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Springer

Journal of Mechanical Science and Technology 35 (10) 2021

Original Article
DOI 10.1007/s12206-021-0909-1

Keywords:
· Design optimization
· Stiffness
· Composite structure
· Failure modes

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Citation:
Elzayady, N., Elghandour, E. (2021). Design optimization to improve the performance of the aircraft composite structures. Journal of Mechanical Science and Technology 35 (10) (2021) 4381~4388.
http://doi.org/10.1007/s12206-021-0909-1

Received October 13th, 2020
Revised May 6th, 2021
Accepted June 24th, 2021

† Recommended by Editor Chongdu Cho

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Design optimization to improve the performance of the aircraft composite structures

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Abstract Specific properties such as the stiffness and strength-to-weight ratio of the sandwich structure have a great impact on aircraft performance. The current research introduces a design methodology to replace the honeycomb core. Four configurations of structure members with a corrugated core were utilized. The skin sheets were made from pre-preg carbon fiber composite lamina and the corrugated cores were made from the same composite with three different thicknesses in addition to a corrugated core of pre-preg fiberglass lamina. Also, other configurations were assembled boxes from the separate structure members. All configurations were subjected to edgewise compression testing. The failure modes combined with the experimental results demonstrate the importance of design optimization in developing the sandwich structure properties. Changing from open-contour structures to closed-contour ones, utilizing different core materials with good wettability, and controlling the load direction enhance the compression capacity-to-weight ratio of the structural composites and improve their fracture resistance.

1. Introduction

The use of optimized lightweight structures is very common in the aerospace field [1]. Weight minimization is a crucial design element in aerospace applications and is the main incentive for enhancing the design of sandwich construction [2]. The geometry of the core should allow the minimization of the amount of material needed to reach the least weight and minimum cost [3]. The construction of sandwich panels can improve characteristics for specific types of loading [4]. The sandwich panel consists of low-density core material as a sandwich between two sheets with a high modulus of elasticity. The sheets and the core are bonded to each other to transfer the forces between the components [5, 6]. Insufficient support to the face sheets when the core undergoes a compression load can lead to different kinds of failures; face sheet buckling, face sheet/core delamination, and face sheet yielding [6]. The mode of failure is the onset of elastic or plastic buckling, particularly for core configurations with a low relative density [7]. More research is required to develop sustainable materials for use in aerospace and automotive structure applications. The flooring of aerospace and marine vessels with sandwich panels having high structural rigidity is an essential demand [6, 8]. The increase in the second moment of area and hence increasing the moment of inertia of the panel is possible by increasing the core thickness between the face sheets. Regarding the interior components, materials play an important role in product differentiation [9]. Despite a large number of studies available in the literature on the mechanical behavior of sandwich panels, the mechanisms leading to buckling deformations and buckles propagation through the structure are not well-understood [10]. Merging the flat laminates composite (skins) with corrugated cores from laminate composite allows obtaining high stiffness-weight ratios and eliminates the problems arising due to properties variation between the core and skin. The trapezoidal corrugated cross-section is adopted by some studies [4, 11, 12].

The trapezoidal shape is proved to possess the highest efficiency compared to square, triangle, and half-circle corrugated shapes. Some investigations studied the sandwich panels under the edgewise compression test [1, 4, 13]. In the current study, the core of the sandwich structure is manufactured from corrugated composite laminates. The corrugated shape has been suggested to create a more bonded area between the skin face and the core. However, one of the weaknesses of the honeycomb sandwich composite is the small joined area between the core and skins. In the current study, the dimensions of the corrugated ligament are large enough to the extent that their large open cells could be utilized as channels for many purposes. Furthermore, they are efficient for improving the ventilation to overcome the moisture accumulation associated with using the honeycomb core. The current investigation aims to develop structure members with lighter core and higher specific properties; stiffness-weight and ultimate force-weight ratios. These structural members were designed to be utilized as new wide-open cell-core members for sandwiching applications by locating and ordering them in a certain direction. The maximum compressive capability of the structural members was measured. To take the advantage of the high second moment and high inertia of the corrugation, the load was applied in the longitudinal direction of the corrugation. Thus, the edgewise compression test was adopted. The current research takes into account the linearity as well as the material nonlinearity behavior under the load. Specimens with different core thicknesses, different designs, and different materials were investigated.

2. Experimental work

2.1 Sample preparation

Many sheets of TC-250 prepreg woven carbon fiber composites were cut for the manufacturing processes. Skin faces were composed of two plies for all configurations while the core corrugated sheets were prepared as; one ply for the first case, two plies for the second case, three plies for the third case, and the fourth one is a hybrid-composite with carbon fiber skins and a fiberglass core with one ply. The pre-preg plies were staked to manufacture the skin and core using a vacuum technique. The ply thickness was 0.25 mm and 0.5 mm for carbon fiber and fiberglass, respectively. The core sheet was formed first onto an aluminum corrugated mold with a trapezoidal cross-section of 63° and 13 mm height. Then a vacuum bag technique was applied for both the core and the skins (Fig. 1). The curing process was carried out at 130 °C for two hours inside the autoclave. An example of the cooked corrugations is presented in Fig. 2. The corrugations were inserted between the upper and lower skin sheets and bonded with epoxy resin. The curing of the epoxy resin occurred at room temperature (30 °C) for 24 hours. The required number of test samples was cut with a rectangular cross-section of 160×40 mm. The cutting pass was perpendicular to the corrugation direction (Fig. 3).

The height of the samples was 14 mm. This way of cutting was adopted to prepare specimens for the edgewise compression test. The cut samples relative to the load direction were ordered as in Fig. 4. The overall specimen's size and outer rectangular dimensions were the same for the first four separate member configurations ((160×40×14) mm). In addition, four configurations of a closed-contour were prepared for heavy-duty practical applications. In these closed-contour cases, four kinds of boxes were assembled from the separate members of the first configuration group.

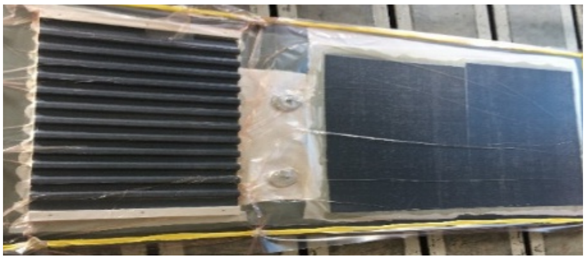


Fig. 1. Manufacturing processes with vacuum bag technique.

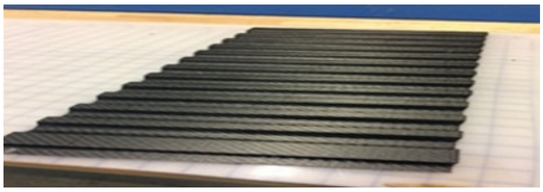


Fig. 2. A cooked corrugated core.

Fig. 3. Cutting processes after core sandwiching.

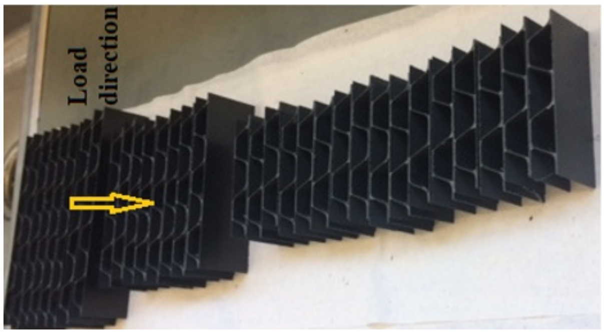


Fig. 4. Finished separate composite members.

2.2 Boxes preparation

In the structural materials field, structure members testing at laboratory scale does not deliver the exact behavior of those of the real scale in the practical applications. Constructing rectan-

Table 1. Specifications of different configurations.

Mat.	Outer size (cm^3)	W (gm)	ρ (kg/m^3)
	Individual samples		
1-ply C	90	12	133
2-ply C	90	14	155
3-ply C	90	18	200
1-ply glass	90	19	210
	Boxes		
1-ply C	171360	48	0.280
2-ply C	171360	56	0.326
3-ply C	171360	72	0.420
1-ply glass	171360	76	0.435

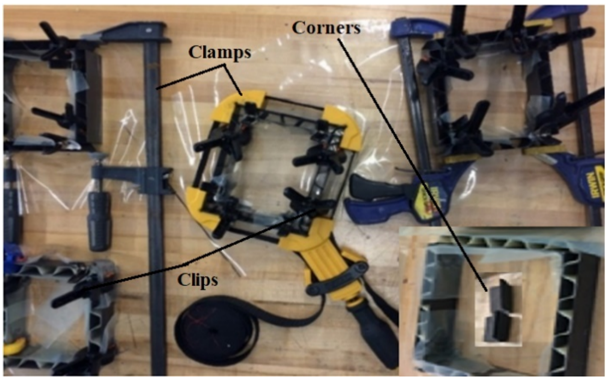


Fig. 5. Boxes assembling.

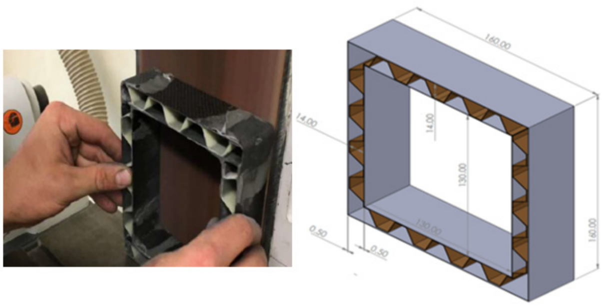
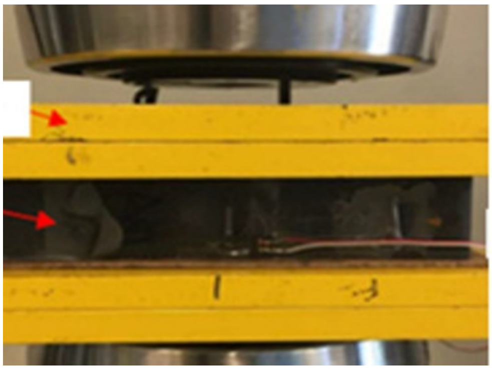


Fig. 6. Sanding of surfaces and final dimensions of the box.

gular boxes from the four-ligament samples were suggested as practical units for building aircraft interior for heavy-duty applications. An example of these applications is the flooring area. Assembling these boxes was made with the aid of clamping and clips to keep their shapes right after curing. The box sides were welded to each other by small corners using epoxy resin as shown in Fig. 5. The curing process took two days at room temperature. The boxes were subjected to a sanding process using a belt sander to obtain even surfaces and accurate final dimensions (Fig. 6). The specifications of the individual samples, as well as the boxes', are listed in Table 1.



(a)

(b)

Fig. 7. Compression testing: (a) Instron LD50; (b) Satec M/c.

2.3 Test procedures of individual samples

The sample edges were even and had parallel surfaces after finishing. These samples were tested under a compression load in the edgewise type, the load direction is shown in Fig. 3. Two flat thick plates were placed above and under the specimen during the test to ensure even load distribution over the cross-section during the testing. A universal testing machine (LD50 Instron) with a load capacity of about 90 KN was used for the testing process (Fig. 7(a)). The results were recorded on an attached PC.

2.4 Test procedures of boxes

The first round of testing was conducted using the LD50 machine as in Fig. 7(a). The objective of the first round of testing was to focus on the linear elastic region. Two trials were conducted for each box. In the third round, failure testing was conducted on a much stronger compression test machine. To accommodate this need, testing was conducted using a Satec machine (Fig. 7(b)) that has 1800 KN capacity.

3. Results and discussion

3.1 Properties of different configurations

The results of the experimental work of the crushing force and stiffness are summarized and graphed in Figs. 8 and 9 for the individual members and the boxes, respectively, to facilitate

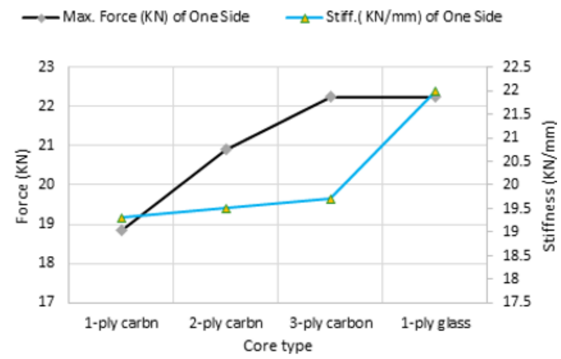


Fig. 8. The properties of individual members.

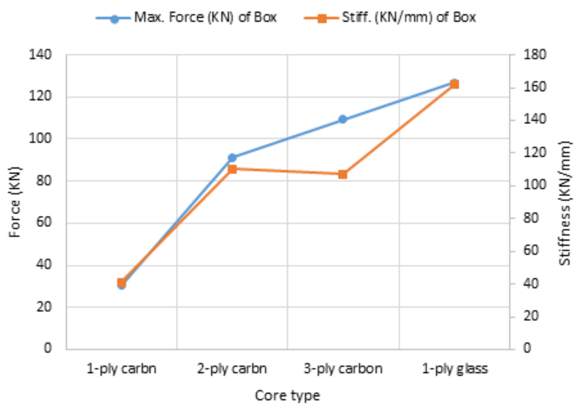


Fig. 9. The properties of boxes.

the comparisons between the alternative designs. Also, the compression behaviors of different configurations are plotted in Figs. 10(a) and (b). The results of the individual samples are based on testing a cross-section of (160×14 mm). The core specifications greatly affected the compression behavior (Fig. 10(a)). In the very thin-core condition (1-ply carbon), quick failure and the least energy were encountered (least force and shortest displacement). Thus, the 1-ply carbon was excluded from the comparisons. The 2-ply and 3-ply carbon cores exhibited high compression capacity (high load and long displacement). Concerning the 1-ply fiberglass core sample, it demonstrated a high crushing force (22.4 KN) which was comparable to that of the 3-ply carbon. Nonetheless, the 1-ply fiberglass underwent short displacement before fracture compared to the 2-ply & 3-ply carbon ones (Fig. 10(a)).

A compatible trend in other individual samples (having less size & less cross-section dimension ratio (L/W)) was also reported by Elghandour et al. [14]. Whereas the displacement of the glass corrugation and the carbon one was 6 mm & 12 mm, respectively. These results could be compared by the ones in the current work as in Fig. 10(a). On the other hand, their work displayed the crushing force carried by the glass sample was 20 KN which is slightly less than that supported by the carbon one (21.9 KN). However, the comparison between alternatives is based on the specific properties-to-weight ratio which will be discussed in Sec. 3.2.

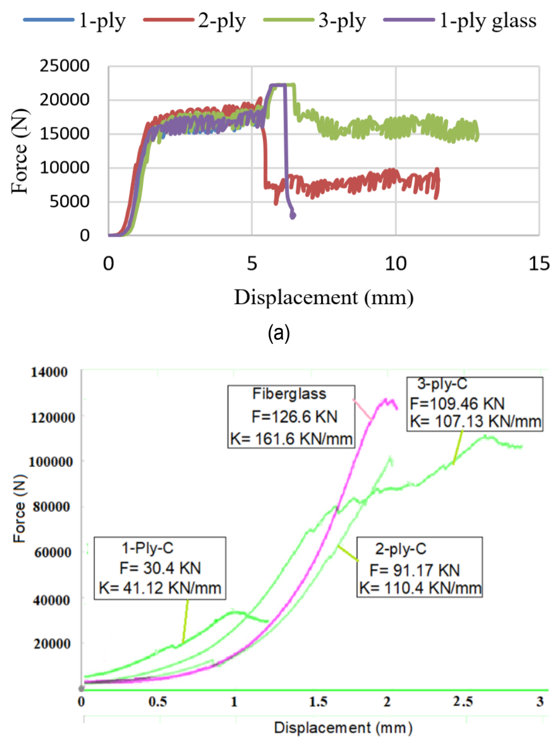


Fig. 10. Force-displacement curves of (a) samples; (b) boxes.

Regarding the curve behavior of the boxes in the current work, Fig. 10(b) shows very short displacements for all box configurations compared to the separate samples (Fig. 10(a)). A 3 mm displacement took place for the 3-ply carbon box which is 25 % of that of the individual member (12 mm). This is probably due to the restrictions on the four assembled members in the form of a closed-contour (box). This outcome manifests the importance of the material design.

Similarly, the 1-ply fiberglass core box demonstrated the highest crushing force in all box configurations while it underwent short displacement before fracture compared to the 3-ply carbon. This behavior was similar to the 2-ply carbon's one.

However, the results of the current investigation demonstrated strong bonding between the glass core and carbon skin, this led to supporting high load value before crushing. On the other hand, less-strength core material (fiberglass) experienced a severe fracture after smaller displacement took place.

Other researchers Elhabak et al. [15] and Vlot [16] concluded that strong bonding between the fiberglass/fiber-glass composite laminates exhibited, as well as, between the glass & metallic aluminum sheets in the case of the fiber metallic laminates [15]. They referred that the strong bonding is due to the good wettability of fiberglass composites. Also, Vlot [16] demonstrated that there is poor wettability between the carbon fiber/carbon fiber composite laminates.

The results of the current work are in agreement with the fracture behavior of the examined samples, which will be discussed in the fracture mechanism section. Regarding the boxes, a marked increase in the structural properties in closed-contour members (boxes) has been obtained. The box was assembled from four sides but did not carry loads as much as the total load of the four individual samples. The box carried 126.6 KN compression force in the case of the fiberglass core while the total load supported by the same number of individual samples was 89.6 KN (22.4×4). Thus, design optimization is an essential element in aircraft manufacturing.

3.2 Properties-to-weight ratio

It is essential to estimate the specific properties of the structural members to be able to properly compare alternatives. Discussing properties relative to their weight ratio is possible with the aid of Fig. 11. Despite the 1-py carbon core exhibiting the highest specific properties-to-the weight ratio (Fig. 11(a)), the specimens of 2-ply carbon core are recommended when building the interiors with separate sandwich members. This is to avoid the instability of those thin-core members (1-ply carbon) that undergoes a short displacement, and a very low absorbed energy before fracture (Fig. 10(a)). Concerning the 3-ply carbon box, Fig. 11(b) shows that this box possessed high weight relative to its compression values (low specific properties-to-weight ratio). Among the box configurations, the fiberglass-core box with 1.7 KN/gm & 2.18 (KN/mm)/gm had slightly higher specific properties but still is comparable to the 2-ply carbon box. However, both alternatives of closed-contour configurations; (2-ply carbon box & 1-ply glass box) with the same core thickness (0.5 mm), are heavy-duty structures under compression loads in aerospace applications. Besides the higher compression capacity of fiberglass, it is cheaper than the carbon fiber one.

Other studies on the sandwich structures have been carried out [14, 17]. Elzayady et al. [17] concluded an opposite impact on the stability under loads when the cross-section dimensions' ratio (L/W) is high. This is regardless of similar magnitudes of the cross-section area.

A comparison study between different core materials by Elghandour et al. [14] showed that carbon and glass corrugation core samples (2.19 & 2 KN/gm) exhibited better specific compression properties-to-weight ratio than those of the honeycomb core (1.4 KN/gm). The study of Elghandour et al. [14] also focused on the plastic stage of the compression and showed that energy absorbed before the fracture was extremely high; 12 J/gm for the carbon corrugation core & 5.7 J/gm for the glass corrugation one while the honeycomb-core member had 0.85 J/gm of absorbed energy, as it experienced the least displacement before fracture. On the other hand, the specific compression values-to-weight ratio of the corrugation-core samples by Elghandour et al. [14] were slightly higher compared to those tested in the current work. Thus, it confirms the less stability under the load when the cross-sections have a higher dimensions ratio. Furthermore, the sandwich structures with 70-degree trapezoidal corrugation core were studied by Kazemahvazi et al. [18]. According to their study, the maximum specific load before the fracture was around 1 KN/gm for a carbon fiber corrugation-core sandwich.

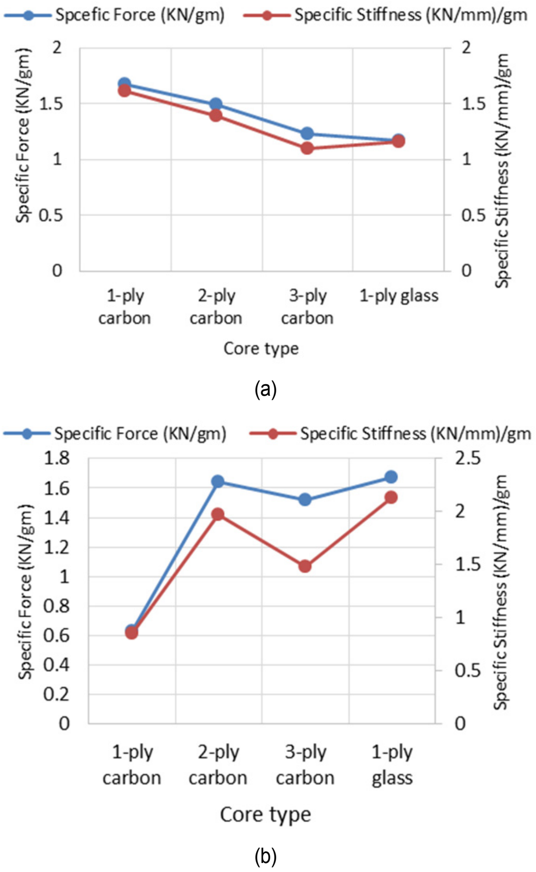


Fig. 11. Specific properties of (a) separate samples; (b) boxes.

However, the advantages of using a closed-contour sandwich (box) over the open-ends (separate) one, make the focus in the current work on the boxes' discussion. The compressive properties of the box were measured based on the overall box density. Their density ranged from 0.280-0.430 Kg/m^3, which is very low and suitable for aerospace applications. On the other hand, the density of the individual samples varied from 133-210 Kg/m^3. For all choices, separate or closed-contour structures, utilizing moderate thickness in the corrugation core (0.5 mm) introduce good compression capacity to their weight ratio which is suitable for the aircraft industry.

4. Fracture modes

4.1 Fracture modes of individual samples

When the specimens do not have complete adhesion between contact areas, this would cause a premature material failure as a result of the stress concentration on local debonded regions. It was observed that the fractured samples of 1-ply core often failed early due to elastic buckling and entire debonding between skin and core. This is without damage to the skin. Both skin and core of thin-core buckled samples after

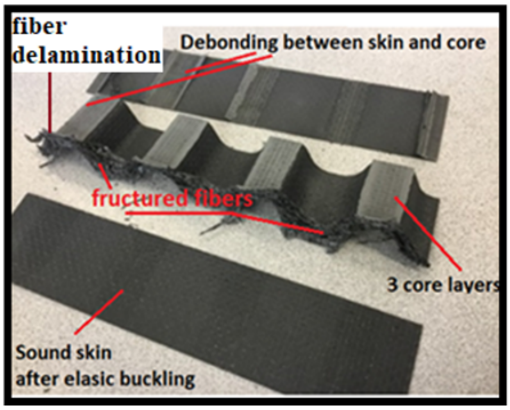


Fig. 12. Fractured 3-ply carbon fiber-core sample.

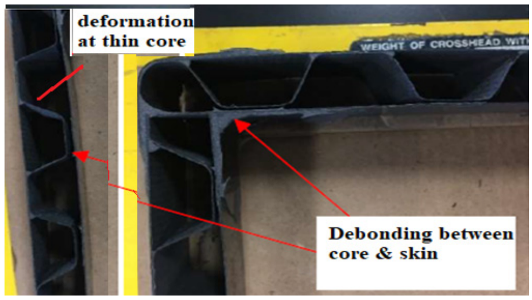
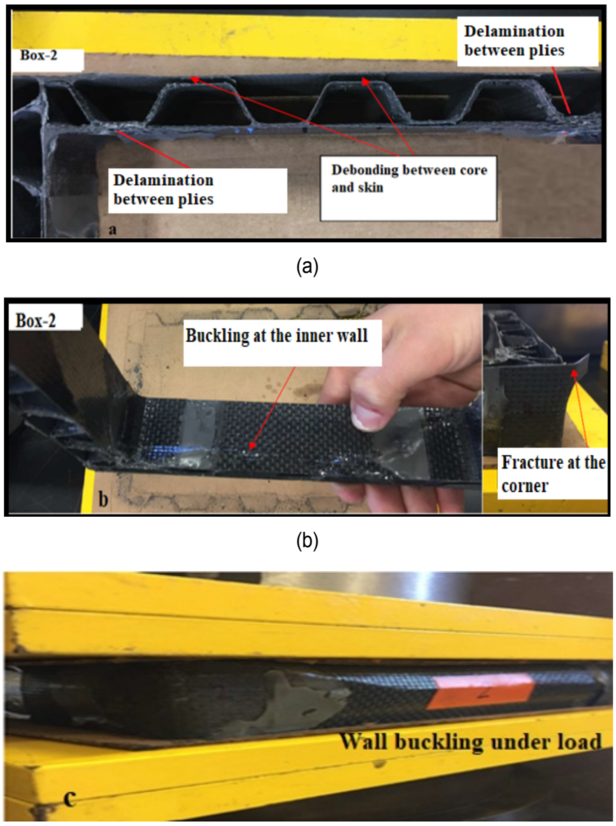


Fig. 13. Failure modes of 1-play carbon fiber-core box.



(a)

(b)

(c)

Fig. 14. Failure modes of 2-play carbon fiber-core box: (a) wall edges; (b) inner walls and corner; (c) outer walls.

debonding, almost return to their original shapes after releasing the load. On the other hand, other samples of the thicker corrugated core (2-ply or 3-ply core) underwent late debonding between skin and core besides the delamination and fracture of core fibers, and severe tear at the core edge as well (Fig. 12). As a result, samples of the 3-ply carbon-fiber core after partial delamination were able to withstand high load (15000 N) for an extended displacement (about 7 mm), started at 6 mm and ended at 13 mm on X-axis as in Fig. 10(a). In other words, regardless of the fracture's existence, the thick core samples still experienced more energy absorption in the plastic stage of testing. This result demonstrates the importance of the plastic region for these structures under compression.

Regarding the fiberglass-core samples, the fracture mode has been discussed before by Elzayady et al. [19]. The failure mode in Ref. [19] exhibited fracture at the mid-plane of the core which was perpendicular to the load direction, whilst the carbon skin plies underwent less delamination and their edges experienced less tearing (i.e., less energy absorbed) as shown in Fig. 10(a).

4.2 Fracture modes of boxes

4.2.1 Box-1 (1-ply carbon-fiber core)

During the experiment, the failures manifested loud cracking sounds. Examples of failure modes were early debonding between the skin and the thin core (elastic failure). The thin core suffered a little plastic deformation as exhibited in Fig. 13. The 1-ply carbon-fiber core box had a significantly small stiffness and small crushing force compared to the others (Fig. 10(b)). This was likely attributed to the lack of material amount in the core, and hence elastic failure followed by a buckling of the skin lamina were induced.

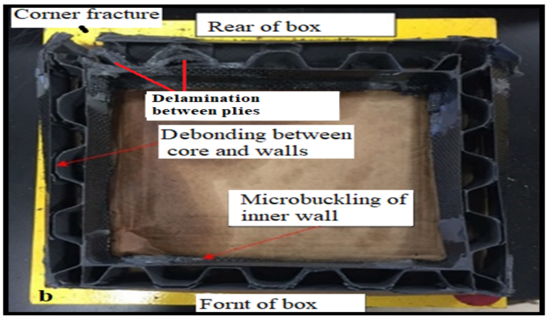
4.2.2 Box-2 (2-ply carbon-fiber core)

The failure modes in box-2 as in Fig. 14 were; debonding, buckling, core and skin delamination, and edge-tearing. Also, shear failure was encountered at the corner of box-2. It is demonstrated that the delay of debonding between the core and the skin resulted in this box configuration suffering more plastic deformation, and hence, it experienced high stiffness and carried more load. The failure mode of box-2 of moderate core thickness (0.5 mm of 2-ply) and then moderate weight, interprets its highest specific properties over the other carbon fiber-core boxes (Fig. 11(b)).

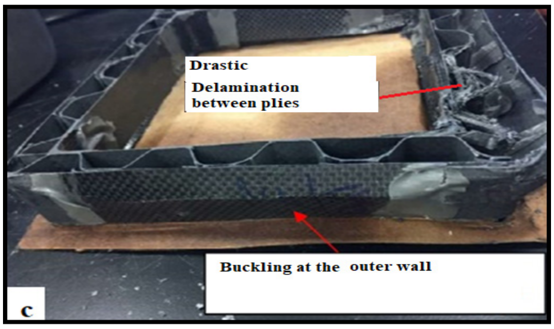
4.2.3 Box-3 (3-ply carbon-fiber core)

The failure of this box configuration seemed to be similar to that of the 2-ply core one. There was a fracture of the rear corners of the box due to the shear failure in the connecting epoxy (Fig. 15(a)). After the failure of the rear corners, as the force increased, the fracture of the remaining sides occurred, and

(a)



(b)



(c)

Fig. 15. Failure modes of 3-play carbon fiber-core box: (a) corner; (b) inner wall edges, and corner; (c) outer walls.

then buckling eventually developed in the inner and the outer walls (Figs. 15(b) and (c)). However, the failure modes of the 3-ply specimen exposed severe delamination between the plies and harsh damage at the edges of the core as well. This indicated that more delamination was associated with more plies in the core. Thus, so much absorbed energy has been dissipated in such a hard fracture at the core edge. The fracture mode of the 3-ply-carbon core boxes explains their high compression capacity, irrespective of their high weight. Hence, the fracture mechanism of this kind of box is in agreement with the results displayed in Fig. 10(b).

4.2.4 Box-4 (1-ply fiberglass core)

The failure modes of the 1-ply fiberglass core hybrid box were different than those of carbon fiber boxes as displayed in Fig. 16. Elastic buckling of the carbon skin has been observed during loading while micro-cracks were initiated in the core. The plastic deformation in the glass core, as well as fracture levels at the middle plane of the glass core, increased with higher loads. The examination of the fiberglass box proves strong bonding between the core and skin which explains the

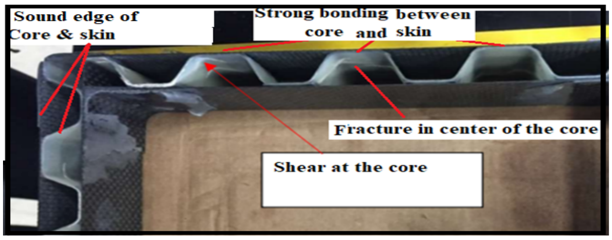


Fig. 16. Failure modes of the 1-ply fiberglass core box.

highest crushing force of this kind of boxes. Also, the fiberglass-core box exhibits excellent edge-tearing resistance at both the core and skin.

Finally, the failure modes combined with the experimental results of the current study demonstrate the importance of design optimization in developing the sandwich structure properties relative-to-the weight ratio. Comparing between the heavy-duty alternatives (2-ply carbon core and 1-ply glass core) is a material designer decision, whether high crushing force associated with glass or high absorbed energy associated with the carbon (very long displacement with high load) is needed before the fracture.

The carbon fiber composite laminates as corrugation cores with their high strength properties, still could not be utilized well. And their moment of inertia is disabled due to the early delamination between the core and skin surfaces (elastic failure), caused by the poor wettability of such composite.

5. Conclusions and future work

The corrugated-core structure members suggested in the current investigation could be utilized in aerospace applications as lightweight core webs or inserts and also, as unit cells for building large panels. The failure modes combined with the experimental results of the current study demonstrated the importance of design optimization in developing the sandwich structure properties. Changing from open-contour member to closed one (box), utilizing different core materials having good wettability (fiberglass lamina), and controlling the load direction (edgewise compression), enhance the specific properties of the compression-to-weight ratio of the structural composites.

Carbon/carbon composites possess high strength properties. Future research is needed to improve the wettability of carbon/carbon composites to overcome the early delamination between their surfaces. Thus, proper exploitation for sandwich structures having a corrugated core with such high moments of inertia could be achieved. Also, more investigations are necessary to study different material combinations for the corrugation core and flat skins to obtain lighter weight, less cost, and high-performance structural members.

Acknowledgments

All Mechanical Engineering Department Team (California Polytechnic State University, U.S.A.) are gratefully appreciated for their support and permission for manufacturing and testing the samples of the current investigation as a part of a large effort for enhancing the compressive capacity of sandwich structures.

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