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Experimental investigation on flexural behavior and energy absorption of lightweight sandwich panels with aluminum honeycomb core embedded by thin-ply carbon-glass fibers/epoxy face sheets

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ABSTRACT

Generally, designing lightweight and thin-walled structures with high mechanical performance is one of the challenging issues for mechanical and civil engineering sciences. To this aim, sandwich panels which have been designed and analyzed in present research include aluminum honeycomb core (H) and UD-thin-ply carbon (C)/glass fiber fabric (G) composite facings and investigated the effect of hybridization and stacking sequence on their static and dynamic mechanical properties while keeping thickness constant. Hybrid face sheets panels with three lay-up configurations of $[G_2C_2G_2\overline{H}]_s$, $[GCG_2CG\overline{H}]_s$, $[CG_4C\overline{H}]_s$ and non-hybrid configurations (i.e., $[G_4\overline{H}]_s$, $[C_2\overline{H}]_s$) were also produced as baseline. Series of 3-point flexural tests, Charpy impact tests, visual inspection and scanning electron microscope (SEM) investigation were performed. The results showed improvement of the flexural strength, core shear strength, facing bending strength and static energy absorption of the $[G_2C_2G_2\overline{H}]_s$ in comparison with $[G_4\overline{H}]_s$, by 100%, 109.1%, 59.87% and 70%, respectively. Furthermore, the dynamic energy absorption of the $[GCG_2CG\overline{H}]_s$ increased by 123.53%. The characterized failure mechanisms in the panels with the hybrid face-sheets were the delamination between plies; brittle fracturing of the carbon fibers, pulling out the glass fibers, deformation of the honeycomb's cell, and delamination between skin and core. Therefore, the results of this research can be helpful for designing lightweight and high mechanical performance sandwich panels which have thickness limitation.

1. Introduction

Composites are advanced and engineered materials (consisting of reinforcement and matrix). They can be classified in various ways, but generally fall into three categories: a reinforcement type (i.e., particulate and fiber), a matrix type (i.e., metal, polymer, and ceramic) [1,2], and structural composite (i.e., sandwich panels) [3] so that, among various composite materials, sandwich structures can be formed by adhering two stiff, thin layers (called skins, face-sheets, or facings) to the thick, lightweight rigid or flexible core [4]. These structures yield high specific strength/modulus (strength/modulus per density) and acoustic damping performance, which make them applicable in various aerospace, automobile, marine, railways and building fields [5]. Sandwich panels' mechanical properties can be tailored to meet specific structural requirements by using different cores or face-sheet materials [6] and varying panel geometries (i.e., skin thickness and core unit-cell pattern and height) [7]. Generally, materials that are used for face-sheets are composite laminates and metals that almost carry all of the bending and in-plane loads while conventional sandwich core helps stabilize the facings against buckling and characterizes the flexural stiffness, out-of-plane shear and compressive behavior and includes lattice materials, synthetic polymer foam cores, metal cores, hybrid lattice-foam cores, bio-based cores and their hybrids [8,9].

Sandwich cores are made in a variety of material and geometry combinations to optimize the structural performance (i.e., transverse impact resistance). Sandwich cores used in engineering applications include primarily honeycomb core then porous foam core and the newest concept is lattice-based cores (including foldcore, truss core foam, cork, pyramid, Y-shaped, and corrugated cores) [10,11]. The most common sandwich core configuration is a metallic or Nomex (aramid fiber paper) honeycomb core, which has been studied by various research groups over the past few decades. Cai et al. [12] used 3003

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aluminum honeycomb core and 6A02 aluminum face-sheets for fabricating the sandwich panels.

Farooq et al. [13] studied on the sandwich panel with the Nomex honeycomb core and carbon fibers/epoxy composite facings for aerospace applications. They concluded that the sandwich panel cured at the temperature of 130 °C for 3 h had the optimum mechanical properties. Some researchers used the other novelty for fabricating the sandwich panels with the better mechanical properties, for example Hoch et al. [14] investigated the hyper-velocity impact (HVI) characteristics of novel carbon/epoxy Miura foldcore and facings. This work showed that the carbon/epoxy foldcore could redirect a projectile, thus greatly tolerating HVI damage in the sandwich panel.

Using and hybridization different fibers such as basalt, kevlar, jute and so on as face-sheet can be an alternative for tuning the structural performance of sandwich panels for desired applications [15,16]. Han et al. [17] used the basalt fiber fabrics for fabricating the basalt-epoxy/aluminum honeycomb panels. The basalt fibers are not as expensive as carbon fibers and exhibit higher mechanical properties than glass fibers as well. Moreover, hybridization of thin-ply carbon with basalt fibers has proper resistance against the impact conditions and leads to ductile behavior [18].

Fu and Sadeghian [19] investigated sandwich panels with honeycomb core and flax FRP composite face sheets and tested the samples under three-point flexural loading and they showed fulfilling core and hybrid skin panel will increase the flexural performance of sandwich panels. In the following, Lv et al. [20], Zhang et al. [21] and Xiao et al. [22] analyzed response of sandwich panels with honeycomb core and hybrid composite face sheets under low velocity and dynamic response. Furthermore, Rizzo et al. [23] investigated completely about static (i.e. flexural loading) and dynamic (i.e. low velocity impact) behavior of Al-honeycomb and hybrid face sheets and showed the improvement of sandwich panel behavior due to hybrid composite face sheets.

Hybridizing the face-sheet materials of sandwich panels is an effective way for improving structural performance [24]. Rolfe et al. [25] fabricated the sandwich panels with the foam core and hybrid glass/-carbon fabric skins to investigate HVI characteristics. The results showed that the hybrid panels have less transverse deflection in comparison with carbon and glass fabric skin sandwich panels. In addition, Rolfe et al. [26] attained that the transverse deflection was not affected by position of glass fiber and carbon fiber layers under blast loading. Furthermore, hybrid glass/carbon fabric skins reduced normalized deflection of the sandwich panel by 23% and 41% compared to carbon fabric skin and glass fabric skin sandwich panel respectively.

Samlal et al. [27] investigation was performed on sandwich panels with foam core and variety face sheets containing two types of non-hybrid and three configurations of hybrid face sheets while non-hybrid face sheets included Carbon Woven skin and Kevlar woven skin which hybrid face sheets were stacking sequence of both Carbon and Kevlar. They tested the samples under low-velocity impact and found out the 34.1% peak load capacity enhancement of hybrid skin panels in comparison with non-hybrid Carbon woven skin panels.

According to sandwich panels with hybrid face sheets, Eyvazian et al. [28] worked on buckling behavior of panels with foam core and different stacking sequence of glass, fiber metal laminate (AL 2024-T3) and Dyneema-woven fabrics for use in skins through hybrid and non-hybrid forms. The results showed the highest buckling load for hybrid samples in comparison with non-hybrid skins panels.

In general, thickness plays a significant role in most cases such as designing airplanes due to their thickness limitation. This work aims to investigate the effects of hybrid carbon/glass fabric skins and stacking sequence on aluminum core sandwich panels subjected to static and dynamic loadings. The flexural strength/modulus, core shear strength, facing bending strength and impact energy of the sandwich panel were evaluated by using three-point flexural loading and Charpy impact test. The carbon fabric layer which was used in this work was the thin-ply grade. A thin carbon ply has fewer fibers (per ply) than a standard carbon ply with the same thickness and as mentioned previously hybridizing thin-ply carbon with high strain fibers can increase not only ductility but also mechanical behavior of composites so in this research thin-ply carbon with glass fibers and honeycomb core has designed and investigated these behaviors on sandwich panels [18]. Moreover, thin-ply carbon allows for a relatively large variation in ply angle orientation and more homogenous microstructure with less voids and defects, thus providing higher mechanical performance than a standard carbon ply [25]. Visual inspection and scanning electron microscope (SEM) analyses were performed to understand various damage modes occurring within the sandwich panels.

The sandwich panels which have been investigated in this work can be used in many applications of engineering such as airplanes, space craft and even building structures like walls and roofs.

The novelty of this work is including the thin carbon (fabric) ply into skins with different stacking sequence which can improve the mechanical performance of sandwich panel with nearly constant thickness. Hybridization of thin carbon (fabric) ply with glass fabrics in face sheets of honeycomb core sandwich panels had not been done before this current study.

2. Experimental

2.1. Raw materials

The aluminum core which was used in this work was Alcore PAA-CORE® 5052 aluminum honeycomb with a cell size of 3/16 in. (4.76 mm), a thickness of ¼ inch (6.43 mm) and a density of 3.1 pounds per cubic foot (PCF). The combination of EPL 1012 epoxy resin and EPH 112 hardener was used as matrix of the face-sheets and adhesive agent to bond the face-sheets to the aluminum core. The mixing ratio between the epoxy and the hardener was 100:12 wt%. The face-sheets were prepared with unidirectional (UD) thin carbon fabric prepregs (38 g/m^2, TeXtreme) with thickness of 0.03 mm and 2 × 2 plain woven glass fabrics (100 g/m^2, AMP Composites).

2.2. Composite fabrication

A hand lay-up method was used to fabricate the sandwich panel with the hybrid face-sheet and aluminum honeycomb. According to the manufacturer's recommendation, the sandwich panels were cured at the ambient temperature for 24 h, followed by 7-day post cure. A total of five sandwich panel configurations were considered and labeled using the notation of thin-ply carbon fabric (C), glass fabric (G) and aluminum honeycomb core ($\overline{H}$). Two baseline sandwich panels with the non-hybrid face-sheets were $[G_4\overline{H}]_s$ and $[C_2\overline{H}]_s$, named "Glass" and "Carbon" panels respectively. The three hybrid sandwich panels were $[G_2C_2G_2\overline{H}]_s$, $[GCG_2CG\overline{H}]_s$ and $[CG_4C\overline{H}]_s$, each named "Sandwiched carbon", "Interlayer" and "Sandwiched glass" panels respectively. Table 1 includes stacking sequence, the nominal dimensions and density of five sandwich panels in accordance with ASTM D790 [29] and ISO 179–1 [30] standards prepared in this work.

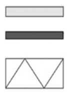
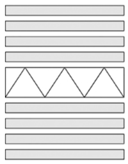
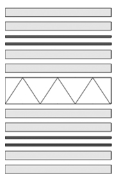
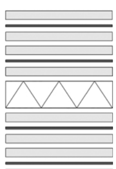
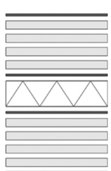
2.3. Mechanical Testing

2.3.1. Three-point flexural tests

A series of three-point flexural tests were conducted in accordance with ASTM D790 standard [29] by using Hounsfield H25KS. Each test was performed at least 5 times and the average data was reported herein. Fig. 1 shows the flexural specimens and one sample which is placed in a testing fixture. The span length and crosshead speed for this test were 122 mm and 1 mm/min respectively and sandwich panels were cut into 160-mm long and 30-mm wide specimens.

The flexural strength (σ_f), flexural modulus (E_b), strain at failure (ε_f) and static specific energy absorption (A_e) can be determined by using

Table 1
Stacking sequence, dimensions and density of the sandwich panels.

Sample	Stacking sequence  (Glass fabric) (thin-ply UD carbon fabric) (Al honeycomb)	Thickness of panels (mm)	Thickness of core (mm)	Nominal thickness of each face sheet (mm)	Density of panels ($\times 10^{-6}$ g/mm^3)
Glass		7.53	6.43	0.55	357.89
Sandwiched carbon		7.63	6.43	0.6	410.15
Interlayer		7.63	6.43	0.6	431.82
Sandwiched glass		7.63	6.43	0.6	385.2
Carbon		7	6.43	0.29	218.41

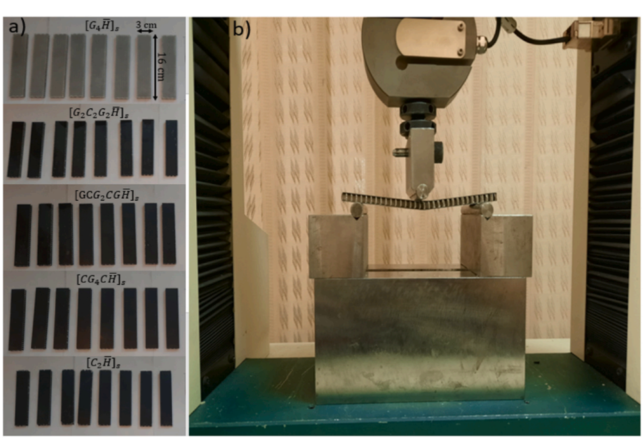


Fig. 1. Figures of three-point flexural test; a) image of all specimens for three-point flexural loading, b) close up view of flexural test equipment with sample.

Eqs. 1–4, as follows:

$$\sigma_f = \frac{3PL}{2bd^2} \quad (1)$$

$$E_b = \frac{L^3 m}{4bd^3} \quad (2)$$

$$\varepsilon_f = \frac{6Db}{L^2} \quad (3)$$

$$A_e = \frac{\int_0^D P(\delta)d\delta}{W} \quad (4)$$

where P, L, b, d, m, D and P (δ) each denote the maximum load measured at mid-span, span length, specimen width, specimen thickness, slope of force/displacement cure, maximum deflection, force at displacement δ.

The facing bending strength (σ) and core ultimate shear strength (F_s^{ult}) each can be calculated in accordance with ASTM C393 standard by using Eqs. 5 and 6 [31]:

$$\sigma = \frac{PL}{3t(d+c)b} \quad (5)$$

$$F_s^{ult} = \frac{P}{(d+c)b} \quad (6)$$

where P_{max}, L, d, c, b, and t are the maximum applied load, span length, total specimen thickness, core thickness, specimen width, and facing thickness, respectively.

2.3.2. Charpy impact tests

The Charpy impact test was performed with constant impact energy of 20 J to measure the required energy of specimen against sudden impact load according to the ISO 179–1 standard [30]. Each test was performed at least 5 times and the average data was reported. Sandwich panels were cut into 70-mm long and 10-mm wide specimens for Charpy impact tests. The specific absorbed energy E_c can be determined by using Eq. 7:

$$E_c = \frac{E_1 - E_2}{W} \times (bLd) \quad (7)$$

where E_1 and E_2 are initial and final energy respectively. Each can be calculated as follows:

$$E = mgh \quad (8)$$

$$h = S(1 - \cos\theta) \quad (9)$$

where W, b, L, d, m, g, h, S, and θ are weight, width, length and thickness of specimens, mass of pendulum, gravity, height of pendulum, length of pendulum, and angle of fall or rise respectively. These parameters are adjusted to produce 20 J impact energy. Fig. 2 shows specimens of Charpy impact test and specimen placed in a testing fixture.

2.4. Damage identification and assessment

The scanning electron microscope (SEM, TESCAN VEGA) analysis was employed to investigate microstructure and corresponding failure mechanisms. The samples were sprinkled with gold to prevent the event of the charging phenomenon then mounted on specimen stage of SEM with following parameter: acceleration voltage of 15 kV, magnitude up to 1000 ×, working distance to the sample surface of 10–30 mm.

3. Results and discussion

3.1. Flexural properties

Fig. 3 presents the average flexural load-displacement curves of the five sandwich panels. As shown in the Fig. 3, all hybrid skin sandwich panels exhibited larger flexural stiffness (i.e., the slope of load-displacement curve) and flexural load than those of the non-hybrid skin panels. Hybrid skin sandwich panels with the same thickness (7.63 mm in Table 1) resulted in nearly identical stiffness. Among three hybrid skin sandwich specimens, the Sandwiched carbon specimen showed maximum flexural load (1025 N) and failure displacement (3.38 mm). In this panel maximum flexural load have improved 248.64% and failure displacement have increased 113.92% in comparison with Carbon skin panels and also in comparison with Glass skin panel, maximum flexural load has changed 96.51% and failure displacement has decreased 18.9%. According to Fig. 3 improvement of hybrid skin panel compared with non-hybrid skin panels is obviously.

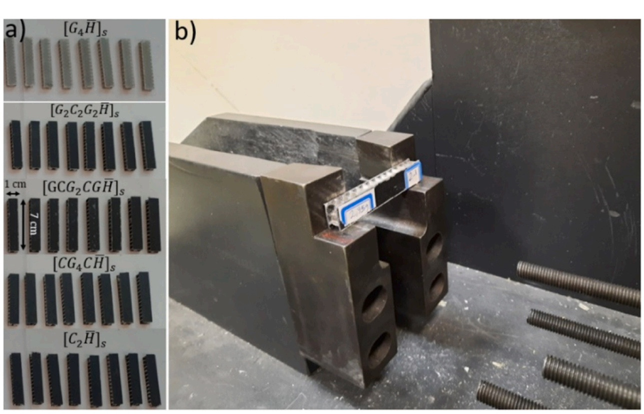


Fig. 2. Charpy impact test: (a) image of all specimens, (b) close-up view of specimen in place.

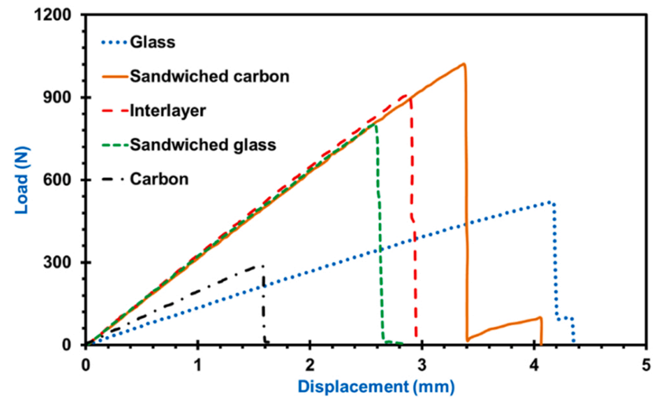


Fig. 3. The flexural load-displacement curves of sandwich panels.

Table 2 includes the maximum flexural load and displacement at failure obtained from a series of flexural tests. The flexural properties, core shear properties, and static flexural energy absorption were determined using Eqs. 1–6.

Fig. 4a presents the flexural strength of all sandwich panels studied in this work. The flexural strength of the Glass skin panel was 51 MPa. By hybridizing the glass fabric skins with two thin-carbon plies, the flexural strength of Sandwiched carbon panel improved by 100% (i.e., 102 MPa). In contrast, the Sandwiched Glass panel exhibited nearly 65% improved flexural strength; this is the lowest improvement among all three hybrid skin sandwich specimens. The interlayer hybridization of glass and carbon plies had a great influence on flexural strength, but the improvement was about 84%, that is between other two hybrid sandwich panels. The results suggest that an inclusion of thin-ply carbon fabric layers in facing is highly beneficial for improving the flexural strength of sandwich panel.

Fig. 4b shows the flexural modulus of the sandwich panels. The carbon fabric skin sandwich panel had the highest specific flexural modulus (40 MPa.m^3/kg), while the glass fabric skin panel exhibited the lowest specific flexural modulus (13.7 MPa.m^3/kg). Similar to flexural strengths (Fig. 4a), three hybrid carbon/glass fabric skin sandwich

Table 2
Stiffness, maximum flexural load and displacement at failure of sandwich panels.

Specimen	Maximum flexural load (N)	Deviation for flexural load data (N)	Displacement at failure (mm)	Deviation for displacement data (mm)
Glass	521.6	±20	4.17	±0.21
Sandwiched carbon	1025	±35	3.38	±0.15
Interlayer	914	±30	2.89	±0.15
Sandwiched glass	803	±35	2.58	±0.12
Carbon	294	±15	1.58	±0.08

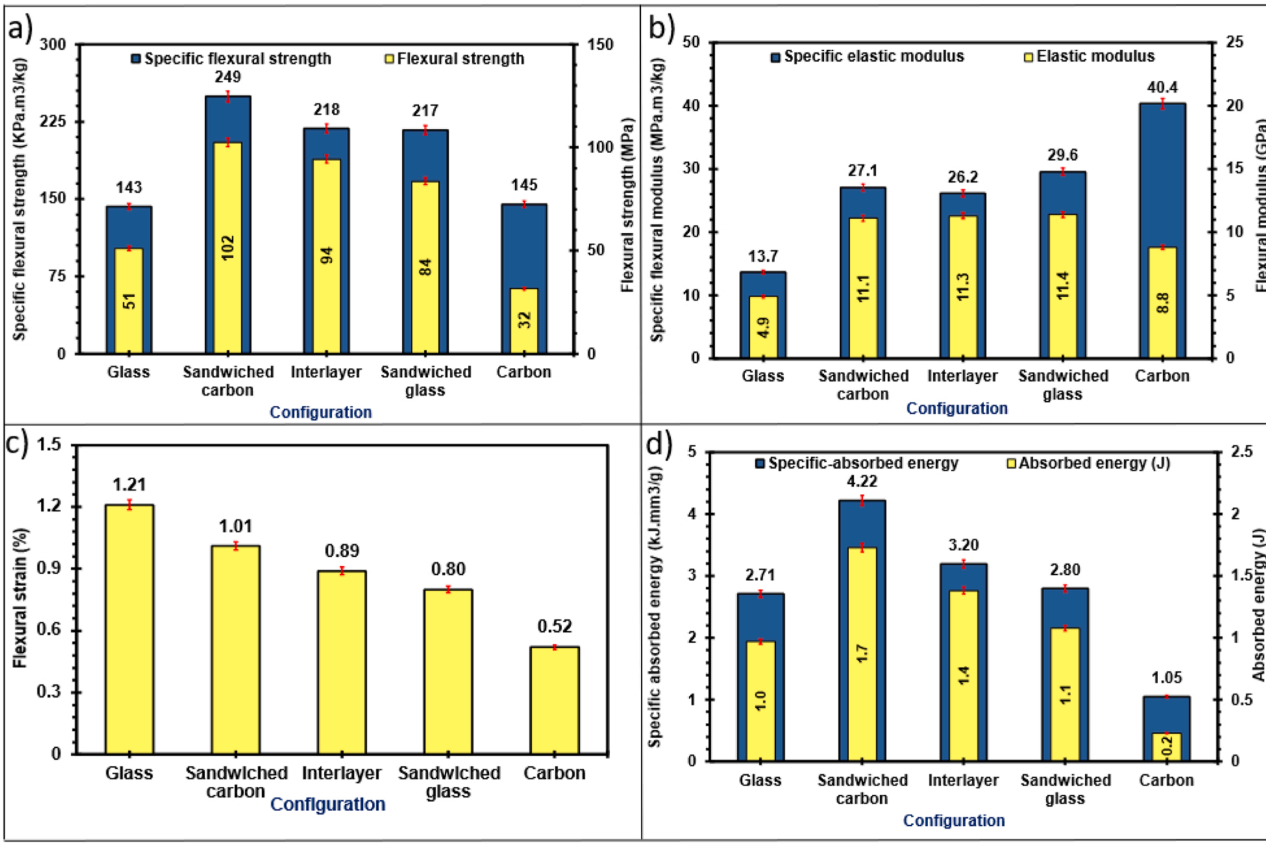


Fig. 4. Results of flexural loading test for sandwich panels with the hybrid and non-hybrid face sheets in bar graph: a) The (specific) flexural strength, b) The (specific) flexural modulus, c) The flexural strain, d) Static (specific) energy absorption.

enhanced the specific flexural modulus compared to the non-hybrid glass skin sandwich panel. However, the highest flexural modulus was obtained from the Sandwiched glass skin panel where glass fabric layers are sandwiched between two thin carbon fabric layers; the flexural modulus improved approximately by 131% compared to the glass skin panel. These results are somewhat in consistent with the flexural strength results (Fig. 4a). This behavior may be explained by the brittle nature of carbon fibers. Carbon fabrics have higher flexural modulus and strength than glass fabrics, but suffer from their brittle nature. Thus, glass fabrics are typically used as exterior layers for protecting the carbon fabrics (due to their relatively good impact resistances) to achieve the highest improvement in mechanical strength [32]. Another potential reason is kink band damage that may occur in the top layers of hybrid carbon/glass composites under flexural loading [33]. If carbon fabrics are used as exterior layers, the kink bands forms and propagates until carbon fabric layers are buckled in the middle glass fabric layers, due to their relatively higher stiffness. In fact, the failure mechanism in the hybrid composite is more complex and different, when the glass fabric layers are placed toward the outer surfaces. In this case, failure can initiate at lower stress and higher strain values because of stacking sequence as shown in Table 1. The higher strain of the outer glass skin layers can also reduce the tensile and compressive strengths. In contrast, the carbon fibers experience lower stresses. Thus, the initial failure of carbon fibers occurs in a higher level of stress indicating an increase in the failure strength of the hybrid structures. Therefore, the strength of the sandwich panel with the hybrid face sheets can be maximum when the glass fibers are used as the exterior layer.

In the light of the above, it can be seen when carbon is put as the exterior layer in face-sheets, the tolerance of strain in panels goes to lower level. Consequently, the flexural modulus of the Sandwiched Glass panel is the highest among three hybrid skin panels.

Fig. 4c compares the failure strain of the sandwich panels under flexural loading. An apparent failure strain reduction was observed from the glass to carbon skin panels. This is because glass fibers have higher toughness than carbon fibers [34]. Similar to flexural strength (Fig. 4a), flexural strain of the Sandwiched carbon panel (i.e., 1.01%) yielded higher than the Sandwiched glass panel (i.e., 0.8%). This trend is associated with different failure mechanisms in hybrid structures, which will be discussed in the following sections.

According to the Eq. 4, the flexural energy absorption of the sandwich panel is calculated, as shown in Fig. 4d. Both non-hybrid Carbon and Glass skin sandwich panels showed lower static specific absorption capability (each 1.05 and 2.71 kJ.mm^3/g). The hybridization of skin layers has an incredible effect on energy absorption of sandwich panels. These results occur where glass fabric layers tolerate flexural strain and thin-ply carbon fabric layers withstand flexural stress simultaneously. About hybrid skin panels, using glass fabric as an outer layer in the face sheets showed the highest improvement in flexural energy absorption performance because glass fibers reduce the compressive and tension stress via tolerating strain on the carbon fibers as an inner layer which was previously discussed.

The results show a significant different performance between hybrid skin panels and non-hybrid skin panels while the core is constant in all sandwich panels, so it is necessary to calculate the facing bending strength and core shear strength for attaining the amount of load that each part carries. It can be achieved by Eqs. 5 and 6 from the ASTM C393 test method that were compared in Fig. 5. All hybrid skin panels had both higher facing bending strengths and higher core shear strengths than non-hybrid skin panels. The Sandwiched carbon skin panel had the highest strength (235 MPa) because glass fabric as the outer layers reduces the compressive and tension stress on the inner carbon fabric layers [31]. Having the outer face sheets with higher strength causes a

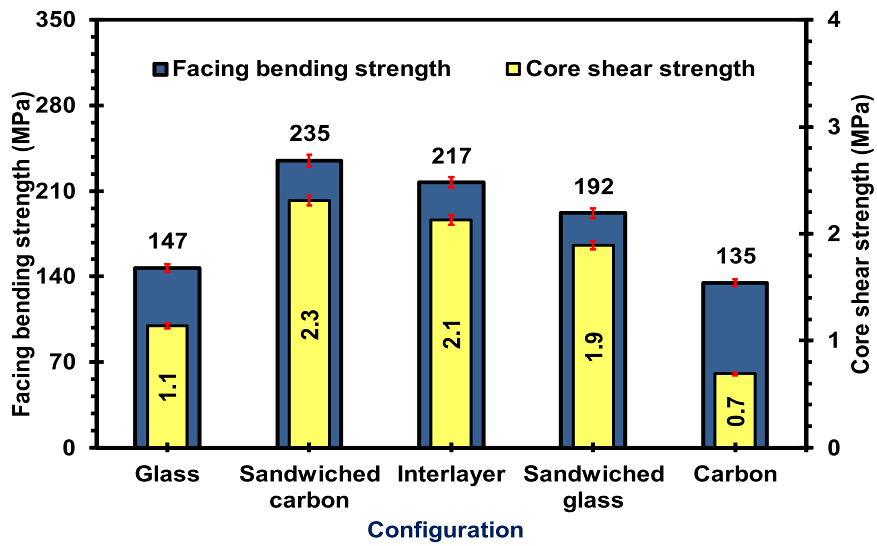


Fig. 5. Facing bending and core shear strength of sandwich panels under flexural loading.

reduction of stress on the core. So higher stress level is required to fail the honeycomb core. For this reason, the Sandwiched carbon panel can resist higher core shear strength than other hybrid panels consistent with the work done by Wu et al. [35].

3.2. Impact properties

A series of Charpy impact tests (20 J) was performed to determine the dynamic (specific) energy absorption of the sandwich panels with the hybrid and non-hybrid skins. Specific impact energy absorbed in sandwich specimens was calculated by using Eqs. 7–9. As shown in Fig. 6, the absorbed dynamic impact energy in the Glass and Carbon panels each were 1.7 J and 1.4 J. All hybrid skin sandwich panels showed significant improvement in dynamic impact energy absorption capability. The Interlayer panels exhibited the highest absorbed energy (3.8 J), followed by the Sandwiched Glass panel (2.5 J) and the Sandwiched carbon panel (2.1 J). The Interlayer panel had the highest energy absorption under the dynamic loading (Fig. 6), while the Sandwiched carbon panel yielded the highest energy absorption under the static loading (Fig. 4d). This is result of the failure modes (i.e., delamination, partial delamination, fragmentation and partial fragmentation, fracture of the face sheet, crack path deflection, opening cell, delamination between core and face-sheet and pulling out the fibers) which are very different in hybrid skin sandwich panels under dynamic and static loading conditions [36]. By comparing the data of graphs in Fig. 6, the Interlayer panel was found to be the optimal configuration, showing 37% and 85% improvement in specific absorbed impact energy compared to the Carbon and Glass panels. The most important reason that can be mentioned for the highest dynamic energy absorption of Interlayer panel in comparison with other hybrid panels is changing of plies material along with the thickness which led to occurrence of more delamination mechanism in dynamic loads for damping energy while changing material along with thickness is less in Sandwiched carbon and Sandwiched glass. An in-depth investigation of macro- and micro-structural damage (each via visual inspection and SEM analysis) is critical to understand complex damage modes in hybrid sandwich panels. More details are discussed in the following sections.

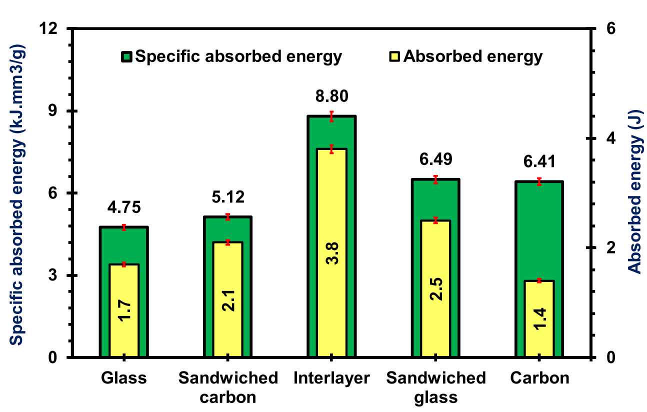


Fig. 6. Dynamic energy absorption of sandwich panels after Charpy impact tests (20 J).

Table 3 summarizes the percentage of variations in flexural strength/modulus, static energy absorption, core shear strength, facing bending strength, and dynamic absorbed energy absorption of all hybrid-skin sandwich panels compared to those of the Glass skin panel. As clearly shown in the Table 3, all hybrid carbon/glass skin sandwich panels showed greatly improved mechanical properties. Considered in this study; stacking sequence of face sheets, while keeping thickness constant is an important factor for improving the mechanical performance of hybrid skin panels.

3.3. 3.3. Visual inspection

Fig. 7 shows the top and cross-sectional views of sandwich panels after flexural testing with showing different failure mechanism via different color arrows (i.e., different colors which used for arrows is for avoiding confusion). The partial delamination and delamination of skin plies and the fracturing of glass fibers are the failure mechanisms that played an important role on failure of the Sandwiched carbon panel face sheet as shown in Figs. 7a and 7b. Also, the plastic deformation of the honeycomb was seen in this sample. It seems that the face sheet has significant effect on the mechanical strength of this structure. So that, this face sheet absorbed the energy of flexural loading. These results agree with the flexural strength of the panel and the stress of the face-sheet. Figs. 7c and 7d are visual inspection of the Interlayer panel. The fracture of the face sheet which occurred on the surface is the failure mechanism. Furthermore, the cell of the honeycomb was opened and deformed (Fig. 7d). Therefore, the degree of destruction of Interlayer panel core was higher than the Sandwiched carbon panel because the core of Sandwiched carbon experienced just deformation though Interlayer panel experience opening and deformation, simultaneously.

Figs. 7e and 7f depict the fracture behavior of Sandwiched glass

Table 3
Mechanical properties improvement of hybrid-skin sandwich panels.

Specimen	Flexural Strength (%)	Flexural Modulus (%)	Static Energy Absorption (%)	Facing Bending Strength (%)	Core Shear Strength (%)	Dynamic Energy Absorption (%)
Sandwiched carbon	100	126.5	70	59.9	109.1	23.5
Interlayer	84.3	130.6	40	47.6	90.9	123.5
Sandwiched glass	64.7	132.7	10	30.6	72.7	47.1

All properties are normalized by those of the glass skin sandwich panel.

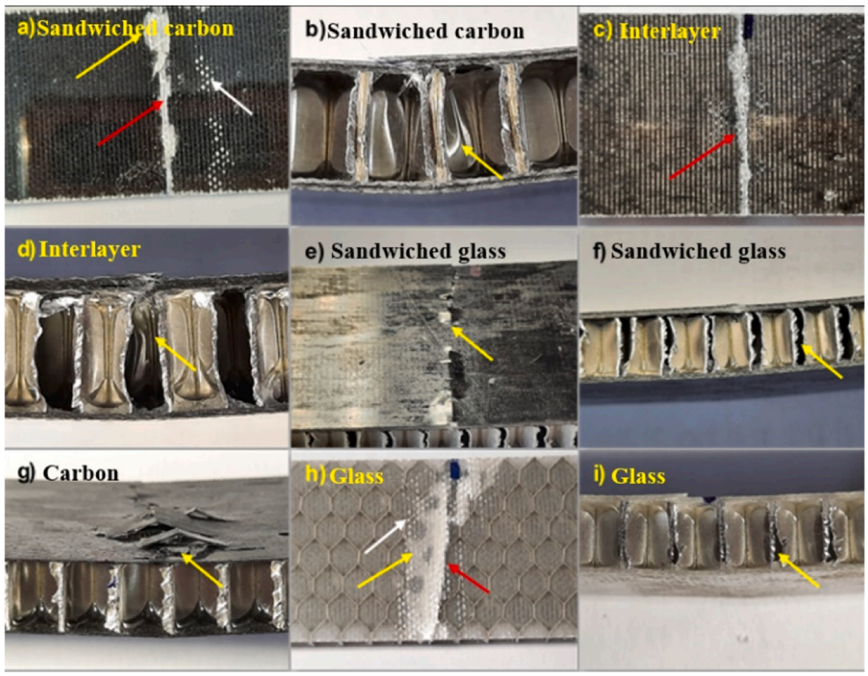


Fig. 7. Visual inspection from the fracture surface sandwich panels with the various face sheets after the flexural test; a, c, e, h) top view of sandwich panels, b, d, f, i) cross view of sandwich panels, g) top and cross view of sandwich panels.

panel. The brittle nature of the carbon fiber layers is clearly seen on the surface of the face sheet. Thus, the Sandwiched glass panel can be the most sensitive panel to crack growth compared to other hybrid skin sandwich structures. As previously discussed, it is better to use glass fabric as an exterior ply in hybrid skin panels. From Fig. 7f, the cells of the honeycomb in this structure were completely opened, but its extent is lower than the Interlayer panel. Fig. 7g shows the brittle fracture behavior of the Carbon panel and no core failure was observed in the panel. It seems that the brittle fracture of carbon fibers is the dominant failure mechanism. Figs. 7h and 7i show the delamination, partial delamination, and crack path deflection on the Glass panel face sheets. Also, the opening cell and slightly plastic (permanent) deformation were observed in the core structure. All these mechanisms are suitable for controlling crack propagation and absorbing the energy in the static and dynamic loadings. In other words, the static and dynamic loads are spent for these failure mechanisms.

Visual inspection of sandwich panels after Charpy impact tests is shown in Fig. 8. In the Sandwiched carbon panel (seen Figs. 8a and 8b), the failure mechanism were the delamination of glass fibers, partial delamination, and delamination between core and face-sheet.

Figs. 8c and 8d show the top and cross-view of Interlayer panel with failure mechanisms such as deflecting cracks from the glass fibers, delaminating the glass fibers and fracturing the skin layer. The other characterized failure mechanisms which occurred in the core were the delamination between skin and core, and crushing honeycomb completely. Therefore, this sample has a high resistance against dynamic loads. The obtained data from the impact test confirmed this assumption.

From Figs. 8e and 8f, it can be realized that pulling out the glass fibers and fracturing were the dominant failure mechanisms. Deforming the face sheet and opening the cell of the honeycomb were other absorbing mechanisms in this sample. Fracture in the surface of the Carbon sandwich panel shows that this sample has a brittle fracture in both face sheets (seen Fig. 8g). Fracturing the glass fibers, delamination of glass plies, delamination between core and face-sheet and opening cells were the failure mechanisms in the Glass panels (seen Figs. 8h and 8i).

3.4. SEM Investigation

Microstructural observation of fractured specimens is one of the effective ways for understanding dynamic damage behaviors of sandwich panels. Figs. 9 and 10 illustrate the SEM images from the surface of non-hybrid and hybrid skin panels respectively, after impact test.

As shown in Figs. 9a-9c, the skin in the Carbon skin panel exhibited the brittle nature of fracture and skin-to-core debonding. In contrast, the Glass panel (Figs. 9d-9f) showed a clear evidence of fiber pull out. Similar to the Carbon panel, the delamination between the skin and core is one of fracture mechanisms for absorbing the energy of the impactor.

Fig. 10 reveals that the pulling out of the glass fibers and delamination in the interface of the honeycomb's cell and skin are two dominant failure mechanisms consistent with the non-hybrid (Carbon and Glass) panels. According to the other works [37], these two failure mechanisms can damp the energy of the impactor in the composite

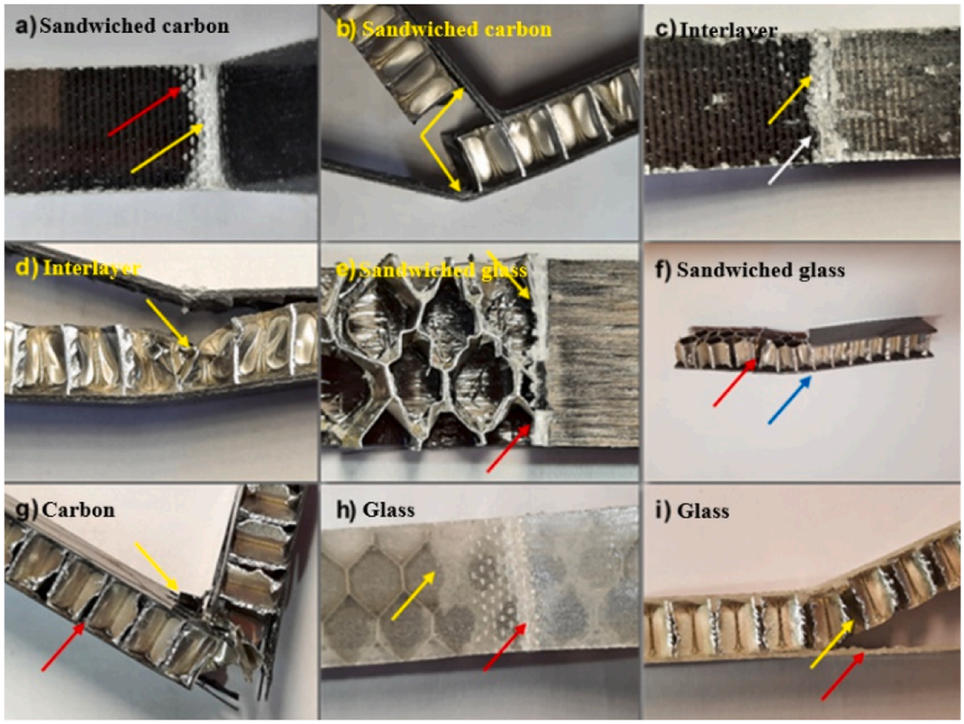


Fig. 8. Visual inspection of sandwich panels after impact test; a, c, e, g, h) top view of sandwich panels, b, d, f, i) cross view of sandwich panels.

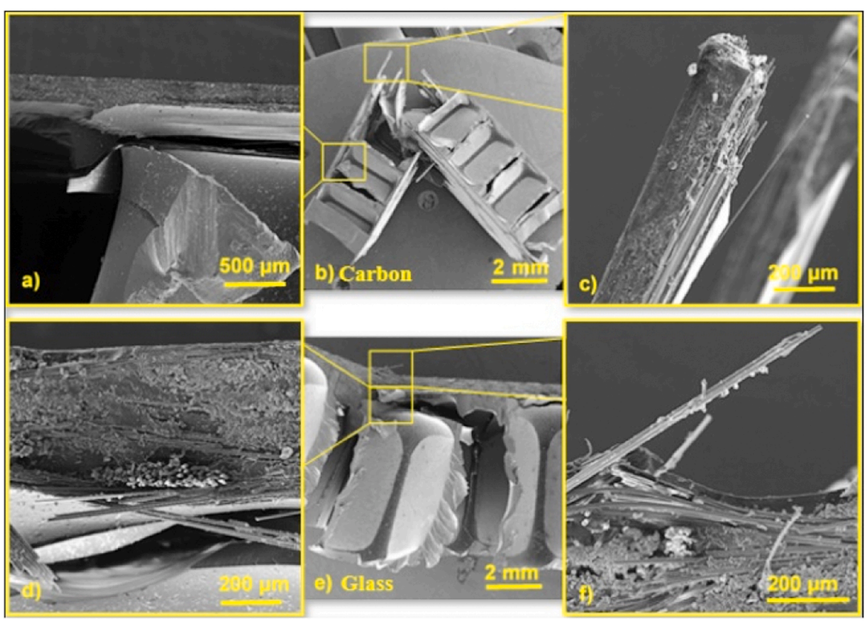


Fig. 9. The SEM images from the fracture surface of the non-hybrid face sheet sandwich panels after impact tests; a-c) Carbon panel, d-f) Glass panel.

structures. Comparing the Interlayer panel (Fig. 10e) with two sandwiched skin panels (Figs. 10b-10h) shows that pulling-out fibers has occurred more in the sandwiched skin panels. Also, the level of delamination in the interface is approximately equal. The new mechanism which has been activated is called the lateral crack that is growing in the interface of hybrid plies. In this mechanism, the crack grows in the lateral direction instead of the penetration direction. So, the energy of the impactor is damped by the delamination or partial delamination of distinct fibers as a result of lateral crack in interface of hybrid plies. Hence, because changing of plies material along with the thickness in Interlayer panel is more than sandwiched skin panels (Fig. 10), this mechanism can be one reason for having higher absorbing ability in the panel with interlayer skin than others under the impact test.

4. Conclusion

In this study, the effects of thin-ply carbon fabric (C) in Glass (G) skin panel with three stacking sequences and aluminum honeycomb (H) core sandwich panels on flexural and dynamic response were investigated. The configurations of hybrid skin panels (i.e. $[G_2C_2G_2\overline{H}]_s$, $[GCG_2CG\overline{H}]_s$, $[CG_4C\overline{H}]_s$) and non-hybrid panels (i.e. $[G_4\overline{H}]_s$ and $[C_2\overline{H}]_s$)were named Sandwiched carbon, Interlayer, Sandwiched glass, Glass and Carbon,

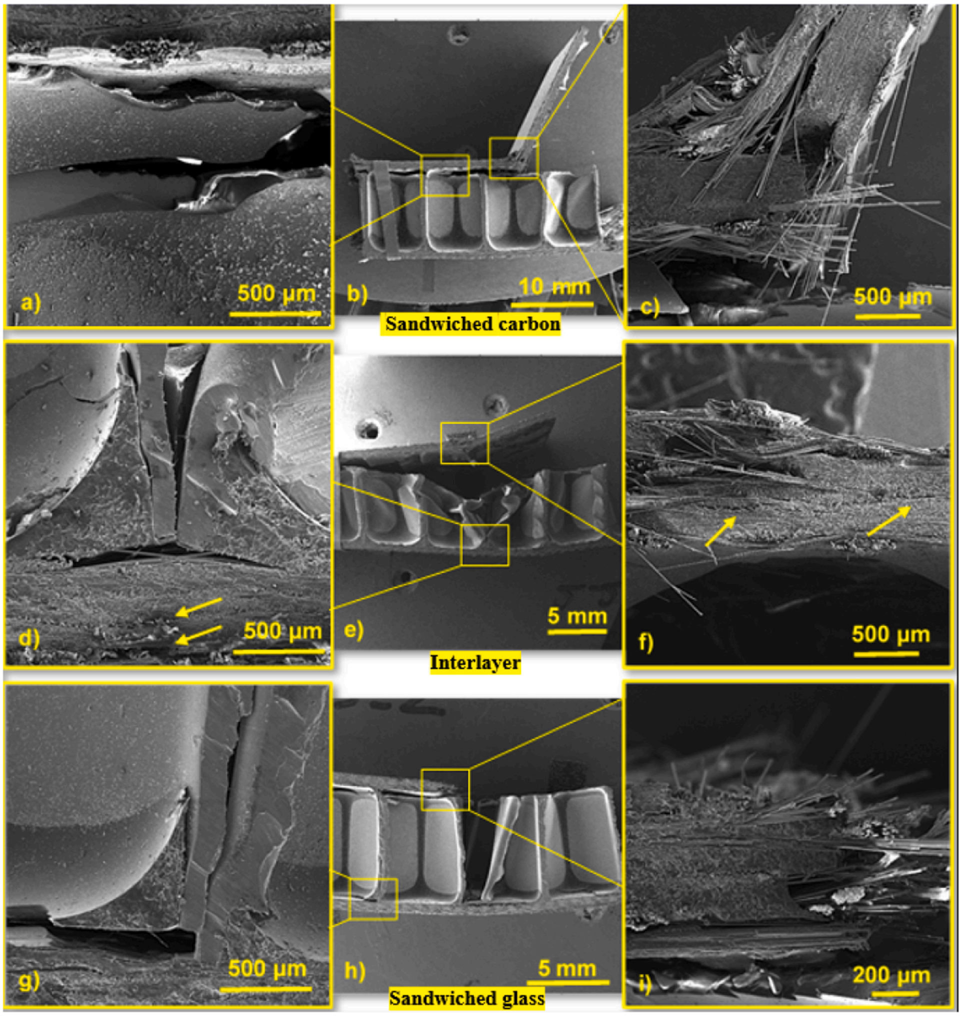


Fig. 10. The SEM images from the fracture surface of the hybrid face sheet sandwich panels after impact tests; a-c) Sandwiched Carbon panel, d-f) Interlayer panel, g-i) Sandwiched Glass panel.

respectively. In both, three-point flexural and Charpy impact test were obtained that the hybrid skin panels performed much better than non-hybrid skin panels. The results of flexural loading showed Sandwiched carbon skin panel had the best performance because glass fibers which were positioned in outer layer tolerates higher strain and can reduce tensile and compressive stress so that thin-ply carbon that was positioned in inner layer experience lower stress, therefore this sample can sustain more stress. Furthermore, kink bond damaging doesn't occur because glass is the outer layer (not thin-ply carbon) in Sandwiched carbon skin panel. On the other hand, the results of Charpy impact test showed that Interlayer skin panel had the best performance as a result of delamination due to changing material of plies along thickness. In other words, damping energy occurs better via delamination between various plies in Interlayer skin panels at short time. The other outcomes of obtained data are as follows:

1. Hybridizing the glass skin panels with thin-ply carbon fibers while the thickness doesn't change significantly, showed the astonishing improvement of all properties. In some cases, mechanical properties enhanced more than 100%.
2. Flexural strength in Sandwiched carbon face sheets (i.e. 102 MPa) which was the highest measurement in panels increased 100% in comparison with Glass panels and its specific flexural strength was 249 KPa.m^3/kg that shows improvement of non-hybrid skin panel when they hybridized.
3. The highest specific energy absorption in the impact test (8.8 KJ. mm^3/g) was seen in the panel with the Interlayer configuration. Its energy absorption was 3.8 J that shows 123.5% improvement in comparison with Glass skin panels.
4. The characterized failure mechanisms in the panels with the hybrid face-sheets were the delamination between plies; brittle fracturing of the carbon fibers, pulling out the glass fibers, deformation of the honeycomb's cell, and delamination between skin and core.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as employment, patent-licensing arrangements, etc.), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter discussed in this manuscript.

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