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Experimental and numerical study of foam filled corrugated core steel sandwich structures subjected to blast loading

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ABSTRACT

The influence of foam infill on the blast resistivity of corrugated steel core sandwich panels was investigated experimentally using a shock tube facility and high speed photography and numerically through Finite Element Methods (FEM). After verifying the finite element model, numerical studies were conducted to investigate the effect of face sheet thickness (1, 3 and 5 mm), corrugated sheet thickness (0.2 mm, 0.6 mm and 1 mm), and boundary conditions (Simple Supported and Encastre Supported on the back sides) on blast performance. Experimental and FEM results were found to be in good agreement with R^2 values greater than 0.95. The greatest impact on blast performance came from the addition of foam infill, which reduced both the back-face deflections and front-face deflections by more than 50% at 3 ms after blast loading at a weight expense of only 2.3%. However, increasing face sheet thickness and corrugated sheet thickness decreased the benefit obtained from foam filling in the sandwich structure. Foam infill benefits were more prominent for Simple Supported edge case than Encastre Supported edge case.

1. Introduction

A major consideration in the design of military vehicles is their resistance to explosive blast loading. With the fast development of modern military technology, monolithic plates are continuing to fall behind the desired levels of blast protection. Sandwich structures with cellular solid cores, such as metallic foams and honeycomb structures, have shown superior weight specific stiffness and strength properties compared to their monolithic counterparts in blast resistant structural applications. Their cellular microstructure allows them to undergo large deformation at nearly constant nominal stress and thus absorb more energy [1–3]. To date, the effect of foam filling on blast mitigation of corrugated core sandwich panels under shock loads has not been fully understood. In this study, shock tube experiments and FEM were used to investigate the influence of foam infill on the blast resistivity of corrugated steel core sandwich panels. In addition, monolithic face sheets and foam core sandwich panels were tested and analyzed to validate the FEM. More studies were numerically conducted to investigate the effect of face sheet thickness and corrugated sheet thickness under two different boundary conditions, namely simply supported and Encastre Supported. In order to see the effect of corrugated core rigidity, soft, medium, and hard core cases were studied numerically utilizing both filled and empty conditions under blast loading.

In recent years, a number of micro-architectured materials have been developed to use as cores in sandwich panels. These include pyramidal cores [4–6], diamond celled lattice cores [7], corrugated cores [8], hexagonal honeycomb cores [9], foam cores [10], and square honeycomb cores [11]. The benefits of sandwich construction depend on core topology. Core designs that afford simultaneous crushing and stretching resistance are preferred. One of the most preferred practical core topologies in blast resistant sandwich panel construction is the corrugated metallic core. These cores provide manufacturing advantages as well as high strength in both the normal and longitudinal directions of the structures [7,12,13].

Sandwich structures have various energy dissipation mechanisms, such as bending and stretching of the face sheet, as well as compression and shear of the core. This is especially pertinent in the case of impulsive loading, wherein the interstices in the metal cellular core can provide adequate space for the large plastic deformation, which is an efficient mechanism to dissipate the energy produced by blast impact [14–17]. During blast loading, the cellular solid core can absorb more than one half of the initial kinetic energy imparted to face sheet of the sandwich plate. This is due to crushing in the early stages of deformation, prior to significant overall bending and stretching, which causes a reduction in the separation between the face sheets. The high crushing strength and energy absorption per unit mass of the core is therefore important [18–22].

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Different material properties have been suggested to provide blast attenuation. Depending on the acoustic impedance of the interacting medium, the shock wave will reflect, transmit, and/or dissipate to differing degrees [23]. Zhuang et al. [24] examined the scattering effects of stress waves in layered composite materials. Their experimental results show that due to the scattering effects, shock propagation in the layered composites was dramatically slowed, and that shock speed in composites can be lower than that of either of its components.

Wakabayashi et al. conducted experiments that suggest that low-density materials may provide the most effective blast mitigation [25]. In recent years, sandwich structures with strong face sheets and lightweight cores have become central structural components for blast mitigation. Polymeric foams offer unique structural, impact, thermal and acoustic properties, which make them an excellent choice as core materials to obtain low density blast resistive sandwich structures [2,26]. Based on these ideas, extensive research on blast mitigating layered sandwich structures has been performed in recent years, using foam cores with different wave impedances to minimize shock effect [27–29].

Studies on metallic sandwich panels subjected to air blasts [17,8] indicate that sandwich plates with high ductility and high energy absorption capacity per unit areal mass show good performance. Liang et al. [30] and Wei et al. [31] studied the behavior of metallic sandwich cores with varying strengths and found that soft cores (those in which the core is much less stiff then the sandwich panels' faces) reduce the momentum transferred, thus providing better mitigation for blast loading. For metallic structures, energy absorption in metallic lattice cores is through large scale plasticity, shear and compressive buckling, and eventual tearing of core walls and face sheets [26].

Another possible application of structural foams is for use as a filler material inside cellular metallic core sandwich structures. It is possible to obtain a new sandwich structure by combining these two cores' shock absorption advantages and decrease the transmitted shock load due to differing acoustic impedances. Moreover, foam filling stabilizes the core cell walls against buckling and increases the strength of the core. Vaziri et al. [21] studied two different types of PVC foam filled stainless steel honeycomb and folded core sandwich plates using FEM under various restrictions. They found no clear advantage or disadvantage implemented by foam filling for structural purpose under quasi static and impact loading.

Jhaver and Tippur [32] investigated syntactic foam filled aluminum honeycomb composites compression response by experimental and computational methods. They obtained considerable increases in elastic modulus and plateau stress through foam filling the honeycomb composites. Murray et al. [33] studied polymer filled aluminum honeycomb structures to investigate the filling effect on damping using numerical methods with experimental validations. It was found that high damping improvements in the filled honeycomb explained the significant strain energy in the polymeric infill due to the Poisson's mismatch between the honeycomb and the infill. Yungwirth et al. [34] showed that low modulus elastomer infill in pyramidal lattice truss metallic core increased the impact energy absorption capacity. Other studies have had success improving the impact resistance of honeycomb cores by fully or partially filling the cells of the honeycomb [35–38].

In this study the influence of face sheet thickness, corrugation thickness, boundary condition and foam filling on shock mitigation is explored. Encastre boundary conditions generally decreased panel deflection. The decrease was more prominent with face thickness change than with core thickness change. Generally soft core structures performed better under shock loading than strong or slapping cores with the one exception that completely foam filled panels were the best core having the least back-face deflection. Foam filling reduced the deflection of the panels in all cases although the degree of improvement decreased with the increase in corrugation and face sheet thickness.

2. Experimental procedure

2.1. Specimen preparation

Corrugated steel core sandwich structures used in this study were produced with low carbon steel face sheets and galvanized, low carbon steel sinusoidal corrugations in a four-layer match-up. A schematic of the sandwich panels is shown in Fig. 1.

The face sheets had lateral dimensions of 50.8 × 203.2 × 3.2 mm. The sinusoidal corrugated sheet reference dimensions are shown in Fig. 1a. Thickness of the corrugated sheet was 0.44 mm (29 gauge) with galvanization. The corrugation sheets and the face sheets were bonded to each other with epoxy adhesive G/Flex (West System Inc.). The shear strength of this material was 20 MPa. The specimens' average mass was 616.2 g, 630.4 g, and 491.9 g for empty corrugated steel core sandwich panels, foam filled corrugated steel core sandwich panels, and foam core sandwich panels, respectively. All three different sandwich panel configurations (see Fig. 2) were subjected to blast loading with simply supported boundary conditions.

2.2. Shock loading procedure

A shock tube apparatus was used to generate shock waves with planar wave fronts. A photograph of the shock tube used in these studies can be seen in Fig. 3. A typical pressure profile generated by the shock tube and used in these experiments is shown in Fig. 4. The exit muzzle inner diameter of the shock tube was 38.1 mm (see Fig. 5) [39]. Two pressure transducers (PCB102A) were mounted at the end of the muzzle section to record the incident and reflected pressure profiles. The first pressure sensor was mounted 20 mm away from the muzzle, and the second was mounted 180 mm away (160 mm separation from the first pressure sensor). The incident peak pressure of the shock wave was chosen to be 1.1 MPa and the reflected peak pressure of approximately 5.5 MPa was obtained in the current study.

The specimen was placed onto a simply supported boundary condition fixture with a 152.4 mm span. The flat front face of the specimen was set normal to the axis of the shock tube with the face completely covering the muzzle. A diagram of this set up can be seen in Fig. 5. At least three specimens of each type were shock loaded to insure repeatability.

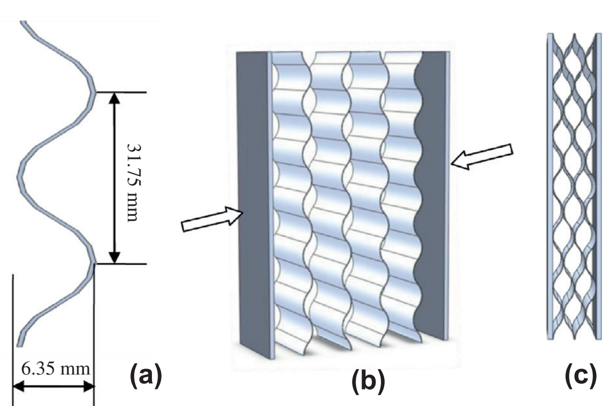

Fig. 1. (a) Corrugated core sheet dimensions. (b) Assembly procedure of corrugated steel core sandwich structures. (c) Final sandwich panel side view.