DESIGN AND PROCESSING OF SANDWICH COMPOSITES WITH MULTI-FUNCTIONAL FEATURES

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SUMMARY: Sandwich composites are finding increasing applications in aerospace, marine and commercial structures because they offer high bending stiffness and lightweight advantages. Currently, foam and honeycomb core sandwich composites are widely used. However, affordability continues to be the driver to develop sandwich constructions that can be processed at lower costs and containing integrated design features. Recent developments in sandwich constructions use reinforced core designs including; three-dimensional (3D) Z-pins embedded into foam, honeycomb cells filled with foam, and space accessible cores. Functions such as ability to route wires, mount electronic components, increase transverse stiffness, tailored vibration damping are some of the benefits offered by these integrated designs. With the assumption that these sandwich constructions would be part of a larger structure, impact damage is often of concern. This paper provides a *review* of the developments in multi-functional sandwich composites, and recent studies on the low velocity impact (LVI) response of sandwich composites with reinforced cores. Wherever applicable, comparisons are made to traditional foam core and honeycomb core sandwich constructions.

KEY WORDS: Sandwich Composite, Reinforced Core, Impact

INTRODUCTION

Sandwich composites find increasing use as flexural load bearing lightweight sub-elements in air and space vehicles as well as other commercial structures. Typically, a sandwich construction stiffens a structure without substantially increasing its weight [1,2]. The commercial applications (aerospace, marine and rail/ground transportation) of sandwich structures primarily utilize foam, balsa and honeycomb as core materials. These cores exhibit lightweight advantages, energy absorption and good damage resistance. The limitation with the traditional core sandwich structures however, is the likelihood of core-to-facesheet delamination under impact loading [3,4], and the space inaccessibility to the core once the facesheets are bonded on. In situations of impacts such as in tool drops, hailstorms, runway debris etc., the structure undergoes reduction in strength and stiffness.

Reinforced core sandwich constructions possess potential for multi-functionality and damage tolerance. Multi-functionality is generally referred to as value added to the structure in terms of advantages that the design has to offer (in comparison to a conventional sandwich structure). In addition to conventional load bearing, the structure has integrated design capabilities. Such designs would include enhanced vibration damping, increased damage resistance, improved transverse stiffness, acoustical transmission/ absorption, noise control, ability to route electrical wires, store fuel, provide fire retardant capability, enable self-healing, and possibility to embed electronics/sensors etc. These benefits would be in addition to conventional load bearing, lightweight and high flexural strength / stiffness requirements. Three reinforced core designs have been investigated in recent work, including - 3D Z-pins embedded into foam, foam-filled honeycomb core, integrated core and hollow / space accessible Z-pin core [5-8]. This paper provides a review of recent studies in reinforced core sandwich composite designs.

Z-Pin Reinforced Foam Core

The design concept utilizes pultruded glass/epoxy tow rods, steel, titanium and/or graphite/epoxy Z-pins which are embedded in foam core in a 3D configuration. The Z-pins are at angles with respect to the facesheet according to predetermined geometry. The Z-pins penetrate into the facesheets during the curing process, thereby mechanically interlocking the facesheet to the core. Reinforcing the foam with pins has the advantage that the transverse stiffness of the foam is enhanced as compared to the non-reinforced foam core [5, 6]. In the event the foam is washed away from the core, the resulting sandwich composite provides space advantages to route wires, store fuel, add electronics among other conceivable functions. A schematic of the Z-pin reinforced core sandwich composite, microstructure and a sample constructed from steel pins is illustrated in Fig. 1a-c.

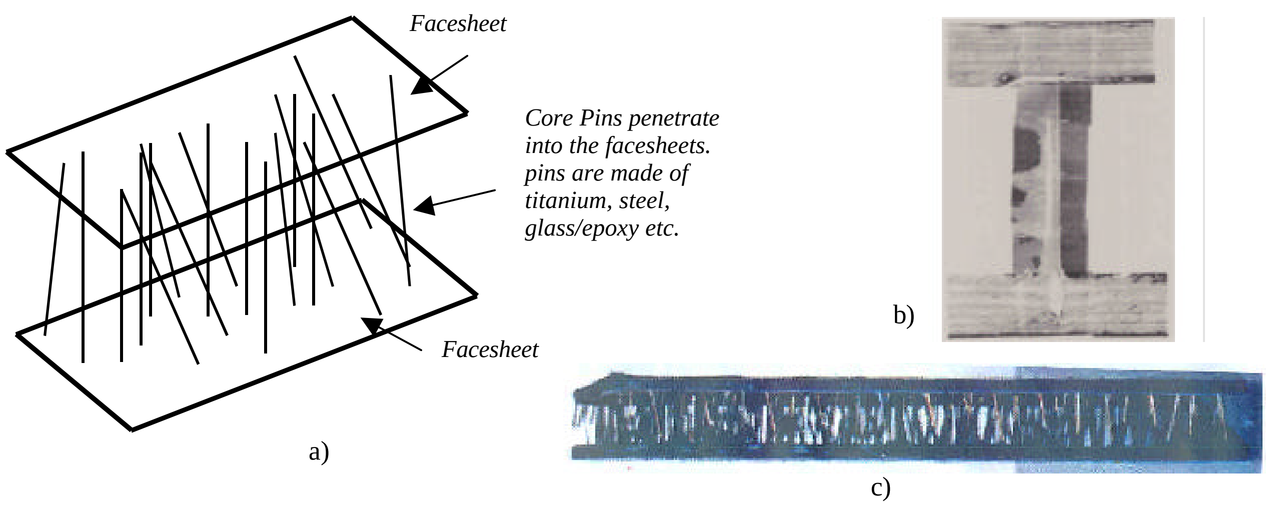


Figure 1. a) Schematic of Truss Core, b) Illustration of a Pin-Facesheet and, c) Truss Core Sandwich Panel

Palazotto et al [5], investigated the LVI response of sandwich composites with 0.508-0.889 mm steel Z-pins oriented at 10^0 and 20^0 angles with respect to graphite/epoxy facesheets. They determined that the prominent modes of failure in Z-pin core structures occurred from pin compression failure, pin buckling, pin-pull out from the facesheets, micro-delaminations and debonding. All or some of these damage modes can be more pronounced under LVI. Vaidya et al [6] investigated experimentally the LVI damage characteristics of foam, Z-pin reinforced foam and hollow Z-pin foam core.

Impact Response: The energy levels at which the sandwich samples were impacted [6] were classified as; A: 11 J, B: 20 J, C: 28 J, D: 33 J and E: 40 J. Typical force-time-energy curves for the unreinforced foam core (Rohacell IG-71, PMMA foam) and the Z-pin (titanium pins) reinforced foam core are shown in Fig. 2a and 2b respectively. For the unreinforced foam samples, (Fig. 2a), the first major load drop at 3000 N, corresponded primarily to the localized debonding of the cell-to-facesheet and compression related core-crushing just below the point of impact. The damage develops by compression crushing of the core cells and lies within the bulk core, a few microns below the top facesheet.

In the Z-pin reinforced foam core samples, the pin clusters were 19.05 mm (0.75") apart. The pins are seen to stiffen the panels considerably. For all the energy levels A through E, the contact stiffness (the slope of the force-time) (Fig.2b) is higher than observed for the unreinforced foam core samples. The average load at which the first major load drop occurs in these samples is 2800 N, which is 7% lower than the unreinforced foam core samples. This is attributed to the pins that create microcracks in the facesheet as they enter the facesheets during manufacturing. The first major load drop is not at the identical load level as was observed for the unreinforced foam core samples, because of the statistical variation in position and extent of penetration of the pins into the facesheet with respect to the point of impact. The major failure mechanisms were; a) localized facesheet delamination (within a span of two pin supports around the impact location) along with associated localized facesheet push-out, fiber breakage and matrix cracking. The fiber breaks assume the direction of the impact, b) localized debonding between fiber/core interface, c) pin-push out, where fibers follow the pin direction (opposite to the impact direction), and d) shear cracking of plies between push-out location and impact location. In terms of LVI damage, the Z-pin reinforced design provides better damage containment at the loss of approximately 7% peak load capacity [6].

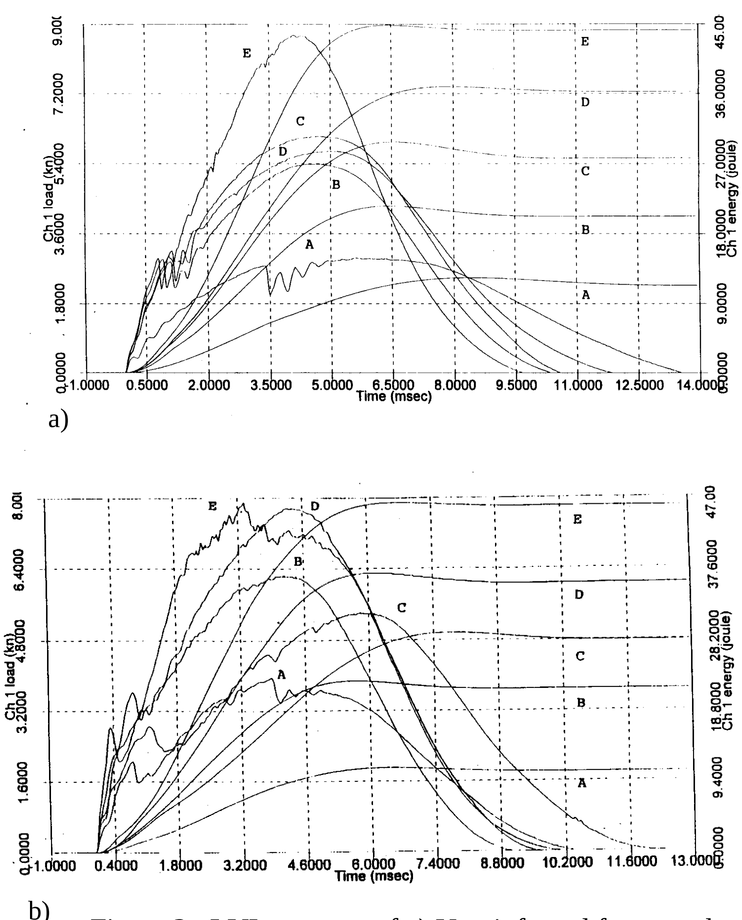


Figure 2. LVI response of a) Unreinforced foam, and b) Z-pin reinforced foam core [6]

Integrated Fiber Core

This concept utilizes a fully integrated glass fiber hollow core with integrally stitched facesheets. This design uses advances in textile technology. The fabric preform is a 3D-glass fabric, consisting of two bi-directional woven fabrics, which are connected with vertical fibers [7]. The two bi-directional woven E-glass fabric surfaces are mechanically connected with vertical woven plies (Figs. 3 and 4). This produces a fabric, which has a pre-set space between the two surface decks. The advantages this design offers are multifold. The sandwich panel can be; a) made in one process and from one material, b) the upper and lower decks are integral to the core material,

c) the delamination mode between the facesheet and the core is completely suppressed, d) the panels are cost effective when the cost of the core and the facesheets are included, and e) the interstitial space can used for routing of electrical wires, embedding electronic components, filling fire retardant foam, or a heated liquid.

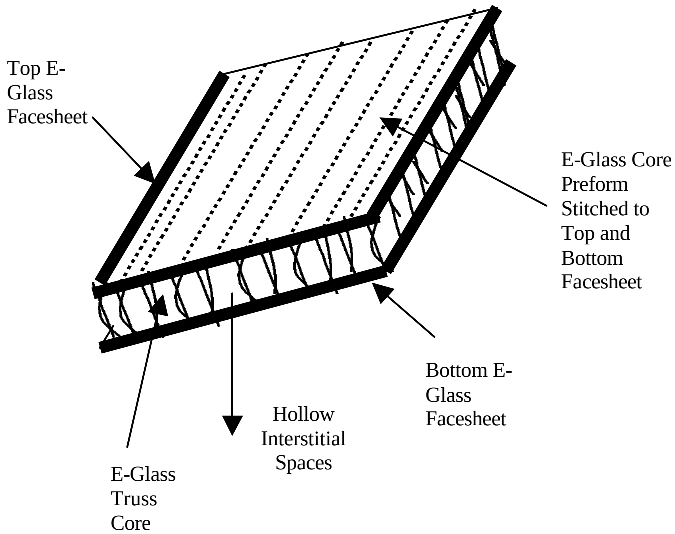


Figure 3. Schematic of Integrated Sandwich Core

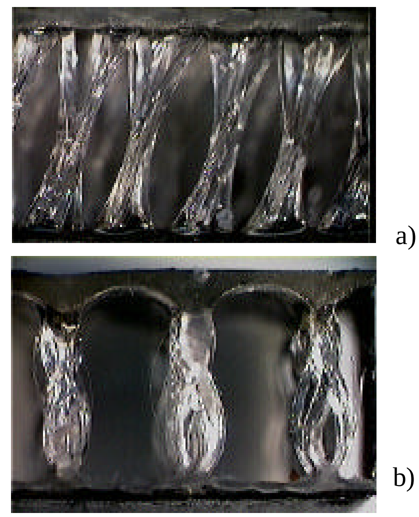


Figure 4. Micrograph of Integrated Sandwich Core. a) Weft Direction, b) Warp Direction

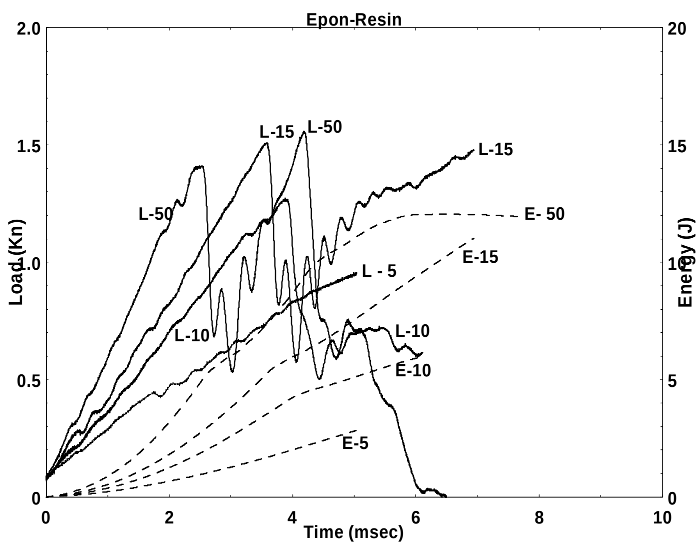
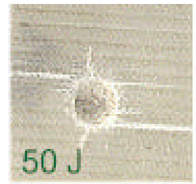
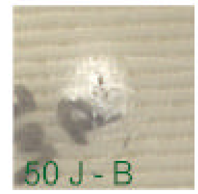


Figure 5. LVI response of integrated core sandwich composites. Note : E-energy, L-load [7]

Impact Response: *LVI-* Figure 5 represents the typical force-time-energy response of the integrated sandwich core composites. Notably, there was no delamination of the facesheet to core (no load drops till peak load is attained). Core failure was primarily in terms of micro fibrillation / separation of the twisted yarns of the core, and in some cases micro buckling and breakage of the core fibers. With increase in impact energy, the contact stiffness of the samples is seen to increase. The damage evolved as follows: At energy of 5J, the sample exhibited, slight indentation of the top facesheet and initiation of tearing of the top facesheet. The glass core members just below the point of impact were seen to exhibit micro buckling on a filament level. These are represented as small magnitude, multiple load drops through the loading history which originate beginning at 0.2 kN. At 10 J of impact energy, the top facesheet exhibited tearing, accompanied by fracture of some of the glass/epoxy core pins as observed for the 5J-impacted samples. A characteristic load drop was seen at 1.3 kN which corresponded to the tearing of the top facesheet. Multiple minor load drops prior to this major drop correspond to onset of the tearing and fracturing of the glass core truss. For the 15 J impact, the top facesheet fails at 1.5 kN indicated by a major load drop at 3.8 msec, and subsequent damage progresses on till 5 msec, after which a second major load drop is observed. This corresponds to penetration of the bottom facesheet. At 15 J, punch-through was observed. Depending upon whether the impact takes place "on" or "between" a system of core members, the tearing load for the top facesheet varies in accordance. For the 50 J impact similar load drops corresponding to the top and bottom facesheet failures are observed (Fig. 6).



a)

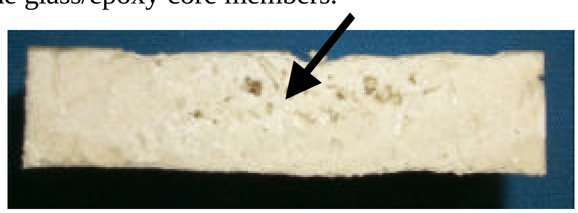


b)

Figure 6. LVI damage to integrated sandwich core, a) top facesheet, b) bottom facesheet

High Velocity Impact Response: The integrated core sandwich samples were also subjected to high velocity impact (64 m/s, kinetic energy 334 J) using a flat head cylindrical sabot made of aluminum (mass 0.16 kg) in a gas gun. The loading simulates flying debris such as stones or rocks. Fig. 7 represents the failure of the open core (0.17 gm/cc) samples. The core members are seen to undergo buckling beneath the point of impact, but notably there is no delamination between the facesheet and the core. For polyurethane foam-filled samples (0.303 gm/cc), the dimensional stability of the sandwich is preserved. The foam supports the reinforcing glass/epoxy core members, and damage evolves through localized debonding between the foam core and the glass/epoxy core members.

a)



b)

Figure 7. High velocity impact test on integrated core, a) open space, and b) polyurethane foam-filled, arrow represents localized debonding

Foam Filled Honeycomb Core:

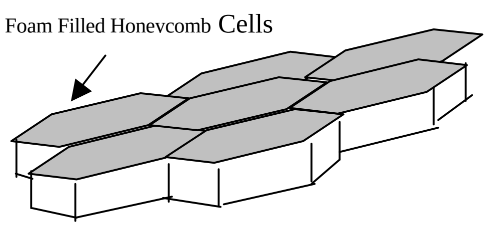


Figure 8. Foam-Filled-Honeycomb Core

This concept optimizes the relationship between the honeycomb and the foam, offering the benefits of both, while selectively eliminating the disadvantages of both. The cell walls of the honeycomb are reinforced by foam (Fig. 8). The increased surface area allows stress forces to dissipate over a larger area than that offered by the honeycomb alone [8-11]. The core absorbs much greater impacts by transmitting forces to the adjacent cells. The effect is greater resistance to shear force perpendicular to the sandwich (fracture), increased moment resistance (less bending) and better dampening of shock waves along the surface (less vibrations).

Polyurethane foam was used to fill honeycomb phenolic impregnated kraft paper cell (6 mm cell size) core. Eight layers of plain weave carbon fabric with vinyl ester resin were used as the facesheets.

Impact Response: LVI Typical force-time-energy curves for the samples are shown in Fig. 9. The load at which the damage initiation occurs was found to be 5800 N. The damage initiation load is seen to be independent of the energy levels at which the samples were impacted. A load drop was obtained at 5800 N, which corresponds to the damage initiated in the top facesheet accompanied by local cell wall crushing and localized debonding of the cell-to-facesheet. The damage is limited to two-three cells, and occurs by cell wall buckling (Fig. 10), interfacial debonding between the cell wall and the foam. At higher impact energies (D & E), the bottom facesheet fails by debonding of the core-facesheet. The bottom facesheet failure is identified as a second load step in the force-time history at 2.5 msec (Fig. 9). Samples A, B, and C did not

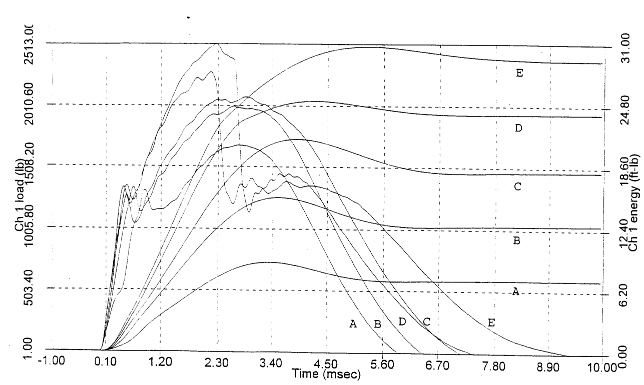


Figure 9. Force-time-energy curves for Foam-Filled Honeycomb Sandwich Composites with Graphite/Epoxy Facesheets [8]

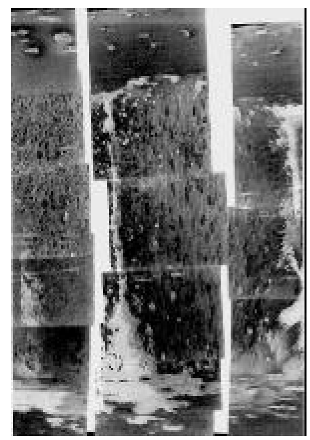


Figure 10. Core Crushing and Localized Cell Wall Buckling

exhibit bottom facesheet damage. The bending of the sandwich plate at high impact energies (D & E) results in cells at the bottom facesheet to debond at distributed locations.

Figure 11. High strain rate impact failure of foam-filled honeycomb core

High Strain Rate Impact Response: The foam-filled honeycomb sandwich samples were subjected to high strain rate impact on a split Hopkinson pressure bar (SHPB) to strain rates of 326/s [12]. A typical damaged sample subjected to 326/s strain rate impact is shown in Fig.11. No visible failure occurred in the case of the facesheets. The cell walls prevent in-plane compression core crushing and localize the effect of the damage. In contrast a foam core sample under similar conditions undergoes complete crushing.

PROCESSING CONSIDERATIONS

The sandwich designs presented above need practical out-of-autoclave and preferably room temperature processing techniques and scale-up in real structures such as boat hulls and transportation bodies. Liquid molded techniques are finding increasing use in high-performance applications in a variety of commercial and defense industries. In the liquid molding category, Co-Injection Vacuum Assisted Resin Transfer Molding (CVARTM) illustrated in Fig. 12 enables rapid processing of the facesheets on both sides of the core simultaneously. CVARTM is a promising low cost innovative processing technique for such multi-functional sandwich constructions, as it uses single-sided tooling (translating to significant savings in tooling costs) and vacuum-bag technology. Here resin is infused into dry fabric preform assembled in conventional tooling that is closed with an inexpensive vacuum bag film. This process has very attractive cost-advantages in comparison to spray-up or impregnation methods, and it is far less expensive than conventional manufacturing methods. Other advantages of CVARTM are low process volatile emissions, high fiber-to-resin ratios and good process repeatability. This process has the potential to make large sized transportation body parts, boat hull, interior cabins, architectural parts and other possible commercial applications. The part is maintained under vacuum from the stage of resin infusion through complete cure [8]. The CVARTM technique has promise to produce the Z-pin reinforced and foam-filled honeycomb designs. The Z-pins are positioned into the foam core prior to impregnation. The pins partly penetrate into the dry facesheet forming fabric during the lay-up. Upon co-injection of the resin, an integral facesheet-to-core structure is obtained through simultaneous wet-out of the top and bottom facesheets, and penetration of the pins into the facesheets.

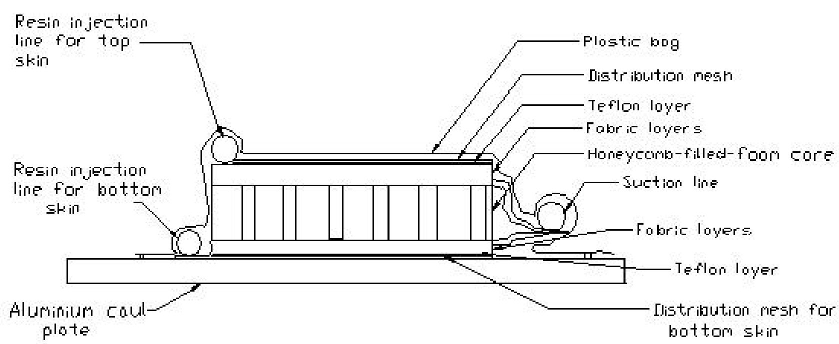


Figure 12. Co-Injection VARTM for Sandwich Composites Processing

For the integrated core design, traditional hand lay-up with paddle rollers is used. The resin is mixed in controlled quantities to enable appropriate wet-out of the facesheets, and the excess enters the core forming fabric to accomplish full wet-out.

CONCLUSIONS

A review of recent developments in reinforced core sandwich composite designs with multi-functional features has been conducted. The reinforced cores have potential benefits over traditional honeycomb and foam core and may be considered selectively for large-scale structures such as boat hulls, rail and ground transportation, as well as aircraft applications.

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