structures under metallic foam projectile impact has thus become increasingly attractive to guide the engineering applications.

Over the past decade, a large number of studies of cellular metal core sandwich structures have been widely reported focusing on the deformation/failure modes, dynamic structural response and energy absorption, and so on. Using a drop weight machine, the low-velocity impact behavior of sandwich structures with different types of face-sheets and cellular metal cores has been investigated [6–11]. Subsequently, based on a one-dimension plastic shock wave analysis, the dynamic response of sandwich beams [12–14] and panels [15–17] has been widely studied using a metallic foam projectile impact technique, as mentioned above, by numerous researchers. All these researches show that sandwich structures have a higher shock resistance than the corresponding solid monolithic counterparts of equal mass. Some typical dynamic failure modes such as face-sheet yielding or wrinkling, core compression or shear, and interfacial failure have also been demonstrated experimentally. For blast-resistance cases, a four-cable ballistic pendulum was employed to investigate the dynamic response of blast-loaded flat and curved sandwich panels [18–20], respectively. By detonating explosive discs in very close proximity range, Nurick et al. [21] studied the inelastic response of aluminum alloy honeycomb core sandwich panels under approximately uniformly distributed loading. Meanwhile, the corresponding finite element analyses were conducted to further study the dynamic response, failure mechanism, energy absorption capability and regimes of behavior of such sandwich structures [22–26].

* Corresponding author.
E-mail addresses: jinglin_426@163.com, jinglin@home.swjtu.edu.cn (L. Jing).

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Theoretically, Fleck and Deshpande [27] developed an analytical model for the finite deflection response of clamped sandwich beams subjected to shock loading, which has become a theoretical frame of studying the shock resistance of sandwich structures. In their model, the whole response of sandwich structures was split into three sequential stages, that is, fluid-structure interaction phase, core compression, and overall bending and stretching phase. Qiu et al. [4,28] extended this analytical model for clamped sandwich beams subjected to impulsive loading over a central loading patch and axisymmetric sandwich plates to a spatially uniform air or underwater shock, respectively. More recently, by incorporating a unified yield criterion considering the effect of core strength into the Fleck-Deshpande model, some theoretical analyses for the response of sandwich beams [29], panels [30] and shells [31] of impulsive loading have been reported. However, due to the coupling influences of sandwich topologies, loading method and manufacturing process, a comparative study on the shock resistance of different core topology sandwich structures still remains to need to be fully understood so as to quantify the structural advantages of sandwich design.

In this study, a comparative experimental study of sandwich panels with three different types of cellular metallic cores under localized impulsive loading was conducted, mainly focusing on the deformation/failure modes, dynamic response and failure mechanism. Based on experimental investigations, a theoretical analysis was developed to predict the dynamic response of sandwich panels. The experimental results were finally compared with theoretical predictions.

2. Experimental process

2.1. Specimens

Square sandwich panel specimens with the length of side 300 mm were fabricated by two thin Al-2024 aluminum alloy face-sheets and a cellular metallic core using epoxy adhesive, as shown in Fig. 1. Three thickness face-sheets ($h = 0.5$ mm, $h = 0.8$ mm and $h = 1.0$ mm) and three different cellular cores (closed-cell or open-cell metallic foam core, and aluminum honeycomb core) were used. The mechanical properties of face-sheet material, which were measured by the standard quasi-static tests, are as follows: Young's modulus $E = 72.4$ GPa, Shear modulus $G = 28$ GPa, Poisson's ratio $\mu = 0.33$, density $\rho = 2700$ kg/m^3, and yield stress $\sigma_{fY} = 75.8$ MPa.

The closed-cell and open-cell aluminum foam core materials were supplied by Hongbo Metallic Material Company (China). Three different core thicknesses c (10 mm, 20 mm and 30 mm) were used for closed-cell cores while three different average cell sizes d_c (0.75 mm, 1.5 mm and 2.5 mm; they are determined by the corresponding SEM photographs as shown in Ref. [14]) were chose for open-cell cores, respectively. The closed-cell foam is with density of 308 kg/m^3 (i.e., relative density $\bar{\rho} \approx 0.11$), which the open-cell foams are with an approximate relative density of 0.40. The aluminum honeycomb core (supplied by HexWeb®.com), which is made of aluminum 5052, comprises a square array of hexagonal cells, with cell length $l_c = 3.18$ mm and three values of cell-wall thickness t_c (i.e., 0.018 mm, 0.025 mm and 0.038 mm). The face-sheet thickness of 0.8 mm and core thickness of 12.5 mm were set for all aluminum honeycomb core sandwich panels. Typical quasi-static uniaxial compressive stress versus strain curves for these three types of cellular metal core materials are shown in Fig. 2(a)–(c). An energy-efficiency based approach [32] with the following equations was employed to calculate the plateau stresses and densification strains of these cellular core materials, and the corresponding results are included in Table 1.

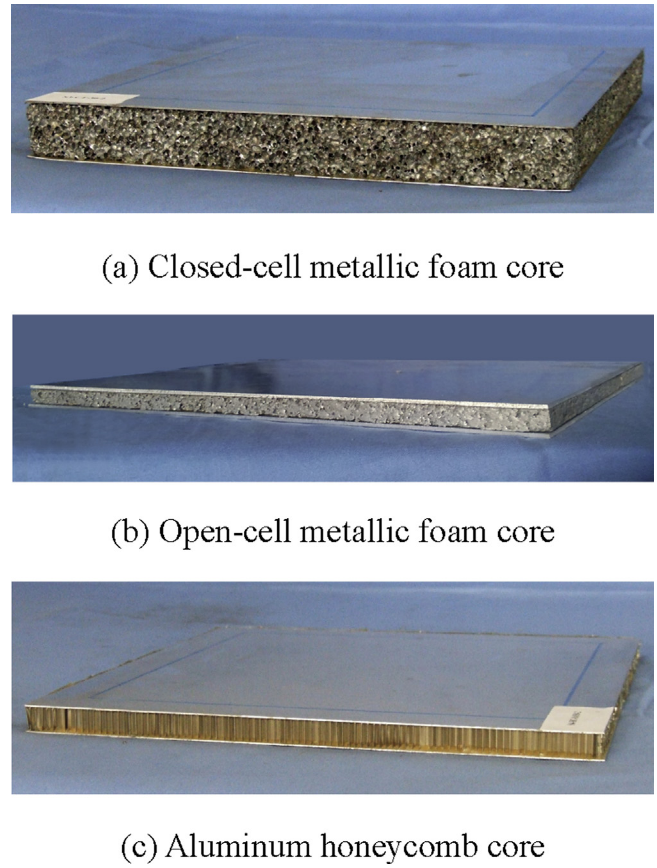

Fig. 1. Photographs of sandwich panels with three different cellular metal cores.

$$\eta(\varepsilon_a) = \frac{\int_{\varepsilon_{cr}}^{\varepsilon_a} \sigma_c(\varepsilon) d\varepsilon}{\sigma_c(\varepsilon)_{\varepsilon=\varepsilon_a}} \tag{1}$$

$$\left.\frac{d\eta(\varepsilon)}{d\varepsilon}\right|_{\varepsilon=\varepsilon_D} = 0 \tag{2}$$

$$\sigma_{pl} = \frac{\int_{\varepsilon_{cr}}^{\varepsilon_a} \sigma_c(\varepsilon) d\varepsilon}{\varepsilon_a - \varepsilon_{cr}} \tag{3}$$

where $\eta(\varepsilon_a)$ is the energy absorption efficiency; ε_a is a given nominal strain and $\sigma_c(\varepsilon)$ is the corresponding stress value; ε_{cr} and ε_D are the strain at the yield point and densification strain, respectively; σ_{pl} is the plateau stress.

For comparison, square monolithic solid plates with side length of 300 mm and thickness of 2.0 mm were also tested, aiming to quantify the structural advantages of sandwich panels. Meanwhile, the quasi-static punch tests were conducted by loading centrally the monolithic and sandwich plates with a flat cylindrical steel punch, whose diameter equals to that of foam projectiles.

2.2. Experimental set-up

Impact tests were conducted by loading the panels over a central area with closed-cell Alporas foam (supplied by Shinko Wire Company, Germany) projectiles using a gas gun apparatus. Cylindrical foam projectiles with the diameter d_p = 36.5 mm and

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