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Novel sandwich panel with metallic millitube grid stiffened polymer core for impact mitigation

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ABSTRACT

Sandwich construction has been extensively used in various fields. However, sandwich panels have not been fully exploited in critical structural applications due to damage tolerance and safety concern. A major problem of sandwich panels is the vulnerability to impact loading, which can lead to a sudden loss of structural integrity and cause catastrophic consequences. In order to improve the energy absorption of sandwich panel under impact loading, a new sandwich core is proposed which is a hybrid core consisting of hollow metallic millitube grid stiffened polymer matrix. The objective of this study is to characterize its impact performances. Quasi-static low velocity impact test and ballistic impact test demonstrate that the new sandwich panel may be considered as a promising option for critical structural applications featured by multiple impact tolerance.

1. Introduction

Protecting structures against explosion-induced blast waves and ballistic impact loads have been traditionally associated with military installations and buildings of high importance such as Embassies, Government facilities, satellites, bunkers, and civilian structures such as nuclear power plants, bridges, aircrafts, tanks, and ships. Therefore, there is a need to develop more economical protective structures that are capable of withstanding extreme loadings.

Advanced composite sandwich structures have been widely used in aerospace structures, autos, armors, wind turbine blades, pipelines, bridge decks, etc. due to their superior structural capacity in carrying transverse loads with minimal weight penalty [1–7]. Sandwich structures typically consist of skins (surfacing and back plates) and a core. The skins are mainly responsible for carrying the bending moment (in blast protective sandwich panels, the surfacing plate is also responsible for eroding, breaking and slowing down the projectiles) and the core takes care of separating and fixing the skin, carrying the transverse shear load, providing impact resistance, and taking other functional duties. Various types of core materials have been studied such as foam core (polymeric foam, metallic foam, ceramic foam, balsa wood, syntactic foam, etc.) [4,5], truss, honeycomb and other web cores [8], 3-D integrated core [9,10], foam filled web core [10,11], laminated composite reinforced core [12], etc. While these core materials have been used with a certain success, they are limited in one way or another. For example, the brittle syntactic foam core absorbs impact energy primarily through macro length-scale damage, sacrificing residual strength significantly [13–15]; and web cores lack of bonding with the skin and also have impact windows [10,11]. Among the foam cores, metallic foam is a new development. Metallic foam material has received rapid and intensive attention over the past decade due to its high specific stiffness and superior energy absorption ability [16–18].

However, there are several limitations for metallic foams: first, their limited static compressive strength is a major obstacle to critical structural application. Meanwhile, the strength and ductility in tension is quite low. For example, the tensile strength and elongation of typical aluminum foams with a 30% relative density is only about 8–10 MPa and a few percents, respectively [19]. These may be caused by the unconsolidated geometry and 3D quasi-isotropic loading status in the foam's ligaments. Additionally, a cost-benefit analysis shows that metallic foams are not very competitive [20]. Although the physical interface bonding between the metallic foam core and the skin is fairly good due to the filling of resin in foam's pores (strong mechanical interlocking), sub-interface failure in the metallic foams was often observed [20].

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Previously, it was found that by filling the empty bays formed by continuous fiber reinforced polymer grid skeleton with polymeric material, the resulting composite sandwich could be an ideal structure for impact mitigation [21–24] because (1) each cell is a small panel or mini-structure with elastic boundary, it thus tends to respond to impact in a quasi-static manner, i.e., similar to the behavior under static load; (2) the periodic grid skeleton, the primary load carrying component with 2-D continuity, could be responsible for transferring the impact energy elastically and dissipating the energy primarily through vibration damping, and providing the in-plane tensile strength and in-plane shear resistance; (3) the light-weight polymer matrix in the bay, the secondary load carrying component, could be primarily responsible for absorbing impact energy through damage; (4) the grid skeleton and the polymer in the bay could develop a positive composite action, i.e., the grid skeleton confines the polymeric bay to increase its strength and the polymer matrix provides lateral support to resist rib local buckling and crippling. In addition, the polymeric bay could also provide additional in-plane shear strength for bi-grids such as orthogrid; and (5) the core and skin could be fully bonded because the bay is fully filled, without the limitation of web cores [21–24]. However, it is found that when the impact is on the rib or node, the residual strength is reduced considerably, due to the brittleness of the glass fibers. Therefore, it is envisioned that if the brittle glass fiber is replaced by hollow metallic tube, the energy absorption can be significantly increased due to the ductility of metals such as steel [25,26]. At the same time, because the tube is hollow, the increase in weight can be minimized. The purpose of this study was to investigate the impact tolerance of a novel sandwich with metallic hollow millitube grid stiffened polymeric core under both low velocity impact loading and ballistic impact loading.

2. Specimen and test set-up

2.1. Raw materials

The face sheets of sandwich panels were made of laminated composite plate. The composite plate was prefabricated by bi-directional woven glass fabric reinforced vinyl ester resin with a uniform thickness of 3.2 mm (1/8 in.). The volume fraction of the glass fiber was 55%. The density of the composite plate was about 1.75 g/cm^3. The elastic moduli of the composite plate were 18 GPa, 16 GPa, and 5.5 GPa along direction one, direction two and direction three in the principal coordinate system, respectively. Direction 1 was aligned to the wrap direction, direction 2 was the weft direction, and direction 3 was the transverse direction.

The hollow metallic millitubes for the grid stiffened core were made of stainless steel. The elastic modulus and yielding strength of the steel tube were 205 GPa and 170 MPa, respectively. The measured inner diameter and outer diameter of the millitube were 1.92 mm and 3.15 mm, respectively.

LOCTITE Hysol 9460, an epoxy based structural resin was used in all three types of sandwich cores. The density of the epoxy resin was 1.31 g/cm^3. According to the manufacturer's test data, the elastic modulus, tensile strength and elongation at break were 2.76 GPa, 30 MPa and 3.5%, respectively.

2.2. Specimen preparation

The steel millitubes were first extruded by using a mold to create equidistant indentation (every 12.70 mm), as shown in Fig. 1(a). The millitubes were assembled together, as shown in Fig. 1(b). Once the designed number of layers was assembled, the adhesive resin was infused into the millitube preform by a Vacuum Assistance Resin Infusion Molding (VARIM) system, as shown in Fig. 1(c)–(e). After curing at room temperature, the cast core was demolded and postcured at 55 °C for 4 h. The surfaces of the grid stiffened core were ground and cleaned before applying the skins. The prefabricated laminated face sheets (E-glass/vinyl ester) were then bonded to the core with the identical polymer resin (LOCTITE Hysol 9460) to form the sandwich panel.

The cross section of the millitubes stiffened grid is shown in Fig. 2. It is obviously seen that each millitube is mechanical interlocked with other millitubes. When the sandwich panel is subjected to an impact load, the impact energy could be transferred from the local impact point to the whole sandwich panel. Therefore, the impact energy and impact wave could be absorbed and transferred by the integrated grid stiffened sandwich structure.

It is noted that mass production of the hybrid core could be easily realized using existing equipment and procedures in the composite industry. Therefore, ease of mass production should be cited as an advantage of the proposed sandwich panels.

In this study, three types of grid stiffened millitubes were fabricated with 40% volume fraction of steel millitubes (the rest 60% was the epoxy resin) for the core based on the number of layers of the millitube grid skeleton. The specimens were divided into 3 groups G1, G2, and G3 which have 1 layer, 2 layers, and 3 layers of millitube grid skeleton.

2.3. Geometry and test matrix

The sandwich panels were prepared after 24 h curing at room temperature and 1 h postcure at 100 °C. Sandwich cores were subjected to two types of static tests: (i) static compression tests; (ii) static three-point bending test (simply supported at two ends). Sandwich panels were also subjected to two types of impact tests (i) low velocity impact test; and (ii) ballistic impact test.

In the axial compression tests and three-point bending test, the strain controlled loading mode was employed using MTS 810 machine with a loading rate of 0.6 mm/min. The experimental setup is shown in Fig. 3(a) and (b). The specimen sizes of G1, G2, and G3 for the bending test are 101.6 mm long, 25.4 mm wide, and 6.2 mm, 12.4 mm, and 18.6 mm high, respectively. The specimen sizes of G1, G2, and G3 for the compression test are 25.4 mm long, 25.4 mm wide, and 6.2 mm, 12.4 mm, and 18.6 mm high, respectively. For the three-point bending test, the span length was 90 mm.

Some sandwich panels were subjected to low velocity impact test. The impact tests were conducted by the Instron Dynatup 8250 HV Impact testing machine with a hemi-sphere tup nose (the diameter is 12.7 mm). Dimensions of the G1, G2, and G3 sandwich panels are 101.6 mm long, 50.8 mm wide, and 12.7 mm, 19.1 mm, and 25.2 mm high, respectively. The initiation energy and propagation energy were calculated using a data acquisition system integrated in the impact test machine. For a 4 g bullet with 308 m/s initial velocity impact on armor, the total impact energy is around 190 J. To simulate this situation, in this study, 25 kg hammer with impact velocity of 3.9 m/s was used which could create 190 J impact energy for the sandwich panels.

Some sandwich panels were subjected to ballistic impact test. The impact tests were conducted by the XD pistol with 9 mm bullet and Ruger 10/22 revolver with .22 caliber hollow point bullet. Dimensions of the sandwich panels are the same as the specimen in low velocity impact test. The high velocity impact test setup is shown in Fig. 4. The bullet speed was measured with laser speedometer. The shooting angle was 90° to the target.