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Three-point bending of sandwich beams with aluminum foam-filled corrugated cores

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ABSTRACT

Sandwich panels having metallic corrugated cores had distinctly different attributes from those having metal foam cores, the former with high specific stiffness/strength and the latter with superior specific energy absorption capacity. To explore the attribute diversity, all-metallic hybrid-cored sandwich constructions with aluminum foam blocks inserted into the interstices of steel corrugated plates were fabricated and tested under three-point bending. Analytical predictions of the bending stiffness, initial failure load, peak load, and failure modes were obtained and compared with those measured. Good agreement between analysis and experiment was achieved. Failure maps were also constructed to reveal the mechanisms of initial failure. Foam insertions altered not only the failure mode of the corrugated sandwich but also increased dramatically its bending resistance. All-metallic sandwich constructions with foam-filled corrugated cores hold great potential as novel lightweight structural materials for a wide range of structural and crushing/impulsive loading applications.

1. Introduction

High performance lightweight sandwich constructions require the cores to have high stiffness and strength as well as energy absorption capacities. It was recently envisioned that this may be achieved by combining stochastic foams with periodic lattice trusses [1]. The concept was simple and straightforward. Sandwiches with lattice truss cores were widely applied as primary loading structures due to high stiffness/strength to weight ratio [2–7], yet they usually softened rapidly once the peak load was reached due to node failure and/or core buckling. With a long plateau region after initial failure was initiated, sandwich structures with metallic foam cores were attractive for energy absorption applications [8,9], yet their stiffness and peak strength were limited by a multitude of initial geometric defects induced during processing [10,11]. To mingle the advantageous attributes of foams and lattices, a variety of approaches had been attempted, including combing polymer foams with metallic lattices [12–15], polymer foams with polymer lattices [16–18], and metallic foams with metallic lattices [1].

The hybrid lattice/foam-cored sandwich panels thus constructed were so far studied mainly under out-of-plane uniform compression (quasi-static and dynamic), both experimentally and theoretically. The beneficial effect of foam filling was found to be strongly dependent upon the type of combination. For instance, combining relatively weak polymer foams with metallic lattices led only to limited enhancement of stiffness/strength and energy absorption [13]. Built upon the existing studies, the focus of the present investigation was placed upon examining the three-point bending performance of metallic corrugated sandwiches filled with aluminum foams using a combined experimental and analytical approach.

Using finite element (FE) simulations, Vaziri et al. [13] found rather limited effect of inserting polymeric foams (Divinycell) into the interstices of metallic sandwich panels with corrugated cores, which was attributed to the insufficient lateral support provided by the filling foam to the core members against buckling. Subsequently, also using sandwich panels having corrugated cores as the prototype, Yan et al. [1] replaced the filling polymeric foam with close-celled aluminum foams and demonstrated, both experimentally and numerically, that the compressive strength and energy absorption capacity of the corrugated sandwich panel were much greater than the sum of those of an empty sandwich panel and the aluminum foam alone.

Besides out-of-plane uniform compression, sandwich panels in engineering applications were commonly subjected to other types of load such as three-point bending. The bending responses of sandwich structures with a variety of lightweight cellular cores

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had been extensively studied, including lattice truss cores (corrugated plates [18–21], Y-frames [21], honeycombs [15,22,23] and pyramidal trusses [24]) and metallic [25–27] and polymeric foam cores [28]. The effect of dynamic loading was also examined [23,29–31]. Nonetheless, the bending performance (including stiffness, failure load and failure mechanisms) of all-metallic sandwich panels with aluminum foam-filled cores was yet to be investigated. In fact, sandwich panels with either periodic lattice or stochastic foam cores were known to have relatively low resistance to shear/bending. How this might be mended by combing metallic lattices with aluminum foams to make use of their respective attributes as the core for sandwich constructions was the main focus of the present study.

The paper was organized as follows. Sandwich beams with aluminum foam-filled corrugated cores were fabricated and tested under quasi-static three-point bending. For comparison, empty (unfilled) corrugated sandwich beams were also tested. Analytical predictions of the bending stiffness, initial failure load and peak load were obtained and compared with those experimentally measured. Failure maps were constructed to reveal the failure mechanisms underlying the enhanced bending performance of the hybrid-cored sandwich structures. Finally, the performance of the foam-filled sandwich was compared with several competitive designs.

2. Experimental measurement

2.1. Fabrication of test samples

Fig. 1 illustrated schematically the fabrication procedures for sandwich beams having empty and aluminum foam-filled corrugated cores. Both the face sheets and core web (*i.e.*, strut) of the sandwich were made of 304 stainless steel (density ρ_s = 7900 kg/m^3). Commercial closed-cell aluminum alloy foam with density of ρ_f = 540 kg/m^3 was selected as the filling material [32]. To this end, triangular foam prisms having the same shape of the interstices of the corrugated plates were cut by electro-discharge machining (EDM) from aluminum foam sheets. The triangular foam prisms were then inserted into the interstices and fixed with epoxy glue. Before assembling, surface cleaning was applied to both the empty sandwich beam and the foam prisms. The foam-filled sandwich was hold at 25 °C for 4 h, heated up to 80 °C for 2 h, and then cooled to ambient temperature.

2.2. Three-point bending test

Quasi-static three-point bending tests (Fig. 2) were conducted on MTS-880 materials test system, with fixed loading rate of 0.5 mm/min according to ASTM: C393 and ASTM: D7249 for beam flexure test of sandwich constructions. Both long and short sandwich beams were tested, as shown in Fig. 3, the former with a total length of 312 mm (*i.e.*, 9 unit cells) and the latter with 180 mm (*i.e.*, 5 unit cells), and the loading span L between the supports were 242 and 112 mm, respectively (Fig. 2). The force and displacement of the specimens were measured by the loading cell of the test machine. Unloading was performed to measure the bending stiffness instead of the loading curve. A rig was manufactured for the test to ensure the loading condition was simplified three-point bending. The support and the head of the loading device were steel cylinders of 10 mm in diameter, each attached to a flat pedestal with width of 10 mm to avoid force concentration. To study the deformation and failure modes of the sandwich beams, digital deforming images of each specimen were acquired by video camera.

As listed in Table 1, the sandwich specimens used for the present three-point bending tests had fixed width of b = 40 mm, fixed strut thickness of t = 0.41 mm, fixed inclination angle of θ = 45°, and fixed core height of h_c = 17 mm. Further, closed-cell aluminum

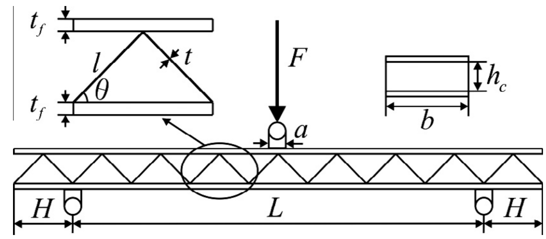

Fig. 2. Schematic of corrugated sandwich beam subjected to three-point bending.

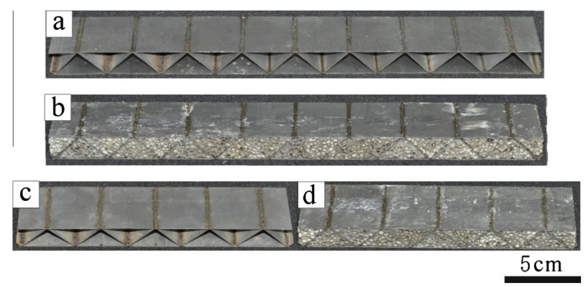

Fig. 3. Typical as-fabricated empty and aluminum foam-filled sandwich beams with corrugated cores. Long beam: (a) empty; and (b) filled. Short beam: (c) empty; and (d) filled.

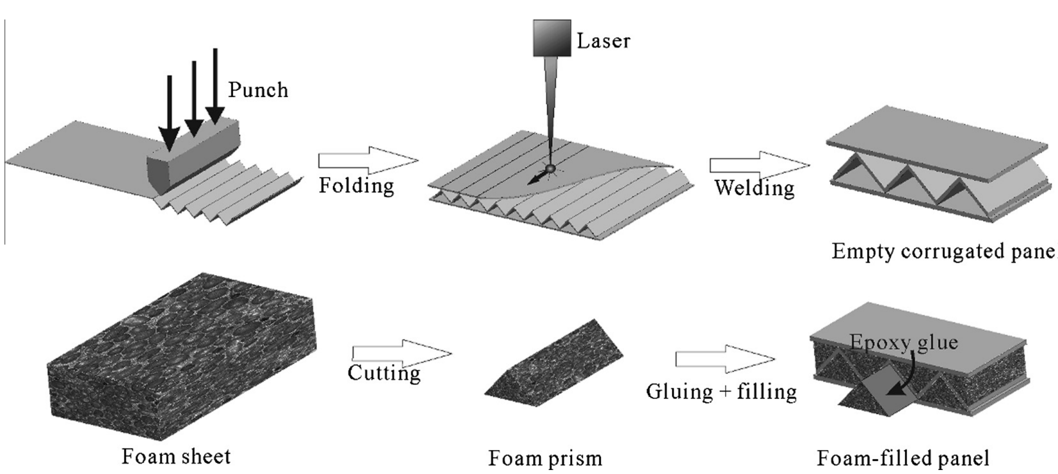

Fig. 1. Fabrication process of corrugated sandwich beams with unfilled and aluminum foam-filled cores [1].