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On dynamic response of corrugated sandwich beams with metal foam-filled folded plate core subjected to low-velocity impact

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ABSTRACT

The paper focuses on fully clamped corrugated sandwich beams with metal foam-filled folded plate core to investigate its response subjected to low-velocity impact. The yield criteria for the metal foam-filled corrugated sandwich beam cross-section are obtained by considering the strength effects of metal foam and folded plate. Based on the yield criteria, dynamic and quasi-static models are developed to analytically predict the large deflections of corrugated sandwich beams, respectively, which agree well with finite element results. Furthermore, it is shown that the strain hardening of face sheets and folded plate do not significantly influence the low-velocity impact response.

1. Introduction

Due to the excellent comprehensive properties over monolithic structures, sandwich structures are widely adopted in critical engineering fields, such as aerospace, aircraft, vehicle, high speed train and marine industries. A conventional sandwich structure comprises of two stiff face sheets separated by a lightweight core, for example, metal foam [1,2], honeycomb [3], corrugated plate [4,5], pyramidal truss [6,7], and Kagome lattice [8]. Sandwich structures with metal foam core are widely used as energy absorption members due to a long region of plateau stress after initial failure, however their load-carrying capability is limited by the relatively low peak strength [9]. On the contrary, sandwich structures with lattice cores are widely used as primary load-carrying structures because of their high peak loads. However their energy absorption performances are somewhat limited since the residual load-carrying capacities usually drop rapidly upon reaching the peak values [6,10]. In order to combine the advantageous properties of the two systems, the hybrid lattice/foam-cored sandwich structures have been designed.

In engineering applications, sandwich structures are often utilized for protection against low-velocity impact, e.g. dropped tools, hailstones, and runway debris. For design purposes, an efficient analysis that adequately captures the impact response is required. This motivates the focus of the paper.

Over the past decades, low-velocity impact behaviors of conventional foam-cored or lattice-cored sandwich structures have been investigated extensively. Crupi et al. [11], Yu et al. [12,13] and Tan et al. [14] experimentally studied the dynamic response of metal foam core sandwich structures, and different dynamic failure modes were observed with different geometry and material properties of the face sheet and core. Crupi et al. [15], St-Pierre et al. [16] and Zhang et al. [17] experimentally investigated the low-velocity impact response of sandwich structures with different lattice cores such as honeycomb, corrugated plate, Y-frame and pyramidal truss. Experimental results revealed that different topological cores induced different collapse modes, which influence the capability of impact resistance. Based on these experimental observations, much theoretical work to predict the impact response of sandwich structures has also been carried out. Hazizan and Cantwell [18,19] theoretically predicted the low-velocity impact response of foam-based and aluminum honeycomb sandwich structures with an energy-balance model. Foo et al. [20] extended the validity of this model beyond the elastic regime. In addition, an analytical spring-mass model [21,22] has also been proposed for the same purpose. Li et al. [23] developed an elastic–plastic model to predict the dynamic response of a simply supported composite sandwich beam, in which the idealized bending hinge was adopted. Furthermore, Wang and co-authors [24–26] theoretically predicted the large deflection low-velocity impact response of slender metal foam core sandwich beam with symmetric and asymmetric face sheets, where a yield criterion incorporating the effect of core strength was adopted. Also, some

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interesting conclusions were reported based on the numerical simulations of sandwich structures under low-velocity impact [20,27,28].

Similar work has also been done on the impact behavior of hybrid lattice/foam-cored sandwich structures. Yazici et al. [29] experimentally and numerically investigated the blast resistance of foam-filled corrugated core steel sandwich structures. It was shown that the addition of foam infill strengthens the performance of sandwich panels against blast. Zhang et al. [30] experimentally studied the energy absorption and low velocity impact response of polyurethane foam filled pyramidal lattice core sandwich panels. Compared to sandwich panels with only lattice or foam filled cores, the results suggest that the load-carrying capacity and energy absorption efficiency of foam filled sandwich panels can exceed the values given by the sum of the two component cores. Zhang et al. [31] theoretically investigated the compressive strengths and blast responses of corrugated sandwich plates with unfilled and foam-filled sinusoidal plate core. Therewith, the compressive strengths of unfilled and foam-filled sinusoidal plate cores were derived and a simplified plastic-string model was developed to predict the large deflection blast response. However, to the authors' knowledge, there is little work on the theoretical investigations of low-velocity impact response of hybrid lattice/foam-cored sandwich structures.

The objective of this work is to investigate low-velocity impact response of fully clamped corrugated sandwich beams with metal foam-filled folded plate core. The paper is organized as follows. In Section 2, the problem formulation is presented. In Section 3, the yield criteria of metal foam-filled corrugated sandwich beam cross-section are derived, considering both the effects of metal foam and folded plate. In Section 4, analytical models for the large deflection responses of the fully clamped corrugated sandwich beams with metal foam-filled folded plate core subjected to low-velocity impact are developed. In Sections 5 and 6, comparisons between numerical simulations and analytical predictions are performed. Finally, concluding remarks are presented in Section 7.

2. Problem formulation

Consider a corrugated sandwich beam of span $2L$ with metal foam-filled folded plate core fully clamped at its two vertical surfaces. A heavy mass G_s of initial velocity V_I struck the beam at a distance L_1 from left support as depicted in Fig. 1. Two identical face sheets, each of thickness h, are assumed to be perfectly bonded to the hybrid core of thickness c comprising of folded plates and filled metal foam. Sketches of corrugated sandwich beam, half unit cell of unfilled and metal foam-filled sandwich beams are provided in Fig. 2, respectively. The width of half unit cell is denoted as b, the thickness and angle of inclination of the folded plate are b_c and θ, and the densities of face sheets, folded plate and metal foam are ρ_f, ρ_{fc} and ρ_c, respectively. It is assumed that the face sheets and folded plate obey the rigid-perfectly plastic (*r-p-p*) constitutive relation with yield strengths σ_f and σ_{fc}, while the metal foam core follows the rigid-perfectly plastic-locking(*r-p-p-l*) material with yield strength σ_c and densification strain ε_D, as shown in Fig. 3.

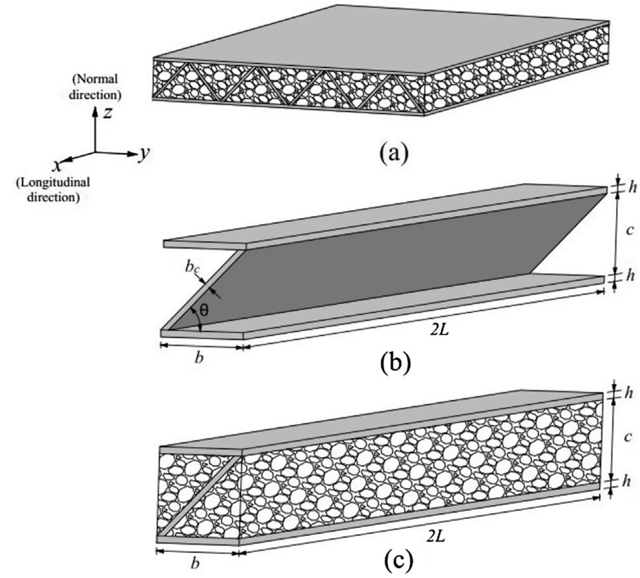

Fig. 2. Sketches of corrugated sandwich beams. (a) Metal foam-filled sandwich beam, (b) half unit cell of the unfilled sandwich beam, and (c) half unit cell of the metal foam-filled sandwich beam.

3. Yield criterion

Consider a sandwich cross-section shown in Fig. 4. It is assumed that the sandwich cross-section has a fully plastic stress distribution resulting from a combination of a bending moment M and an axial force N. The distance between the plastic neutral surface and the external surface of the bottom face sheet is denoted by $H = \xi \times (c + 2h)$, where $\xi \in [0, 1]$. Then the axial force N and the bending moment M can be given by

$$N = \begin{cases} 2\sigma_f b[h-\xi(c + 2h)] + (\sigma_{fc}-\sigma_c)\frac{b_c}{\sin\theta}c + \sigma_c bc, & 0 \leqslant \xi \leqslant \frac{h}{c+2h} \\ [(\sigma_{fc}-\sigma_c)\frac{b_c}{\sin\theta} + \sigma_c b](c + 2h)(1-2\xi), & \frac{h}{c+2h} \leqslant \xi \leqslant \frac{1}{2} \end{cases} \tag{1}$$

and

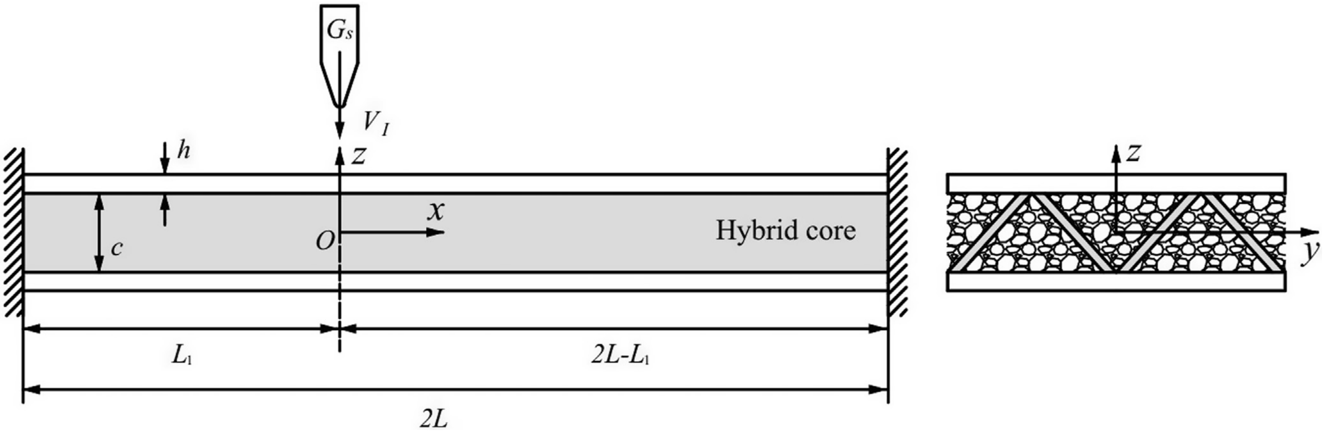

Fig. 1. Sketch of a fully clamped corrugated sandwich beam with metal foam-filled folded plate core struck by a heavy mass with low-velocity.