Comparison between honeycomb and composite corrugated cores in sandwich panels under compression loading

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Abstract: The study is to evaluate the compression properties of the polymeric composite corrugated-core sandwich structure against the honeycomb-core structure. The skin facings are from the prepreg carbon fibre composite laminate, while the core is made of different materials. Four core types are suggested; carbon fibre corrugated-core, fibreglass corrugated-core, Nomex honeycomb-core, and Kevlar honeycomb-core. The study is based on an experimental work of edgewise compression testing, and the comparison between alternatives are based on the specific properties-to-weight ratio. The analysed results prove there is superior compression capacity of the polymeric composite corrugated-core sandwich members to the honeycomb-core members, in particular in the nonlinear stage of compression test. The bonded surface between the honeycomb structure and the skins is often less than that of the corrugated profile for the same sandwich panel sizes. This contact area between the core and skin facings plays an important role in carrying load mechanism.

Keywords: corrugation core; honeycomb core; sandwich structure; edgewise compression; aerospace application.

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1 Introduction

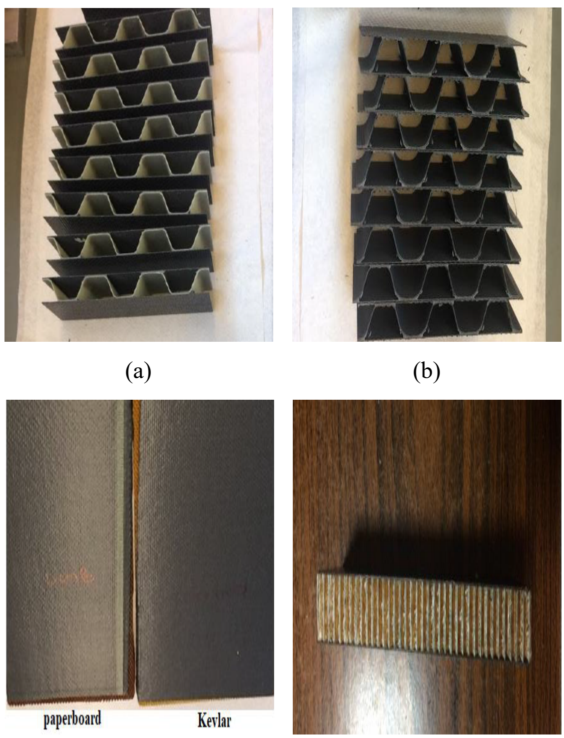
The demand to the sandwich structure increases in recent decades in different sectors' applications due to its anisotropic properties. Sandwich-structures are extremely efficient when it comes to light-weight and stiff components (Reußmann and Oberländer, 2014; Pollard et al., 2017; Jenkinson, 1966). The strength-to-weight ratio is an important criterion in selecting materials for design in aerospace applications. These ratios are an indicator of the relative structural efficiency (Jenkinson, 1966; Ganesh et al., 2015). Sandwich panel's rigidity can be tailored for specific designer demands by the choice of core structural parameters (Janus-Michalska and Jasińska, 2017). The core in sandwich structures is traditionally made out of several materials; foam, honeycomb, balsa wood, cork (Abrate, 2016). Honeycombs are used in aerospace industries since many decades as the preferred core material for buckling sensitive sandwich panels and structures (Pflug et al., 2000). From these industries, honeycomb sandwich panels are used extensively for flooring in most military and commercial aircraft. Aircraft floors are designed to withstand high compression loads (Ganesh et al., 2015). Examples of authors' studies on honeycomb-core structures are; Pflug et al. (2000) who studied the folded honeycomb cardboard production. They indicated that the TorHex cardboard offers superior properties as well as weight and raw material savings compared to corrugated cardboard (Pflug et al., 2000). Pollard et al. (2017), studied compression behaviour of ABS polymeric honeycomb cores with different core densities, with an average density of 180 kg/m^3, approximated values could be estimated from their results; 3.8 (kN/gm), 4.8 (MPa/gm), (5.7 MPa/gm) for specific crushing force, yield strength and crushing strength, respectively. The load direction has been applied in the same direction of the longitudinal axis of the honeycomb cell. Pineda et al. (2014) studied the maximum compressive load carrying capability (buckling load) of large-size panel (36 in wide by 5 in long panel and 1 in thickness) based on carbon fibre/epoxy composite for skin facings and different honeycomb core materials. It was predicted that the panel would fail in buckling prior to failing in strength and the reaction load in the linear stage was obviously high (Pineda et al., 2014). In the meanwhile, the corrugated core have recently intensified in sandwich structures. The corrugated core-panels find wide usage in so many products thanks to their superior stiffness per unit mass, in particular, in the corrugation direction. Corrugated panels are also used extensively in the aerospace industry (Previtali et al., 2015; Rejab, 2013; Dayyani, 2015; Shaban, 2016). Examples of the relevant literature studies are; Zhou et al. (2016), investigated the compression response of composite sandwich structures based on prepreg fibreglass/epoxy and carbon fibre/epoxy corrugated cores. It was indicated that the compression strength increased strongly with the thickness of the corrugation. Also, the carbon fibre reinforced corrugated structures offered superior compressive properties to that of the glass-based counterpart. Shaban (2016) studied the stiffness of the sinusoidal corrugated sandwich panels. It was found that the corrugated sandwich panel strengthened when sheet of core becomes thicker and the out-of-plane properties of the panel weakened with increasing pitch and height of corrugations (Shaban, 2016). Paperboard structural material, which is environmentally friendly by way of its reusable and fully biodegradable properties, was studied in the two forms, (the honeycomb and the corrugation) by Guo et al. (2010). In his works, it was proved that the edgewise crush resistance of corrugated and honeycomb composite paperboard significantly increases than the only honeycomb composite paperboard (Guo et al., 2010). The flooring is a very important segment in the aircraft industry. The common commercial aircraft flooring is about 1 cm thick and often is made of glass or carbon fibre reinforced epoxy skins with a Nomex honeycomb core (Ganesh et al., 2015). Face/core debonding in sandwich structures cause loss of integrity of sandwich structures (Saseendran et al., 2015).

The objective of the current work is to enhance the compression properties of the light-weight sandwich structure for aerospace purposes, in particular the flooring applications. By replacing the honeycomb-core structures with corrugated sheets the bonded surface area between the core member and the skin facings of the sandwich increases and hence the bonding strength increases. This is an essential factor for transferring the load between the components. Four core types were studied, two of them are corrugated-core sheets with an average 1.2 cm core thickness and the other two types are honeycomb-cores with 1 cm thickness. All specimens were made of the same skin facings (carbon fibre laminate composite) while the four core materials are different. The manufactured samples are tested under edgewise compression load and their behaviour are studied and discussed in the following paragraphs.

2 Experimental work

Four kinds of sandwich panels are manufactured, all of them have the same skin facings from the carbon fibre composite laminate. Two flat composite sheets were made using a vacuum bag technique and cured at 130°C for 2 hours. Each sheet consists of two plies of a prepreg carbon fibre-epoxy composite of 0.25 mm thickness. The cooked composite sheets with 0.5 mm final thickness were cut into proper sizes to be used as skin facings to all the sandwich panel types. The corrugated cores are manufactured using vacuum bag technique and cured through the same process as sheets of skin facings. One of them is from a single ply of a prepreg fibreglass-epoxy composite with a 0.53 mm thickness, and the second is from double plies of a prepreg carbon fibre-epoxy composite and has a 0.5 mm final thickness. The fibreglass corrugation was manufactured and stated before by Elzayady and Elghandour (2019, In press). Both corrugations are having the same ligaments profile (trapezoidal cross section of 63° and 12 mm height). After the cooking process, the corrugated core sheets were bonded to the flat carbon fibre sheets (upper and lower skin facings) with an epoxy resin to construct the sandwich structure. The epoxy resin has been cured at room temperature (25°C) for 24 hours. The other two sandwich panels were assembled from honeycomb core structures with hexagonal cells of 3.2 mm size and skin facings from uncooked prepreg carbon fibre plies. One of these honeycomb cores is from the Nomex and the other one is from a Kevlar. Assembly processes have been made before cooking and then the assembled sandwich panels are cooked in an autoclave using the vacuum bag technique. The properties of the parent components used in manufacturing are listed in Table 1 and 2. The manufactured sandwich structure members are shown in Figure 1. Four samples from each type are cut and prepared for testing. The four kinds of composite sandwich structure are entitled as; Nomex honeycomb-core, Kevlar honeycomb-core, fibreglass corrugated-core and carbon fibre corrugated-core sandwich. Their sample weight is 10 gm, 10 gm, 14 gm and 13 gm respectively. The outer dimensions of the tested corrugated core samples are 80 × 38 × 13 mm while the dimensions of the honeycomb-core samples are 80 × 38 × 11 mm. The difference of sample thickness (13 mm for corrugated-core and 11 mm for honeycomb-core) is due to the unavailability of finding a standard honeycomb core with the same thickness as the corrugated-core. However, the results are based on the overall weight of all sample types, i.e., the specific properties-to-weight ratio are compared to get the proper decision between alternatives.

Figure 1 Manufactured samples with, (a) corrugated fibreglass-core samples (b) corrugated carbon fibre-core samples (c) Nomex-core and Kevlar-core panel (d) cut sample of a honeycomb-core type (see online version for colours)



(a) (b) (c) (d)

Table 1 Properties of parent materials used for corrugation cores manufacturing

Material	*Elastic modulus (GPa)*	*Compressive strength (MPa)*	*Density ρ (kg/m^3)*
Prepreg fibreglass laminate	20	500	1,970
Prepreg carbon fibre laminate	77	900	1,600
Epoxy resin	3.5	170	1,200

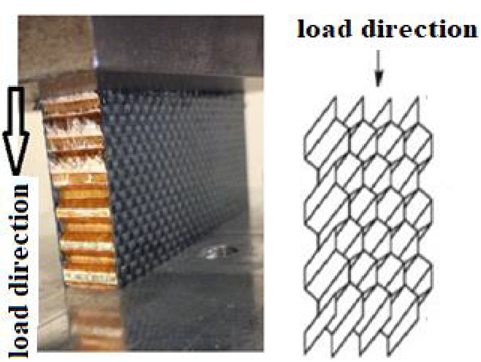
Table 2 Properties of honeycomb cores

Material	*Long.L elastic modulus (M Pa)*	*Trans.W elastic modulus (MPa)*	*Compressive elastic modulus (GPa)*	*Compressive strength (MPa)*	*Density ρ (kg/m^3)*
Nomex® honeycomb	-	-	0.138	1.86	50
Kevlar honeycomb	35.8	19.3	-	2.5	48

3 Testing

Testing has been carried out using a 90 KN universal testing machine. Four samples were prepared from each type to confirm the results. The samples were positioned freely on the lower surface of the machine as shown in Figures 2(a) and 2(c), and the load was applied in the longitudinal direction of the corrugation as shown in Figures 2(b) and 2(d) to examine their compression resistance under the so-called edgewise compression test. The edgewise compression test was applied to take advantage of the highest inertia of the sample and thus getting high values of stiffness. The output data was graphed on Excel sheets.

Figure 2 Samples positioning during testing and the load direction, (a) a sample with a honeycomb core (b) load direction with respect to the hexagonal cell (c) a sample with a corrugated core (d) load direction with respect to the corrugation (see online version for colours)



(a) (b)

Figure 2 Samples positioning during testing and the load direction, (a) a sample with a honeycomb core (b) load direction with respect to the hexagonal cell (c) a sample with a corrugated core (d) load direction with respect to the corrugation (continued) (see online version for colours)

(c)

(d)

4 Results and discussion

4.1 Compression properties

The results delivered from the testing are graphed in the following figures while their values are summarised in Table 3.

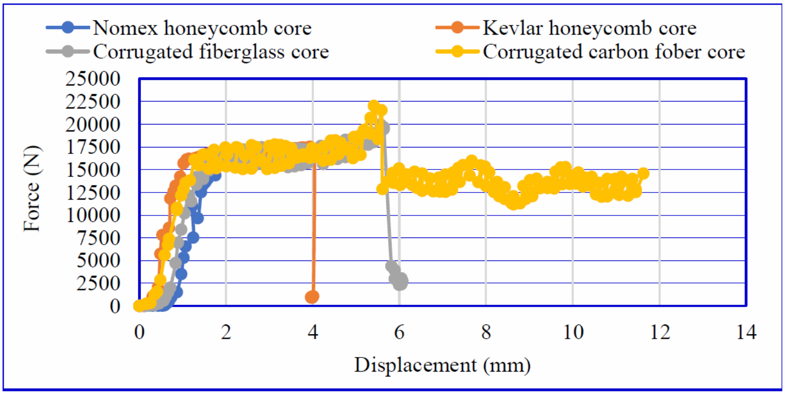
Table 3 Structural properties of sandwich members

Core type	*W (gm)*	*Stiffness (KN/mm)*	*Ultimate force (N)*	*Specific stiffness (kN/mm)/gm*	*Specific ultimate force (kN/gm)*	*Energy (J)*	*Specific energy (J/gm)*
Nomex honeycomb	10	16.56	14,304	1.65	1.43	8.76	0.8755
Kevlar honeycomb	10	18.09	17,498	1.8	1.75	57.37	5.73
Corrugated fibreglass	14	21.12	19,913	1.5	1.99	80.91	5.78
Corrugated carbon fibre	13	18.4	21,955	1.4	2.19	165	12.22

4.2 Force-displacement

Four curves for the force-displacement relations are graphed in Figure 3, each for a certain core type specimen. It is clear that there is a very different behaviour for all of them. The Honeycomb-core samples are having less compression capacity than those with the corrugated-core. In particular, the honeycomb Nomex-core specimen has the least compression carrying capacity as it has the smallest values of both ultimate force and displacement before fracture. On the contrary, the corrugated-core samples display a very high resistance to compression loads, especially the carbon fibre corrugated-core which withstood a very long displacement under the ultimate load without fracture.

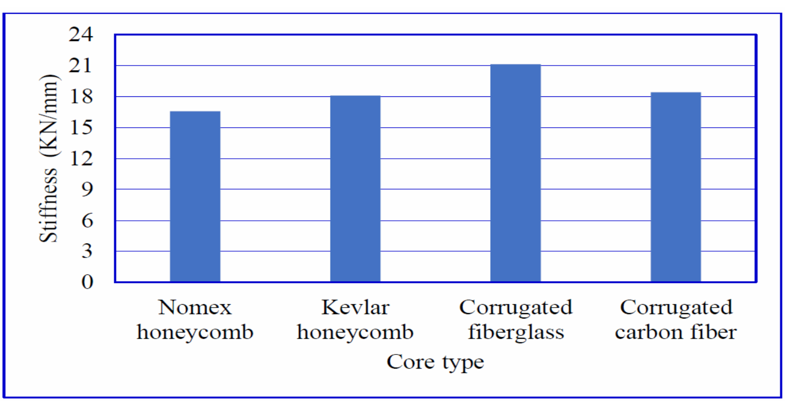
Figure 3 Force-displacement curves of sandwich structure members with carbon facings and different core type (see online version for colours)



4.3 Stiffness

Stiffness values are graphed in Figure 4. The Figure shows that the fibreglass-core sample has the highest value among all core types (21.12 KN/mm). A higher value at structure members of the fibreglass corrugated-core compared to corrugated carbon fibre has been recorded. This result has been delivered although the lower mechanical properties of the fibreglass laminate than those of the carbon fibre one. This outcome is because of the better adhesion between the fibreglass core and carbon fibre skins compared to the carbon fibre core and carbon fibre skin. So a partial separation between core and skins in the structure members of carbon core has occurred earlier and thus the sandwich members underwent early buckling. Buckling reduced the capability for load resistance. On the other hand, the least value of stiffness is for Nomex-honeycomb core sample (16.65 KN/mm) which mainly refers to the low properties of such core material.

Figure 4 Stiffness values of sandwich structure members with carbon facings and different core type (see online version for colours)



4.4 Ultimate compression force

The results of ultimate compression force are plotted in Figure 5. The figure exhibits a significant increase in the ultimate force under compression at the corrugated-core samples. The carbon fibre corrugated-core samples with the highest core mechanical properties manifest the biggest magnitude of the ultimate force which is equals to 21,955 N. On the other hand, the least value of crushing force is for the specimens of Nomex honeycomb-cores (14,304 N) which attributes to the low mechanical properties of the core. Although the Kevlar material has high mechanical properties but the geometry of the core and the bonded surface area between the core and skin facings play an important role in carrying load mechanism. The bonded surface between the honeycomb structure and the skins is often less than that of the corrugated shape for the same sandwich panel sizes.

Figure 5 Ultimate compression force carried by sandwich structure members with carbon facings and different core type (see online version for colours)

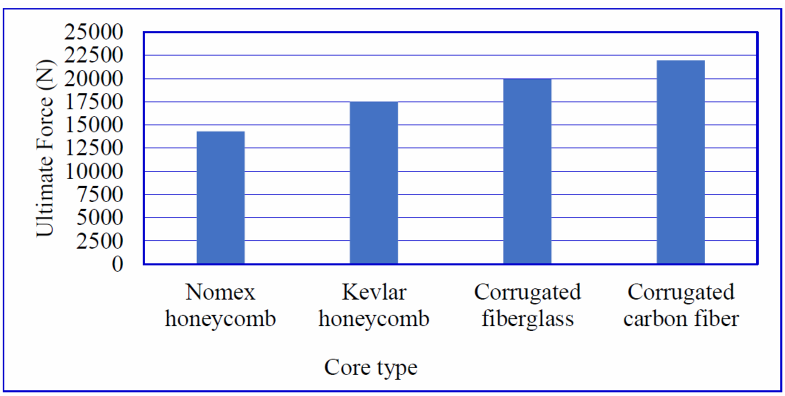
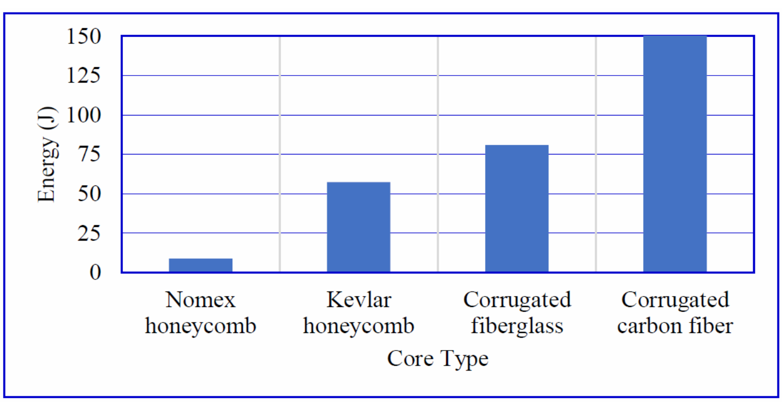


Figure 6 Amount of energy absorbed by sandwich structure members with carbon facings and different core type (see online version for colours)



4.5 Energy and compression capacity

The most promising results arises from the current investigation are the energy values absorbed by the corrugated-core samples. The values of energy were determined by estimating the area under the force-displacement curves using Matlab 16 software. The results are graphed in Figure 6. The figure obviously demonstrates so much energy absorbed in the corrugated-core samples which is so many times of that of the honeycomb-core samples'. The corrugated fibreglass-core sample has absorbed about nine times of the energy absorbed by the Nomex honeycomb-core member (Table 3). Moreover, according to Table 3, the carbon fibre corrugated-core specimen absorbed 165 J which is more than 18 times of the energy of the Nomex honeycomb-core sample's (8.76 J). The splendid result of the carbon fibre corrugated-core members is due to its ability to withstand the ultimate load for a very long displacement without suffering abrupt failing by the test ending (Figure 3). This outcome is mainly attributed to the high mechanical properties of the core material in addition to the geometry features of the corrugation core. On the other hand, when comparing strong material like carbon fibre has a corrugation core profile to another strong Kevlar one in the form of the honeycomb, the carbon fibre sample has almost three times the energy of the Kevlar samples (50.37 J).

4.6 Specific properties to the weight ratio

Comparing between the alternatives are based on the specific properties-to-weight ratio. The tested specimens are having sizes with small difference values but due to the big difference in core material properties and geometries as well, their weights are different. According to Table 3, the weight of the samples are 10, 10, 14 and 13 gm for Nomex honeycomb-core, Kevlar honeycomb-core, fibreglass corrugated-core and carbon fibre corrugated-core sample, respectively. Figures 7, 8 and 9 display the specific mechanical properties results; for stiffness, ultimate force, and energy, respectively. In the linear stage the sensitivity of corrugated-core samples to the debonding initiation between the skin and the core is clear. This is observed through and verified by the results of Figure 4. It was observed that the displacement value increased under low load values during early separation between the corrugated carbon fibre-core and the skins which lead to low stiffness value. On the contrary, the first separation between the corrugated fibreglass-core and the skins started later, as expected. This is due to the strength of the adhesion and stronger bond between the fibreglass-core and the carbon fibre skins. On the other hand, the honeycomb-core with its more amount of stuff exhibited less sensitivity to the debonding beginning. Thus the specific stiffness values-to-weight ratio are better for the honeycomb core structure than those of the corrugated core members. However, the highest value is for the Kevlar honeycomb-core which is equal to 1.8 (KN/mm)/gm. On the other hand, the nonlinear stage is important in sandwich structure – both ultimate compression force and absorbed energy could be estimated from this stage. Regarding the ultimate force sustained under the compression, it is obvious from Figure 8 that the highest values are for the corrugation-cores. They are 2.19 and 1.99 (KN/gm) for the carbon fibre corrugated-core sample and the fibreglass corrugated-core counterpart, respectively. While small specific force magnitudes were recorded for the honeycomb-core ones', 1.75 and 1.43 (KN/gm) for Kevlar and Nomex-core samples. Concerning the specific energy, as in Figure 9, the corrugated-core samples have extremely high values compared to the traditional cellular honeycomb-core types. Corrugated carbon fibre-core sandwich samples has too high a value (12.22 J/gm) which equals about 14 times that of Nomex honeycomb-core and about twice of both of the Kevlar honeycomb-core and corrugated fibreglass-core samples' (Table 3). These results in the nonlinear-stage of compression curves demonstrate that the corrugated-core samples with low and high core mechanical properties are having higher specific properties when compared to the honeycomb-core samples. The excellent properties of the carbon fibre corrugation match well with Zhou et al. (2016) who concluded that the carbon fibre reinforced corrugated structures offered superior compressive properties to its glass-based counterpart. On the other hand, when the honeycomb-core material has high mechanical properties, it is comparable to the corrugated-core material with low properties, as is the case with the Kevlar honeycomb and corrugated fibreglass. When the core material has high properties and takes the corrugation profile, the honeycomb-core structure is not comparable to the corrugation-core members with such extremely high specific properties.

Figure 7 Specific stiffness to weight ratio of sandwich structure members with carbon facings and different core type (see online version for colours)

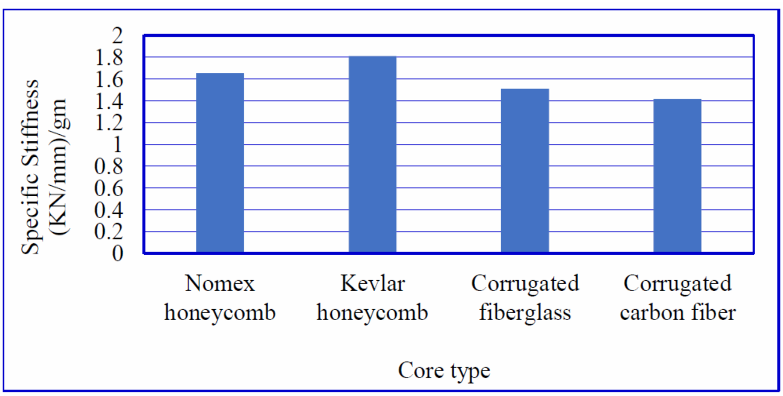


Figure 8 Specific ultimate compression force to weight ratio of sandwich structure members with carbon facings and different core type (see online version for colours)

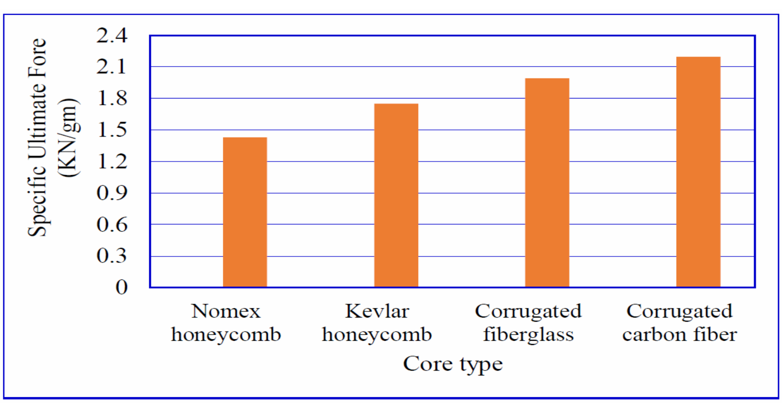
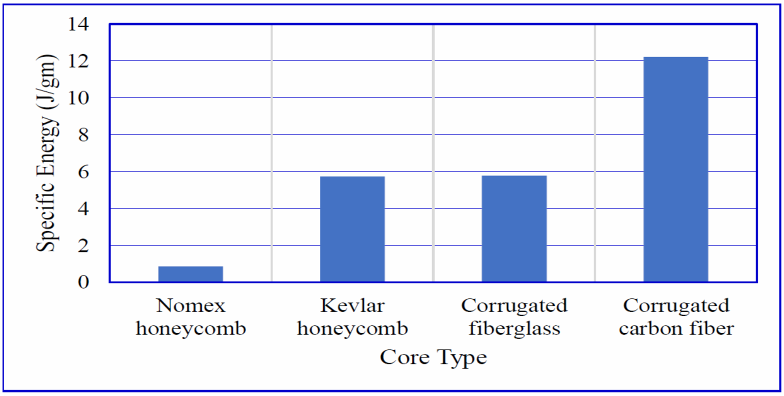


Figure 9 Specific energy to weight ratio of sandwich structure members with carbon facings and different core type (see online version for colours)



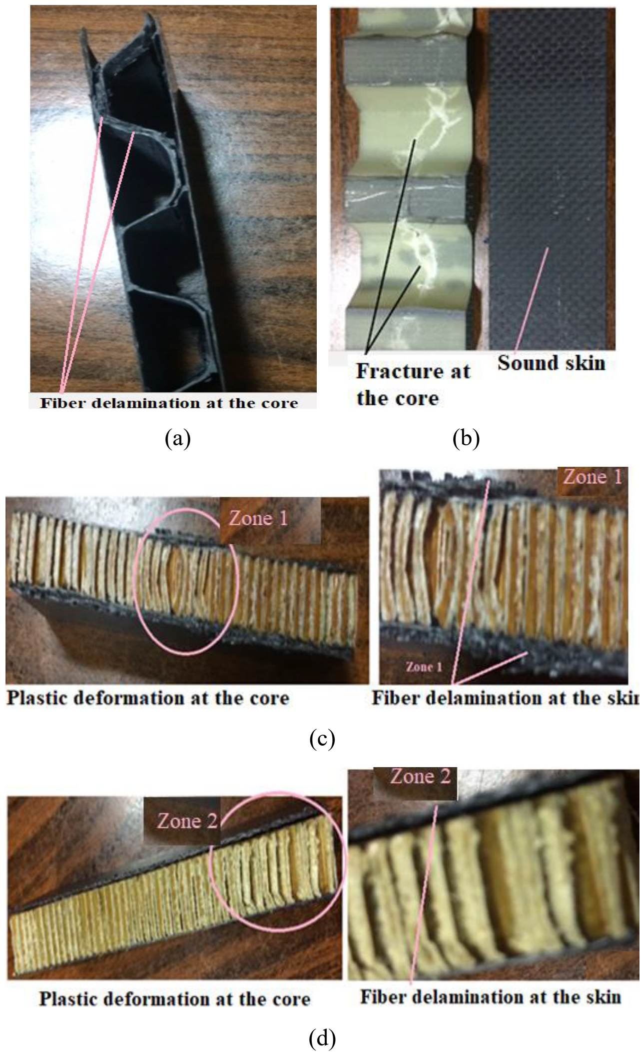
4.7 Fracture mechanism

There is a variation in the fracture mechanisms in different sandwich structure types. The carbon fibre corrugated-core sample components suffer not so much damage (debonding between the core and the skins with a small damage in the core's upper and lower ends due to fibre delamination [Figure 10(a)].

The fibreglass corrugated-core sample [Figure 10(b)] exhibits sound carbon fibre skin facings after testing and a crack in the middle plane of the fibreglass core. The fractured core refers to the lower mechanical properties of the fibreglass composite than those of the carbon fibre one. The nature of fracture modes are clearly interpreted with the results graphed in Figure 3 and also could be explained by the energy values listed in Table 3. Figure 3 indicates a high resistance under a high value of force with a very long displacement for the carbon fibre corrugated-core sample. While a moderate resistance is for the fibreglass-core sample under a high load but with a shorter displacement and with a significant core damage. It can be concluded that the sandwich members would fail in buckling prior to failing in strength in the corrugation-core samples, this outcome agrees with Pineda et al. (2014). On the contrary, the damage in the sandwich structure members of the honeycomb-cores has occurred at the ends of the skin facings of the carbon fibre in the form of fibres delamination which is severe in the Nomex core.

This fracture mode proves that the honeycomb core carries little load due to their less properties and perhaps due to the honeycomb nature, while most of the compression capacity has been carried by the skins in such honeycomb-core types [Figures 10(c) and 10(d)]. On the other hand, the absorbed energy results are matching well with the outcome of the fracture mechanisms. The highest value (165 J) was for the carbon fibre corrugated-core. The fibreglass corrugated-core samples has a 80.9 J energy value followed with 57.37 J for the Kevlar honeycomb-core and the least value (8.78 J) was for the Nomex honeycomb-core.

Figure 10 Fractured samples after testing, (a) carbon fibre corrugated-core (b) fibreglass corrugated-core (c) Nomex honeycomb-core (d) Kevlar honeycomb-core (see online version for colours)



5 Conclusions

Comparison between alternatives based on the specific properties to weight ratio is an important criterion in selecting materials for design. The following outcomes are based on the specific properties' values:

1. By the end of the linear stage of the compression test the sandwich panel suffers instability after first debonding occurrence between the core and skins. In particular, the corrugated-core samples with less core stuff (thin core sheet) suffered high sensitivity to the debonding initiation. The specific stiffness-to-weight ratio appears

to be supported by the amount of stuff material (core) in addition to the mechanical properties of the core. Thus, the specific stiffness value has the maximum value for samples of Kevlar honeycomb-core due to high mechanical properties of the Kevlar material and due to its higher amount of material than that of corrugated ones and hence less crack sensitivity.

2 Nonlinear stage is very essential in sandwich structure applications under compression load. The withstanding of sandwich panel under the load mainly depends on the mechanical properties of the structure components as well as the bonding strength between the core and the facings in addition to the core geometry. Thus, after the partial debonding between structure components, the corrugated-core samples so far resist high values of load and absorb a very large energy before entire failure due to their high mechanical properties and the corrugation features as well.

3 The higher specific mechanical properties to weight ratio in the nonlinear stage are for the corrugation core type. In this concern, the carbon fibre corrugated-core sandwich samples has extremely high values, particularly the specific energy which is more than double of that of corrugated fibreglass-core ones and equal about 13 times that of Nomex honeycomb-core. More over the corrugated carbon fibre-core members did not suffer abrupt decrease in ultimate load till the test ending.

4 Although the Kevlar material has high mechanical properties, the geometry of the core and the bonded surface area between the core and skin facings play an important role in carrying load mechanism. The bonded surface between the honeycomb structure and the skins is often less than that of the corrugated shape for the same sandwich panel sizes.

5 The fracture mechanisms of different kind of sandwich structures indicate that the corrugated core carried most of the load as the skin facings did not undergo a plastic deformation. On the contrary, the skin facings underwent a fibre delamination and plastic deformation which proves that most of the load has been carried by the skins.

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