Usak University Journal of Material Sciences
journal homepage: http://uujms.usak.edu.tr

Research article

Mechanical behavior of fiber reinforced polymer / metal laminate and aluminum foam sandwich composites

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Abstract

In this study, fibre/metal laminated (FMLs) containing glass fibre reinforced polypropylene (GFPP) and aluminium (Al) sheet were developed and consolidated with aluminium foam cores of varying thicknesses (8, 20 and 30 mm) for preparing the sandwich panels. The laminated systems were fabricated by hot pressing technique. The bonding among the composite/metal interface was achieved by silane coupling agent modification or polypropylene (PP) based film introduction containing 20 wt. % a maleic anhydride modified polypropylene (PP-g-MA). Quasi-static compression and bending behaviours of sandwich structures together with their energy absorption characteristics were also investigated and evaluated.
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Keywords: *Fiber/Metal Laminates (FMLs), foam materials, sandwich composites, interfacial bonding techniques.*

1. Introduction

The composite sandwiches consist of face-sheet (skin) and core materials have various application areas including aeronautical, marine and transportation industry. Besides the perfect flexural resistance and stiffness, high corrosion resistance, low thermal and acoustic conductivity are the major advantages of these systems over the traditional materials. The fibre reinforced polymer (FRP) composites or metallic layers are generally used as skin materials. Epoxy is the most popular type of thermosetting resin used for fabricating FRP composites, however due to the long processing time for curing and low fracture resistance, there is a trend to replace them with thermoplastic based composites [1,2].

Besides all these superior properties, the energy absorption capability of the aluminium (Al) foams against dynamic loads makes them useful specifically in impact related applications. Various production techniques with different chemical composition greatly affect the microstructural and mechanical properties of foams. A great number of studies are available in the literature which contains conventional tests applied to the Al foams to reveal their mechanical performances under different loading conditions. Particularly, the quasi-static compressive responses of Al foams were investigated by a number of researchers [3]. McCullough [4] et al. investigated the tensile and compressive characteristics of closed cell ALULIGTH™ Al foams by considering their deformation mechanisms. The foams exhibited semi-brittle behaviour under tension while they

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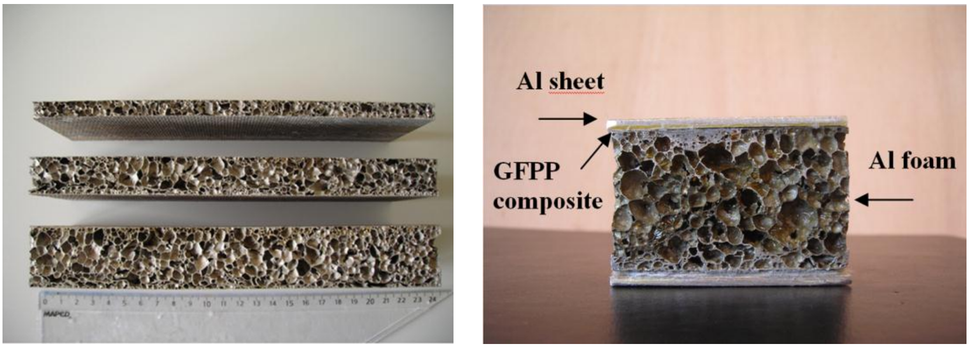
showed ductility under compression due to the different failure modes. Deqing et al. [5] reported the compressive properties of Al foams by considering their cell structures. In their study, it was found that both plastic collapse strength and energy absorption capacities of the closed cell aluminium foams were significantly improved by decreasing the cell size of the foams having the same density. The new generation of FMLs are being developed as armour systems against blast and ballistic impacts due to their high energy absorption characteristics [6]. Langdon and Cantwell [7] reported the applications of aluminium foam sandwiches with fibre-metal laminates (FMLs). Several dynamic tests were carried out in order to evaluate the performance of these sandwiches under low and high velocity impact. The combination of thermoplastic based composite face-sheets with aluminium plate and aluminium foam led to the increase of energy absorption capability. It was also found that the use of fibre-metal laminate systems provides significant improvement in terms of ballistic protection and damage resistance. The failure modes within those sandwich structures have been critical issue to investigate by the researchers. Russo and Zuccarello [8] investigated the mechanical behaviour of fiber-glass laminate skins with PVC foam or polyester mat cores. The authors investigated the failure modes and they found that the shorter specimens failed due to the core shear failure with delamination while the relatively longer sandwiches failed after the lower face-sheet tensile failure. Steeves and Fleck [9] analysed the bending behaviour of sandwich beams consisted of woven glass fibre/epoxy prepreg and PVC foam core. The geometry and component properties significantly affected the failure modes of beams. Core shear, skin micro-buckling and indentation beneath the middle loading roller were the main failure mechanisms observed in the experiments. Styles and co-workers [10] focused on the failure modes of thermoplastic composite skin/Al foam core sandwiches under flexural loading. Three different core thicknesses were used and their effect on the mechanical behaviour was evaluated. In their study, the thinner specimens showed skin wrinkling and fracture with core cracking while the core thickness increase led to the core indentation.

Tanoglu et al. [11] investigated the mechanical and interfacial properties of laminated composites consist of Al foam and GFPP/Al sheet FMLs integrated with various modification techniques. The compression properties and energy absorption capabilities of Al foams and Al foam based sandwiches were determined. The sandwiches consist of Al sheet- GFPP laminates and Al foam were integrated with hot pressing technique. The adhesion between the components was achieved by surface treatment with silane. It was revelaed from the experimental results that the metal/composite laminates were fabricated successfully and these sandwiches exhibits high potential for production of energy absorbing materials with good structural integrity.

2. Materials and Methods

Aluminium sheet and aluminium foam with various thicknesses were used to produce sandwich structures in this study. The closed-cell aluminium foam material (supplied by Shinko Wire Company Ltd., Austria) with the trade name ALULIGHT-AFS® was employed as a core material. Glass fibre reinforced polypropylene (GFPP) composite and 2 mm Al sheets were used as the face-sheet component of the sandwich system. The Al foam specimens were cut from the large panels with the thicknesses of 8, 20 and 30 mm as shown in Fig. 1 (a). The foam panels were covered on both surfaces about 0.6 mm thick and strongly bonded skin, produced during manufacture of the foam. The woven cloth consisting of co-mingled glass and polypropylene fibers (GFPP) with a fiber volume fraction of 34.5 % (Telateks® Inc, Turkey) were placed between Al sheet and Al foam as an intermediate layer for producing different type of hybrid sandwich structure as seen in Fig. 1 (b). The physical and geometrical properties of the materials used in the experiments are tabulated in Table 1.



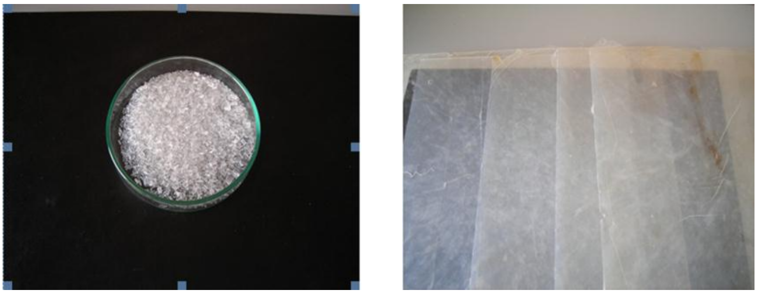
(a) (b)

Fig. 1 (a) The as-received ALULIGTH™-AFS Al foam panels with 8, 20 and 30 mm thickness, (b) Al sheet/GFPP/Al foam sandwich structures.

Table 1
Physical and geometrical properties of materials used to prepare sandwich composites

Material	Average Thickness (mm) (+/- Standard Deviation)	Average Density (gr/cm^3) (+/- Standard Deviation)
Al Foam	7.8 (0.1)	0.409 (0.006)
	18.95 (0.1)	0.395 (0.003)
	29.9 (0.1)	0.456 (0.007)
GFPP	0.65 (0.2)	1.254 (0.040)
Al Sheet	2.01 (0.2)	2.7 (0.010)

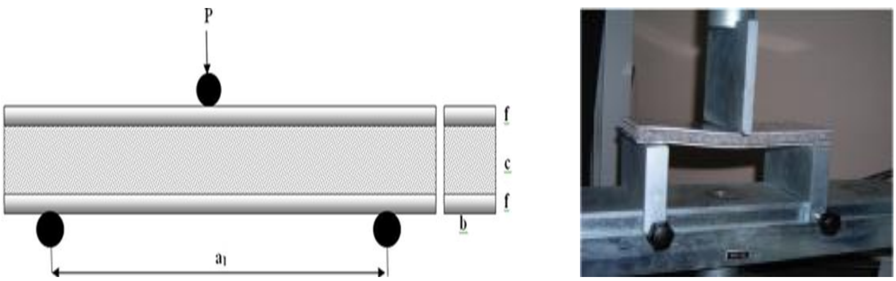
During the experiments, the sandwich components were bonded with two different techniques; 1) silane coupling agent application and 2) introduction of maleic anhydride modified polypropylene (PP-g-MA). Dow-Corning® Z-6032 silane was also used for providing robust bonding between GFPP-Al sheet and GFPP-Al foam interfaces. For the surface modification with silane coupling agent, Al sheet and Al foam surfaces were firstly degreased, and then modified with silanes based on the procedure reported by the manufacturer [12]. Laminated GFPP composite was various layers of Al and GFPP were stacked together, and hot pressed to the processing temperature of the GFPP (200°C) for 10 minutes at a constant pressure of 1.5 MPa by a hot press. Secondly, a maleic anhydride modified polypropylene (PP-g-MA) layer was incorporated between the Al-GFPP interface for providing better adhesion. For this purpose, 20 wt. % PP-g-MA films were prepared by extrusion and hot pressing techniques. The fine granules of blend were obtained using twin screw extruder (EUROLAB®) as seen in Fig. 2 (a). The cooled granules were pressed at 185°C under the fixed pressure of 1 MPa by hot press to obtain films. The prepared films had an average thickness of 0.5 mm as shown in Fig. 2 (b).



(a) (b)

Fig. 2 (a). Fine granules of PP based film, (b) PP based film containing 20 wt% PP-g-MA produced with extrusion and hot pressing.

The compression test samples were prepared with about 50 x 50 mm by sectioning from larger panels. All tests were conducted at room temperature using a Schimadzu™ universal test machine at a crosshead speed of 2 mm/min. In order to reveal the structures of the sandwiches, the samples were also sectioned and their cross-sections were polished. In this study, the macroscopic images of the foam based structures were taken using a Nikon™ optical microscope. The three point bending test (3PB) according to the ASTM C 393-62 standard was applied to the prepared sandwiches to measure the flexural properties. At least three specimens for each type of sandwiches were tested and force versus stroke values were recorded using a 100 kN capacity Devotrans® universal test machine at a crosshead displacement rate of 2 mm/min. The three point bending test configuration and a fabricated test specimen under flexural loading is seen in Fig. 3 (a) and (b), respectively.



(a) (b)

Fig. 3 (a). Three point bending test configuration according to the ASTM C 393-62, (b) test specimen under loading.

In this study, both absorbed energy (AE) and specific absorbed energy (SAE) values of the Al foam based sandwiches were determined. The absorbed energies were calculated from the area under the force-displacement curves of the samples and SAE values were obtained by dividing the energy values by mass. The dissipated energy under bending was calculated from the force-displacement curves of the specimens.

The total sandwich thickness (h) was calculated based on the face-sheet (f) and core thickness (c) values as shown in equation (1). The core shear (S) and face-sheet strength (F) values are expressed in equations (2) and (3). In these equations P is the maximum load, b is the sandwich width and a_1 represents the span length.

$$h = c + 2f \tag{1}$$

$$S = \frac{P}{(h+c)b} \tag{2}$$

$$F = \frac{Pa_1}{2f(h+c)b} \tag{3}$$

3. Results and Discussion

The typical microstructure of an Al foam based sandwich is given in Fig. 4. The 0/90° oriented co-mingled GFPP was placed between Al foam and Al sheet as an intermediate layer. The horizontal lines and small dotted segments in the mid region are the images of the 0° and 90° oriented fibers, respectively. The foam cells are placed under the GFPP composite layer. A typical cell wall image is also seen on the micrograph. The stress-strain behaviour of Al foam sandwiches were obtained based on the compression testing.

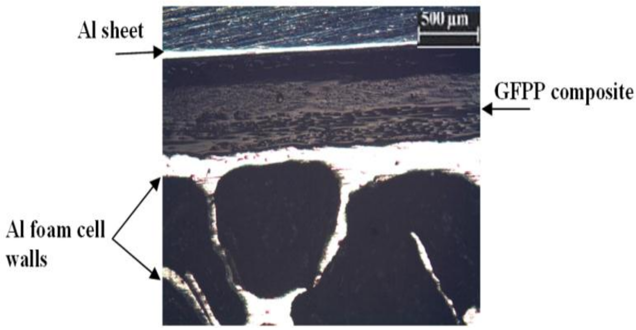


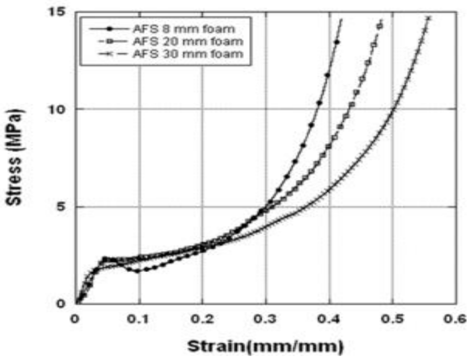
Fig. 4. Microstructural image of Al sheet/GFPP/Al foam sandwich.

A sandwich sample before loading and at 50% deformation is shown in Fig. 5 (a) and (b), respectively.

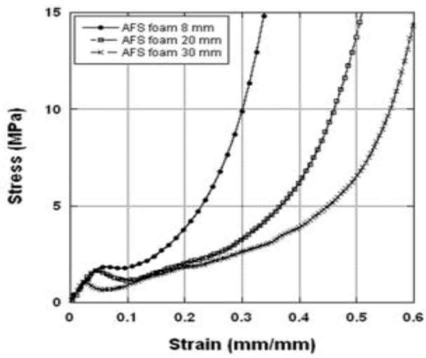
(a) (b)

Fig. 5. The Al sheet/GFPP/Al foam sandwich (a) before loading, (b) at 50% deformation.

Fig. 6 (a) and (b) show the compressive stress-strain behaviour of Al foam based sandwiches with three different thicknesses and bonded with two surface modification techniques under the same loading conditions. The deformations were plotted up to 60% strain and the characteristics of the flat-wise compression stress-strain curves of sandwich samples showed close similarity with the monolithic Al foams. It is the fact that the densities and the morphological features of the foams showed close relation with the densification behaviour of the samples.



(a)



(b)

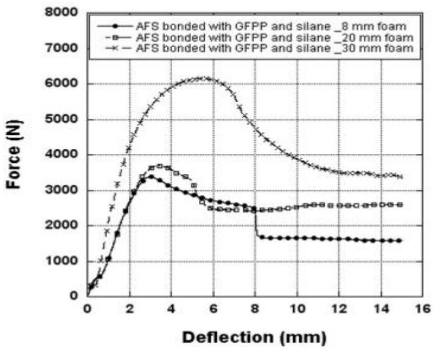
Fig. 6 Stress-strain graphs of (a) Al foam sandwiches bonded with GFPP after silane surface treatment, (b) Al foam sandwiches bonded with PP based film.

It is obvious in Fig. 6 (a) and (b) that the stress-strain curve initially increases nearly linearly up to a specific value of the compressive stress and then the stress remained almost constant up to a certain value (plateau region). The densification region starts at the completion of the plateau region. The collapse of foam cells ends and they start to densify at a specific strain. As the density of the specimen increases, the plateau region begins to shorten and densification starts at lower displacement values. According to the compression test graphs, the stress values of specimens at the same strain vary based on the thickness change. Considering Fig. 6 (a) and (b), Al foam sandwiches showed significantly higher elastic modulus and lower collapse strength. The mechanical parameters referred above are given with respect to their densities in Table 2 and the variations in foam cell shapes, subsistent defects, density and non-homogeneities of the microstructures affect them significantly. It was also understood from the experimental results that, the foams with higher elastic modulus showed generally higher collapse strength for each thickness set of foam based sandwiches.

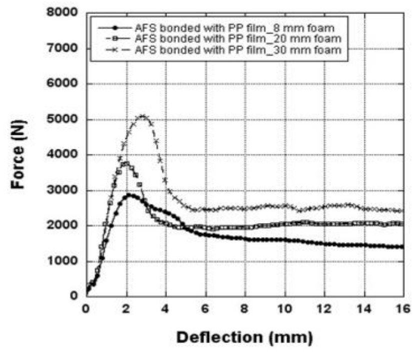
Table 2
Physical and mechanical properties of Al foams and Al foam sandwiches (AFS). The average values are given with standart deviations

Sample Type	Average Sample Density (gr/cm^3)	Average Elastic Modulus (MPa)	Average Collapse Strength (MPa)
AFS-8 mm (silane bonded)	1.14 (0.04)	61.98 (6.39)	2.90 (0.64)
AFS-20 mm (silane bonded)	0.92 (0.02)	63.71 (10.12)	2.39 (0.57)
AFS-30 mm (silane bonded)	0.73 (0.07)	77.80 (40.41)	2.05 (0.86)
AFS-8 mm (PP based film bonded)	1.14 (0.01)	37.37 (17.92)	1.83 (0.41)
AFS-20 mm (PP based film bonded)	0.82 (0.01)	59.10 (33.08)	1.90 (0.92)
AFS-30 mm (PP based film bonded)	0.61 (0.04)	47.22 (12.16)	1.03 (0.48)

The force-deflection data of the sandwiches were recorded during the bending test. Fig. 7 (a) and (b) show the typical flexural force-deflection curves of sandwiches with various bonding types.



(a)



(b)

Fig. 7 Force-deflection graphs of Al foam sandwiches (AFS) containing various foam thickness and bonded with (a) GFPP after silane surface treatment, (b) PP based adhesive film.

The sandwiches exhibited an initial linear elastic region with a subsequent non-linear part resulted in the decrease of slope near to the maximum force. The foam thickness increase led to the increase of both equivalent flexural rigidity and the slope of linear elastic region. The force level after maximum force values showed some differences among the samples. Regardless of the bonding type and the core thickness, some sandwich structures showed a smooth force drop while some of them exhibited a sudden drop followed by a plateau region in which the foams fail by buckling of the cell walls and edges. Based on the test results, the plateau parts in the graphs, in general, showed fluctuation rather than flat characteristics over larger displacements. The average collapse load (maximum load), core shear stress and face-sheet stress values of sandwiches consolidated together with different bonding types with respect to foam thickness are summarized from Fig. (8) to (10).

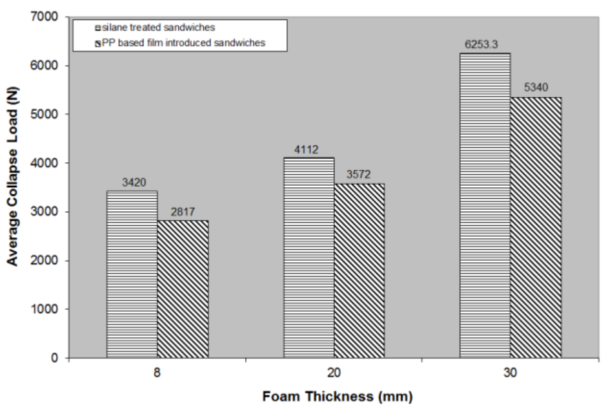


Fig. 8 The collapse load versus foam thickness variation of sandwich samples consolidated with silane surface treatment and PP based film introduction.

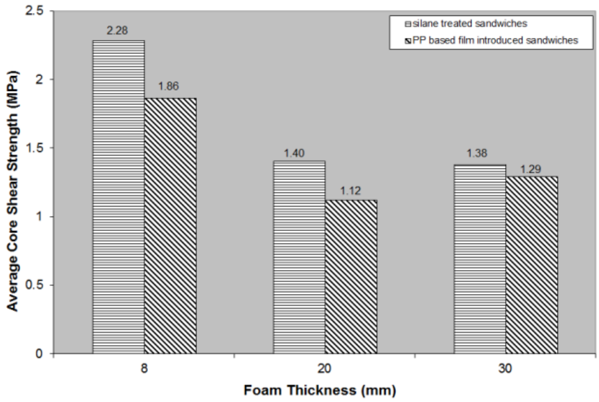


Fig. 9 The core shear strength versus foam thickness variation of sandwich samples consolidated with silane surface treatment and PP based film introduction.

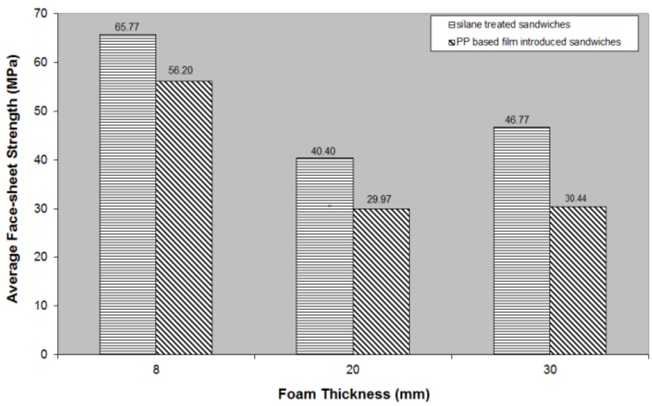
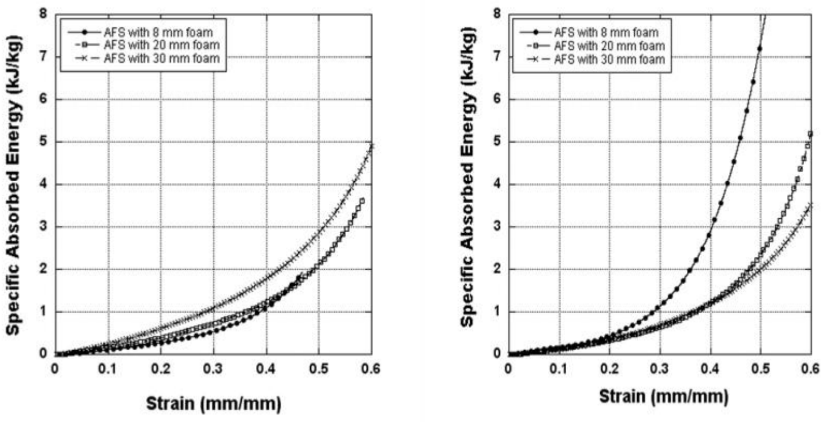


Fig. 10 The face-sheet strength versus foam thickness variation of sandwich samples consolidated with silane surface treatment and PP based film introduction.

The core thickness increase generally led to the increase of maximum load for all of the samples regardless of the type of bonding. Compared to the average collapse loads of sandwiches bonded with silane surface modification and PP based film introduced, the former bonding type is more effective. The silane treated samples showed higher collapse loads regardless of the foam thickness. Similar results were also valid for the core shear stress and face-sheet stress parameters of the sandwich structures. The sandwich samples including 8 mm core showed the highest flexural properties described above. The combination of GFPP composite and Al metal layer resulted in the decrease of the elastic modulus of the hybrid system compared to the monolithic Al. However, the same system exhibited higher tensile/compressive strength values. As it is known, in sandwich structures, the skin materials bear the in plane compressive and tensile stresses. The higher loads exposed to the Al sheet/GFPP/Al foam system was attributed to this fact. The specific absorbed energies (SAE) of the Al foams and Al foam based sandwiches were plotted with respect to displacement as shown in Fig. 11 (a) and (b).



(a) (b)

Fig. 11 Specific absorbed energy (SAE) versus strain of (a) Al foam sandwiches bonded with GFPP after silane surface treatment, (b) Al foam sandwiches bonded with PP based film.

It was found that the foam thickness increase resulted in the increase of absorbed energy. The sandwiches consisted of 8 mm Al foam completed their densification at 30-60% deformation while the other sandwich samples containing thicker foams reached their highest SAEs at 50-70% deformation. The SAE values of silane treated specimens increased depending on core thickness increase while an opposite characteristic was observed for the PP based film introduced sandwich structures. This situation is attributed to the variations in foam cell shapes, subsistent defects, density and non-homogeneities of the microstructures.

The dissipated energy under bending was calculated from the force-displacement curves of the specimens as shown in Fig. 12 with respect to the foam thickness variation.

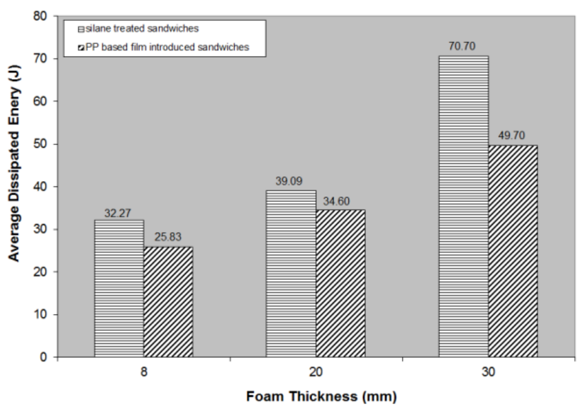


Fig. 12 The energy dissipation versus foam thickness variation of sandwiches with silane surface treatment and PP based film introduction.

Based on the three point bending test results, the increase of core thickness resulted in the increase of energy dissipation. Besides that, the GFPP composite layer might have positive contribution in terms of the energy absorption of the sandwiches. It was revealed from the experimental results that the energy dissipation of silane treated samples' showed higher values compared to the PP based film introduced sandwich specimens.

The main failure modes observed in the three point bending experiments (Fig. 13) were the core shear yield and debonding of sandwich components, independent of core thickness.

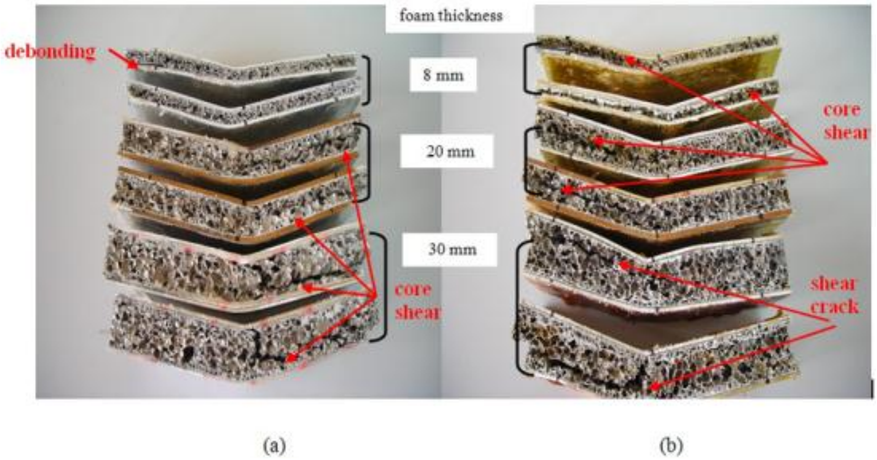


Fig. 13 Failure modes observed during flexural testing of (a) Al sheet/GFPP/Al foam sandwiches bonded with PP based film, (b) Al sheet/GFPP/Al foam sandwiches bonded after silane surface treatment.

The concentrated load application to the sandwiches resulted in the localized bending of the upper face-sheet, as expected. Debonding occurred between FML face-sheet/Al foam core, Al layer/GFPP composite or Al layer/Al foam core probably due to the lower interfacial strength as compared to the core shear strength. In some samples, both core shear and debonding modes were observed sequentially. In terms of the core shear mechanism, shear cracks originated in the foam between the load and the support fixtures since the failure in the core started with cracking followed by some crushing of the cells. The core failed with about 45° angle showing a distinctive failure surface with crack propagation through the foam cells. The damage progression appeared to be steady and consistent with the increase of displacement. In spite of the debonding of the core from the FML face sheet after shear crack formation, the GFPP layer did not show any delamination. Almost no debonding was observed between the GFPP and Al constituents in sandwiches integrated with PP based film indicating the strength of polymeric adhesive film.

4. Conclusion

In this study, fibre/metal laminated (FMLs) consisted of glass fibre reinforced polypropylene (GFPP) and aluminium (Al) sheet were developed and consolidated with aluminium foam cores of varying thicknesses (8, 20 and 30 mm) to prepare sandwich panels. Laminated structures were obtained by hot pressing technique at 200°C for 10 minutes with a constant pressure of 1.5 MPa. The bonding among the sandwich components were achieved by various surface modification techniques. Both quasi-static compression and flexural responses of sandwich structures together with their energy absorption behaviours were investigated. The samples with higher elastic modulus usually exhibited higher collapse strength for each thickness set of foams and foam based sandwiches. The foam thickness increase resulted in the increase of elastic modulus for the Al foam sandwich systems bonded with GFPP after silane surface treatment. However, the samples bonded with PP based film did not show the same characteristics. The differences among the structures in terms of mechanical properties are attributed to the local density fluctuations and inhomogeneous nature of the aluminium foams. The thickness increase generally leads to the increase of absorbed energy and this behaviour was also observed in the present study. The flexural test parameters such as collapse strength, core shear strength and face-sheet strength were also investigated in this study. The sandwiches with 8 mm foams showed the highest core shear and face-sheet strength values independent of bonding technique. However, the samples including 30 mm Al foams were exposed to highest loads compared to the other sandwich structures. The GFPP presence also promoted these values and as expected, the dissipated energy calculated from the area under the force-deflection curve increased with foam thickness increment. The damage progression appeared to be steady and consistent with the increase of displacement and the core shear and debonding were found to be the major failure mechanisms observed during the flexural tests. In summary, metal/composite sandwiches were fabricated successfully and these structures exhibits high potential for the fabrication of energy absorbing materials with good structural integrity; such as for anti-blast armour or impact absorbing automotive bumper systems.

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