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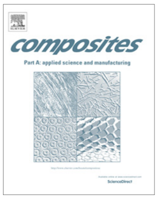

Carbon-fiber and aluminum-honeycomb sandwich composites with and without Kevlar-fiber interfacial toughening

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ABSTRACT

Interfacial bonding, essential to carbon-fiber and aluminum-honeycomb sandwich composites and their structural performance, was investigated under bending and uniaxial compression in this study. The feasibility and effectiveness of short Kevlar-fiber interfacial toughening at the interface between the carbon-fiber face sheets and aluminum-honeycomb core were examined. It was observed that the adhesive joint, in-situ formed from resin and short Kevlar fibers at the interface effectively became a composite. Protruding free fiber ends of the short Kevlar fibers, connecting or bridging the face sheets and core, had effectively increased the adhesion contact areas at both sides of the adhesive joint, leading to strong fiber-bridging in case of interfacial cracking.

The peak load and energy absorption of the sandwich composites, with and without the short Kevlar-fiber interfacial toughening, were compared with predictions from analytical models. Toughening and strengthening mechanisms of the reinforced adhesive fillets were explained together with detailed fractography observations.

1. Introduction

Carbon fiber composites and aluminum honeycombs have been widely used in aerospace industries. Their sandwich panels, consisting of two carbon-fiber face sheets and an aluminum-honeycomb core, can take full advantage of the complementary strength and light-weight properties. Such laminar composite structures can also possess much desired energy absorption capacity and favorable damping properties [1], besides their high specific strength and stiffness. These favorable structural properties, important to many structural applications, make carbon-fiber and aluminum-honeycomb sandwich structures highly desirable. Furthermore, they can be easily fabricated through laminating, offering unique and useful structure–property options to designers [2–4].

Structural performance and characteristics of honeycomb sandwich structures have been studied extensively by many researchers. For instance, failure-mode maps of honeycomb-core sandwich structures under three-point bending, quasi-static indentation and low velocity impact were constructed by Petras and Zhu [5,6]. The failure modes and the corresponding failure loads were found to closely depend on the material properties, structural configuration, distribution of loading and bonding condition of face–core interface. Kaman and Zhou [7,8] examined the effects of cell sizes, core densities, core materials and thickness of face sheets on the damage characteristics of honeycomb sandwich panels. Studies on the collapse behavior of honeycomb sandwich panels under shear and uniaxial compression showed that buckling, debonding and fracture failures frequently occurred [9–11]. Besides those experimental investigations on damage characteristics of honeycomb sandwiches, a number of numerical and analytical studies were also carried out [12–14]. The structural behaviors and failure mechanisms of honeycomb sandwiches were numerically investigated under different loading conditions, including low-velocity impact [15], three-point bending [16] and compression [17].

From those aforementioned studies on the failure mechanisms of honeycomb sandwich structures, it is evident that the structural integrity of the sandwich structures relies heavily on the interfacial bonding between the face sheet and core. Goswami and Becker [18] studied the phenomenon of a delamination crack along the face–core interface of a sandwich structure under transverse loading. The effects of delamination on damping and free vibration behavior of honeycomb sandwich structures were also investigated [19–21]. The interfacial toughness, critical load and stiffness

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of sandwich structures with various pre-existing interfacial defects were studied as well, and the relation between delamination and failure pattern was established [22–24].

Different toughening methods have been explored in order to improve interfacial bonding of various laminar composites. Z-pinning and stitching methodologies, using through-the-thickness Z-directional reinforcements, are most effective against delamination in carbon-fiber composites [25,26]. However, Z-pinning and stitching are not suitable to carbon-fiber aluminum-honeycomb composite panels [27]. The stitching process can evoke core damage during the repeated sewing action, and thus reduce the strength of sandwich structures [28].

In comparison, the interlaminar toughening method using short Kevlar fibers, originally developed for laminar carbon fiber composites [29,30], can be adopted for carbon-fiber aluminum-honeycomb sandwich structures. Sun et al. [31,32] have adopted the short-Kevlar-fiber interfacial toughening technique to toughen and reinforce the interface between the carbon-fiber face sheet and aluminum-foam core. Based on their three-point bending tests, up to 38% improvement in the peak load and about 80% improvement in the energy absorption were achieved from the short aramid-fiber interfacial reinforcement. Because of similarities in the surface structures of aluminum foam and honeycomb, it is expected that the toughened interface can be equally effective for carbon-fiber aluminum-honeycomb sandwich structures.

The existence and favorable role of resin fillets [33] in honeycomb sandwich structures was observed. The resin fillets, formed from moderate excessive resin in curing processing as shown in Fig. 1, can effectively strengthen the sandwich structures. The delamination resistance of honeycomb sandwich panels was effectively increased by the presence of epoxy fillets and the associated "stick–slip" toughening mechanism [33]. Similarly, Jen et al. [34] proposed that the fatigue strength could be increased by the resin fillets based on the "stick–slip" toughening mechanism.

The objective of this study is to combine the concepts of the resin-fillet reinforcement [33,34] and the short-Kevlar-fiber interfacial toughening [31,32] so that stronger interfacial bonding between carbon-fiber face-sheets and aluminum-honeycomb core can be achieved in the sandwich structures. Short fibers are favored over continuous fibers for interfacial toughening because the protruding free fiber ends of short Kevlar fibers can effectively reinforce the resin fillets as illustrated in Fig. 1, contributing to increased adhesion contact areas between the carbon-fiber face sheet and aluminum-honeycomb core. Effectively, both the resin fillet and adhesive joint between the face sheet and core have composite characteristics because of the addition of short Kevlar fibers. In this study, carbon-fiber aluminum-honeycomb sandwich panels with and without the toughened interface are processed, tested and analytically studied to confirm the effectiveness of the toughened interface.

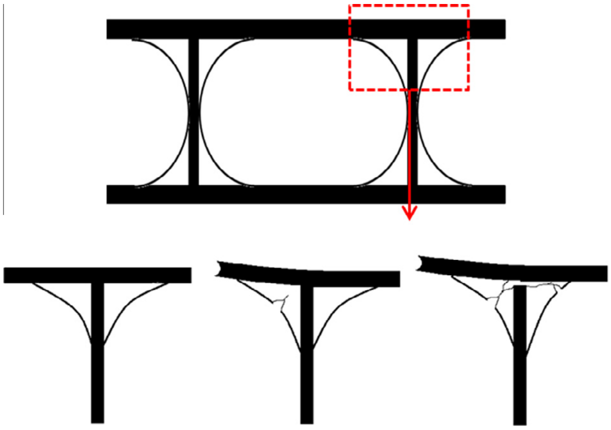

Fig. 1. "Stick–slip" fracture mechanism of resin fillets [33]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Carbon-fiber and aluminum-honeycomb sandwich manufacturing

2.1. Materials

Aluminum honeycomb with 6.35 mm cell size, 0.06 mm wall thickness and 12 mm height from Ayres Composite Panels Pty Ltd., Australia was used as the core material in this study. 200T 2×2 twill weave carbon-fiber fabric supplied by Marineware NSW Pty Ltd., Australia with an areal density of 200 g/m^2 was used as the face sheet. The aramid fiber used in this study was Kevlar 49 developed by E.I DuPont. The epoxy resin used for carbon-fiber face-sheets and bonding with the honeycomb core was the West System z105 epoxy resin mixed with slow hardener 206 as the recommended ratio of 5:1.

2.2. Manufacturing process and specimen design

The chopped Kevlar bundles of 12 mm in length were first dispersed mechanically and then thin tissues were produced [31]. A thin Kevlar-fiber tissue of approximately 12 g/m^2 is shown in Fig. 2(a).

The carbon-fiber fabrics were first impregnated by the mixed epoxy and laminated together. Then the thin Kevlar-fiber tissue was placed onto the wetted carbon-fiber surface. It should be mentioned that the weight of epoxy involved in each sample was kept as constant to examine the effect of short Kevlar fibers on interfacial toughness and strength. Sandwich panels were then made from two five-ply carbon-fiber face sheets on both sides of the honeycomb core, as illustrated in Fig. 2(b).

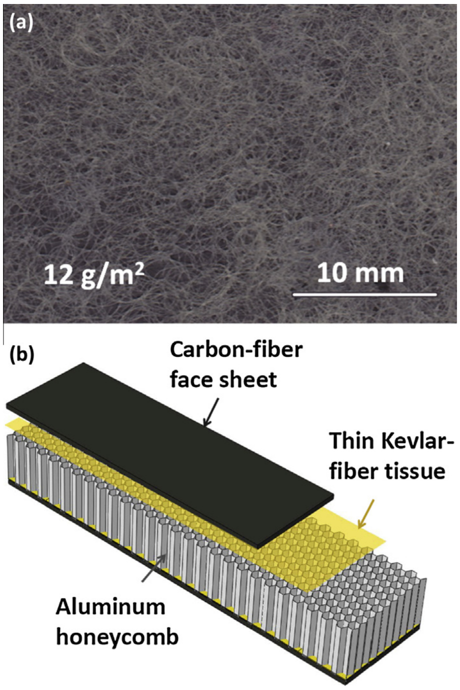

Fig. 2. (a) Thin tissue of short Kevlar fibers and (b) assembly of carbon-fiber aluminum-honeycomb sandwich with thin interleave tissue of short Kevlar fibers, taking full advantage of free fiber ends for effective fiber-bridging. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)