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RESEARCH ARTICLE

Polymer COMPOSITES

Performance evaluation of composite sandwich structures with additively manufactured aluminum honeycomb cores with increased bonding surface area

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Abstract

Modern aerostructures, including wings and fuselages, increasingly feature sandwich structures due to their high-energy absorption, low weight, and high flexural stiffness. The face sheet of these sandwich structures are typically thin composite laminates with interior honeycombs made of Nomex or aluminum. Standard cores are structurally efficient, but their design cannot be varied throughout the structure. With additive manufacturing (AM) technology, these core geometries can be altered to meet the design requirements that are not met in standard honeycomb cores. This study used a modified aluminum honeycomb core, with increased surface area on the top and bottom, as the core material in sandwich panels. The modified honeycomb core was produced through the laser powder bed fusion method. The behavior of the modified sandwich composite panels was evaluated through three-point bend, edgewise compression, and impact tests, and their performance was compared to that of a conventional honeycomb core sandwich panel. The three-point bend test results indicated that the sandwich structure's ultimate shear strength improved by 12.6% with the modified honeycomb core. Additionally, the displacement at the failure of the structure increased by 11%. The edgewise compression tests showed that the ultimate edgewise compressive strength improved by 19.1% when using the modified core. The impact test results revealed that the peak force increased by 8% and the energy-absorbing capacity of the sandwich structure increased by 20% with the use of the modified honeycomb core.

KEYWORDS

additive manufacturing, carbon fiber, edgewise compression, honeycomb, impact test, sandwich structures, three-point bending

1 | INTRODUCTION

A sandwich structure is a type of composite material that consists of two thin and stiff outer layers (known as skins or faces) separated by a lightweight and less stiff core material. The skins provide most of the strength and stiffness of the structure, while the core provides the necessary resistance to compression and shear.[1] Sandwich structures are commonly used in various applications, such as aerospace engineering, marine engineering, construction, and sports equipment, due to their high strength-to-weight ratio and improved impact resistance.[2–6] Some popular types of sandwich structures include honeycomb, foam core, and balsa wood core. The irregular microstructure caused by its fabrication process limits the use of foam as a core material. The choice of core material and its properties are critical in determining the overall mechanical performance of the sandwich structure. Periodic hexagonal honeycomb structures are dominantly used in sandwich applications due to their specific stiffness and strength.[2,7] There are various factors that affect the performance of a sandwich structure like the material of the face sheet, the material of the core, the topology of the core, and the adhesion between the core and the face sheets.[8–11] Numerous studies have been conducted by researchers examining the behavior of various types of sandwich structures through both experimental methods and numerical simulations.[12–17] Traditional honeycombs have several limitations and problems that can arise in sandwich applications like moisture absorption, low compressive strength, and poor impact resistance. Traditional honeycombs are often manufactured using manual or semi-automated processes, which can be time-consuming and result in inconsistencies in the quality of the final product. These problems with traditional honeycombs have led researchers and engineers to explore alternative core materials and manufacturing methods for sandwich structures, including the use of additively manufactured cores. By addressing these limitations, it may be possible to improve the performance and reliability of sandwich structures for a variety of applications.

Additive manufacturing (AM) has revolutionized the way parts are manufactured by incorporating design freedom and material choice. Complex geometries and designs can be manufactured easily that are impossible to fabricate through conventional material processing technologies.[18] In AM, the 3D computer-aided design (CAD) is utilized to sequentially fabricate the part/product. Several researchers have used AM techniques to manufacture the core of the sandwich structures to improve the performance of the structure. Li et al. investigated the applications of polymer 3D-printed honeycomb cores in sandwich applications.[19] Pirouzfar et al. investigated the flexural properties of the 3D-printed aluminum core-based sandwich panels. It was stated that the horizontally printed patterns have better energy absorption with respect to the vertically printed core.[20] Dumitrescu et al. compared the conventional CFRP face sheet/aluminum core with the CFRP face sheet/3D aluminum core.[21] Madke et al. investigated the numerical analysis of the re-entrant aluminum core for the sandwich panels, and it was found that these can absorb about 49% more impact energy.[22] In the investigation by Dou et al., the aluminum core increased the energy absorption of the slotted beam made of polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) face sheets by about 507% under bending.[23] Schmitz et al. investigated on sandwich structures with 3D-printed polylactic acid honeycomb with poly (vinylidene fluoride) nanocomposites.[24] Jung et al. studied the drop weight impact behavior of the Ni/Al composites. The study revealed that using aluminum as the core material increases the impact strength by about 20 times.[25] Liu et al. studied the thickness effect of aluminum core for the impact energy of aluminum core and fiber metal laminate skins.[26] Wang et al. considered the effect of changing the density of aluminum core in the carbon fiber skin-aluminum core sandwich composites and stated that increasing the core density increased the strength and ultimate load-bearing capacity for the three-point bent test.[27] He et al. studied the effect of the cell wall thickness on the impact energy of the carbon fiber-reinforced sandwich composite with an aluminum honeycomb as the core material. It was concluded that the peak load and the initial stiffness increase with the increase in cell wall thickness.[28] Pandey et al. compared the performance of aluminum hybrid foam and bare foam structure. The author found that the hybrid core foam yielded 58% higher energy absorption while the bending stiffness was nine times greater with respect to that of the bare core foam.[29] Zhao et al. investigated the influence of the various specimen parameters on the energy absorption capacity of the aluminum cored-steel face sheet sandwich structures. It was found that increasing the core height has a significant effect on energy absorption, whereas increasing the face sheet thickness has little effect on energy absorption.[30] Fashanu et al. investigated the applications of triply periodic minimal surfaces fabricated through powder bed fusion process using stainless steel as core materials in sandwich applications.[31] There is very limited research data on the use of modified aluminum honeycomb cores in sandwich applications.

This study aims to design and evaluate the performance of a modified increased bonding surface area honeycomb to improve the performance of the sandwich structure. The designed honeycomb was additively manufactured through the powder bed fusion (L-PBF) process using the aluminum alloy A6061-RAM2. To evaluate the performance of the modified honeycomb, a traditional honeycomb was also designed and additively manufactured. Both the core geometries were used in the manufacturing of sandwich structures with carbon/epoxy face sheets through out-of-autoclave (OOA) process. The mechanical performance of honeycombs was characterized by three-point bend, edgewise compression, and impact tests.

2 | MATERIALS AND METHODS

2.1 | Modified honeycomb design

Traditional honeycombs are made up of a network of hexagonal structures with uniform wall thickness. These hexagonal structures are structurally efficient and provide the necessary load-carrying capacity for the structure in use. These traditional honeycombs when used in sandwich applications are joined by a face sheet on the top and bottom surface using an adhesive. The commercially available honeycomb structures that are made of Nomex and aluminum are manufactured through expansion——corrugation and extrusion process respectively. Though these structures provide good strength to weight ratio which is one of the most desirable properties for core materials in sandwich applications, they are accompanied by their set of demerits. Since these unit cells are very thin, they are prone to core crushing in compression and bending loads. Face sheet debonding is serious issue faced by this honeycomb cores as they have minimal surface contact with the facing material. The honeycomb structure derives its excellent strength to weight ratio, uniform stress distribution, and interlocking nature from the very hexagonal shape of the unit cell. Due to the nature of manufacturing process, the commercial honeycomb structures like Nomex and aluminum honeycombs are not perfectly hexagonal. They tend to be elongated and distorted compromising the very hexagonal nature of the unit cell and thereby the properties that are derived from the perfect hexagonal honeycomb structure. With AM perfect hexagonal honeycomb structures can be easily printed and we can easily make design changes that can address the issues in current commercial honeycombs like face sheet debonding. Face sheet delamination is one of the critical problems that is faced by honeycomb sandwich structures.[8,32] This delamination typically occurs due to a limited area of bonding between the core and the face sheet. With conventional manufacturing approaches this contact area between the core and face sheet cannot be increased. With AM technology, non-conventional designs can be printed efficiently. Taking this into consideration a modified honeycomb core was designed with an increased surface area on top and bottom that provided additional bonding area to the face sheet when used in sandwich applications. The design criteria for the modified honeycomb with increased bonding surface included the following factors:

2.1.1 | Bonding surface area

The primary design criterion for the modified honeycomb cores with increased bonding surface area is to maximize the available surface area for bonding with the face sheet. This was achieved by modifying the cell geometry of the honeycomb structure by including a facet in the design to increase the bonding area while maintaining the shape of the honeycomb.

2.1.2 | Weight

The other important design aspect was not to increase the weight of the modified honeycomb. This is achieved by optimizing the cell geometry to maximize the bonding surface area while minimizing the overall weight of the honeycomb core. Hence, a very minor facet was included that did not increase the weight of the structure drastically.

2.1.3 | Mechanical properties

The modified honeycomb core material should possess adequate mechanical properties to meet the required structural performance of the sandwich application. This includes properties such as compressive and shear strengths.

In this work, the bonding surface area of the honeycomb was increased by 24% by including an additional fillet in the top and bottom regions of the honeycomb structure to provide more bonding area to the face sheets. The difference in the weights of the traditional and the modified honeycombs was about 2.5%. The difference in the design of the traditional honeycomb and the modified honeycomb can be seen in Figure 1. The stereolithographic (STL) files for the honeycombs were designed using Solidworks commercial software. The wall thickness of the honeycombs was set to 1.75 mm and the relative density was set to 0.30 to print without any issues.

2.2 | Material

The core was additively manufactured using A6061-RAM2 alloy from Elementum 3D. This is a general-purpose alloy with a good combination of ductility, strength, and corrosion resistance. The alloy has a 2% ceramic content, due to Elementum 3D's reactive additive manufacturing (RAM) process, and was heat treated to T6 condition after L-PBF fabrication. The face sheets were made up of IM7/Cycom 5320-1 carbon/epoxy prepreg laminates from Cytec-Solvay Group. This prepreg system has an aerial weight of 145 g/m^3 with a 65% fiber content. This prepreg system was selected for face sheets due to its consistent mechanical properties in the OOA process.

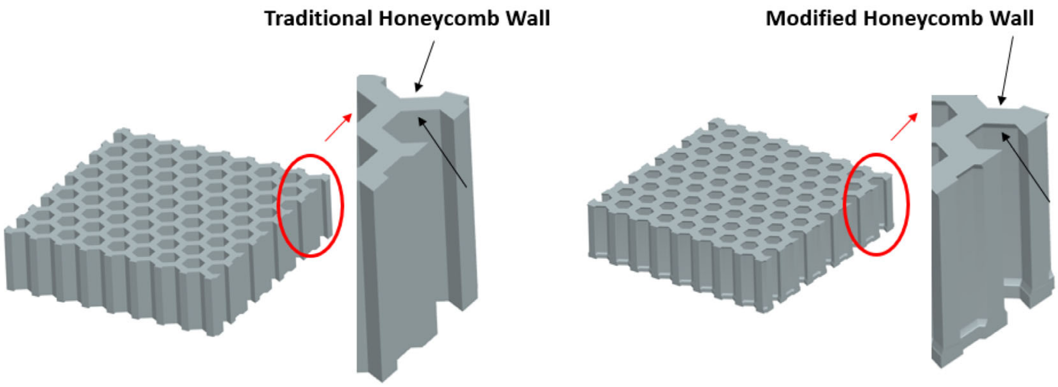


FIGURE 1 Difference in design between traditional honeycomb and modified honeycomb.

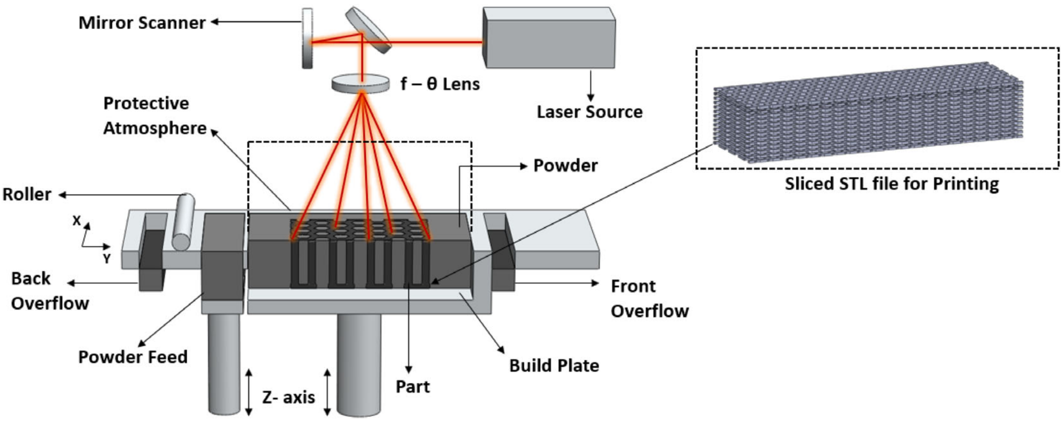


FIGURE 2 Schematic of a powder bed system.

2.3 | Manufacturing of aluminum honeycomb cores

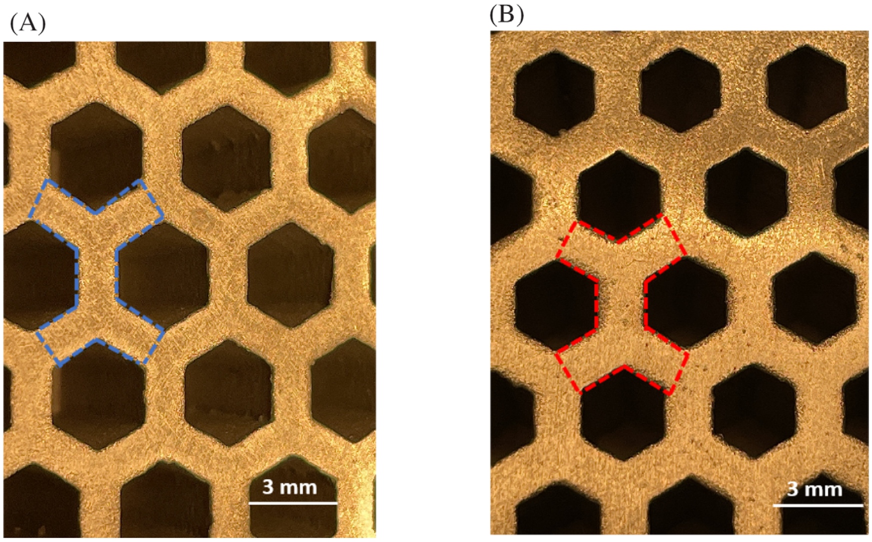
Due to the unconventional design of the honeycomb structure, AM was used to manufacture the cores in this study. The cores used in this study were manufactured using an EOS M280 L-PBF machine with A6061-RAM2 powder feed stock. The CAD models of the parts to be printed are loaded on the machines through a STL file. The L-PBF process generates a near-fully dense part from these STL files. The STL file is first sliced into several individual layers depending on the complexity of the parts to be printed. In a typical powder bed system, a cloud of feed stock material is deposited on the build plate with a hopper. The deposited material is evenly spread across the build plate with a recoater to achieve a uniform layer thickness. This uniformly spread powder bed is selectively scanned by a layer to melt and fuse the powder particles in the initial layer. After the successful completion of the first layer, a second layer of powder is laid on the previously melted layer and this process is repeated. This process is stopped after the desired part is completely printed. The excess powder is removed from the printed part and any necessary post processing can be performed depending on the application. A schematic of a typical powder bed system is shown in the Figure 2. The STL files.

After the cores were manufactured, they were removed from the build plate and finished to obtain the exact dimensions as required for the respective ASTM standards. In this study, two array sizes of honeycomb cores were manufactured, 52 × 52 × 14 mm and 130 × 39 × 14 mm to perform three-point bend, edgewise, and impact tests. The manufactured cores were inspected to check the relative density of the printed material. Figure 3 shows the printed traditional honeycomb core and modified honeycomb core. The relative density ρ^* of the honeycomb structures was calculated from the Equations (1) and (2) and are given by.

$$\rho^* = \frac{\rho_{\text{honeycomb}}}{\rho_{\text{solid}}} \tag{1}$$

where $\rho_{\text{honeycomb}}$ is the density of the honeycomb structure, and ρ_{solid} is the density of the material.

FIGURE 3 Additively manufactured. (A) Traditional honeycomb. (B) Modified honeycomb with increased surface area.



$$\rho_{\text{honeycomb}} = \frac{m_{\text{honeycomb}}}{V_{\text{solid}}} \tag{2}$$

where $m_{\text{honeycomb}}$ is the mass of the honeycomb and V_{solid} is the volume (assuming the entire volume is solid).

The calculated relative densities are tabulated in Table 1. The measured relative densities of the printed honeycomb structures are higher than the original design values due to the thin-walled nature of the honeycomb structure. Printability of the thin-walled structures is still a limitation for many L-PBF machines. The wall thickness in our design was set to 1.75 mm which was the minimum thickness the machine could print without excessive warpage and defects after the manufacturing. Powder bed fusion involves joining the metal powder using the laser energy into the desired shape. If these sintering temperatures are too high in the powder bed, it may result in excessive relative densities of the final printed part. Metal spatter is one of the other factors that contributes to the increased relative density of additively manufactured aluminum parts. Due to the rapid nature of the process, this metal spatter will get into the thin walls and increase the surface roughness and increase the relative density of the printed part. The increase in relative density values in the printed specimens can be attributed to the surface roughness of the printed structures. The table also shows a difference in relative density variation between traditional and modified honeycomb structures. Due to the thin fillet region in the modified honeycomb structure, the relative density variation in these specimens is higher than that of the traditional honeycombs. Closer inspection of the printed specimens revealed that the 52 × 52 × 14 array specimens had a relatively low variation in the relative density values compared to that of 130 × 39 × 14 array specimens which were geometrically larger specimens to print.

TABLE 1 Comparison between target and printed relative densities.

Core type	Set relative density	Measured relative density	Deviation
Traditional	0.30	0.4812 ± 0.0062	+37.5%
Modified	0.30	0.5058 ± 0.0044	+40%

2.4 | Manufacturing of face sheets and sandwich specimens

Face sheets used in this study were manufactured from of IM7/Cycom 5320–1 carbon/epoxy prepreg system. The face sheets were $[0°/90°]_{2s}$ cross-ply panels measuring 304.8 mm × 304.8 mm. The face sheets were manufactured using the OOA method following the manufacturer's recommended cure cycle. The thickness of the face sheets after curing was about 1.24 mm. The manufactured face sheets were cut to the dimensions using a diamond wet saw to manufacture the sandwich specimens. The face sheets were bonded to the core by using an FM-309-1 adhesive system from the Solvay group. This adhesive system provides a unique combination of high toughness, high glass transition temperature, and improved performance at elevated temperatures. This adhesive system is highly compatible with the epoxy-based prepreg systems. The face sheets, adhesive, and the core were bonded to form sandwich specimens using the manufacturer's recommended cure cycle using the OOA procedure. The specimens were cured under vacuum at 176°C for 2 h. The schematic of sandwich specimen manufacturing through the OOA process can be seen in Figure 4A. The actual layup during manufacturing can be seen in Figure 4B.

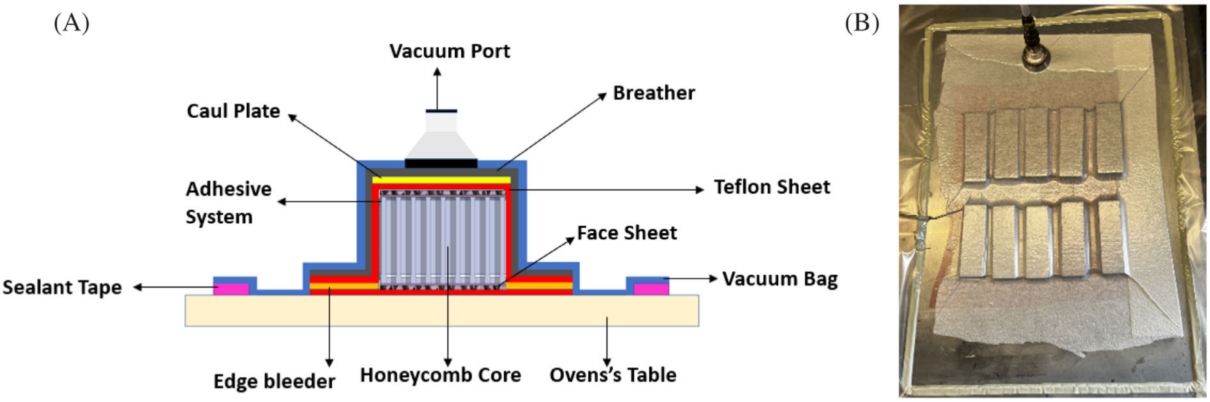


FIGURE 4 (A) Schematic of sandwich manufacturing. (B) Layup in an actual experimental setting.

3 | EXPERIMENTAL TESTING

In this work, to compare the mechanical performance of the modified honeycombs sandwich structures to the traditional honeycombs sandwich structures three different characterizing tests were conducted: (a) Three-point bend, (b) edgewise compression, and (c) impact. All the tests were conducted in accordance with the respective ASTM standards at room temperature.

3.1 | Three-point bend test

To evaluate the core shear properties of the sandwich structure three-point bend test was performed. This test was carried out in accordance with ASTM C393/C393M-20. The specimen dimensions used in this study are ~130 × 39 × 17 mm. This test was conducted on an Instron 5985 testing frame with a 250 kN loadcell. The diameter of the roller supports to mount the specimen was around 6.35 mm. The support span was set to 50.8 mm. The tests were conducted at a loading rate of 6 mm/min. The specimens were loaded in such a way that the orientation of the honeycombs was perpendicular to the direction of the rollers. The test was stopped after the failure was noticeably stabilized.

3.2 | Edgewise compression test

To evaluate the compressive strength of the sandwich structures in the direction parallel to the face sheets an edgewise compression test was performed. This test also demonstrates the load carrying capacity of the sandwich structures with respect to the facing stress developed during the loading conditions. This test was carried out in accordance with ASTM C364/C364M-16. The specimen dimensions used in this study are ~52 × 52 × 17 mm. This test was conducted on an Instron 5985 testing frame with a 250 kN loadcell. The loading rate used in this test was 0.50 mm/min. The load was applied in the direction of honeycombs.

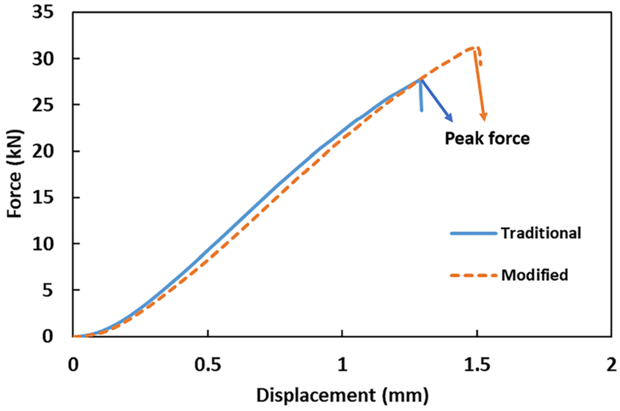


FIGURE 5 Flexural force versus cross head displacement.

3.3 | Impact test

To evaluate the energy-absorbing capacity of the sandwich structures, impact testing was performed. The impact test was carried out according to ASTM D7766/D7766M-16. The specimen dimensions used in this study are ~52 × 52 × 17 mm. This test was conducted on an Instron Dynatup 9250 HV drop tower machine. For these tests, a drop weight of 6.48 kg was used with a 12.77-mm hemispherical impactor. All the tests were performed at an impact energy of 9.3 J. The drop weight was set to a height of 0.15 m to impart this energy.

4 | RESULTS AND DISCUSSION

4.1 | Three-point bend test

Three-point bend testing was performed on both the traditional and modified honeycomb sandwich structures in accordance with ASTM C393. The representative force–crosshead displacement curves from the experiment can be seen in Figure 5. From the plot, it is evident that in both the sandwich structures, the load increased linearly with displacement. The traditional honeycomb sandwich structure failed after a peak load of 27 kN, whereas the modified honeycomb sandwich structure failed after a peak load of 31 kN.

TABLE 2 Three-point bend test results.

Core type	F_s^{ult} (MPa)	Displacement at failure (mm)
Traditional	22.68 ± 1.27	1.32 ± 0.06
Modified	25.95 ± 1.31	1.48 ± 0.07

$$F_s^{ult} = \frac{P_{max}}{(d+c)b} \tag{3}$$

Where F_s^{ult} is the core shear ultimate strength in MPa, P_{max} is the maximum force before failure in N, d is the sandwich thickness in mm, c is the core thickness in mm, and b is the sandwich width in mm.

To quantitatively assess the shear performance of both the sandwich structures under study, the ultimate shear strength of the specimens (Equation 3) and

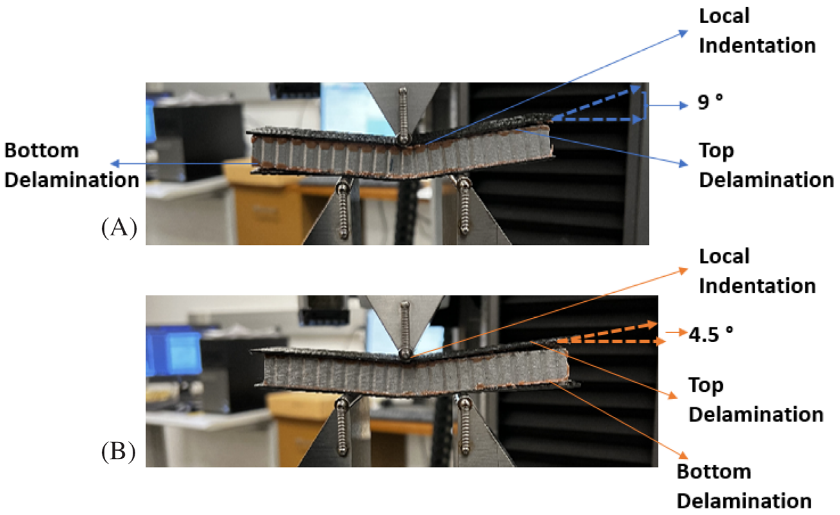


FIGURE 6 Failure of three-point bend specimens. (A) Traditional specimen. (B) Modified specimen.

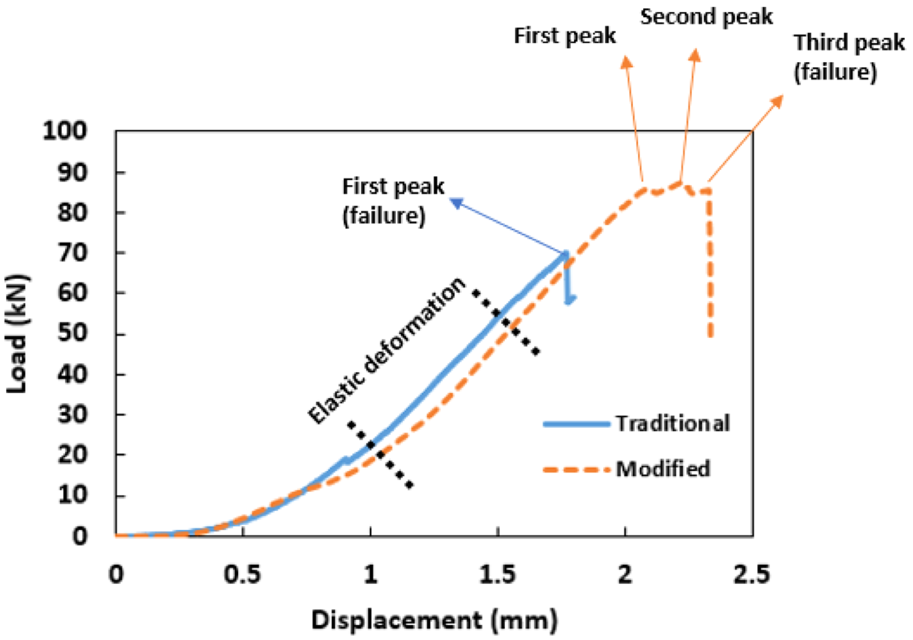


FIGURE 7 Experimental load–displacement curves from edgewise compression test.

displacement at failure was calculated from the experimental data. The results from the three-point bend test are summarized in Table 2. From the table, it can be seen that the core ultimate shear strength increased by 12.6% when the modified honeycomb core was used. The displacement to failure also increased by 11% for the modified honeycomb core. This prolonged deformation before failure can be used as a design advantage while employing these sandwich structures in real world applications, preventing them from sudden catastrophic failures. In three-point bend loading of honeycomb sandwich structures, various types of damage can occur depending on the loading conditions and the properties of the honeycomb core material. Some of the common damage types are core crushing, face sheet delamination, face sheet wrinkling, face sheet debonding, and local indentation. The traditional honeycomb core and the modified honeycomb core with increased surface area are manufactured from same material and are subjected to same loading conditions. The only difference being the modified cell design that incorporates the increased surface area. Post-test inspection revealed that both the structures failed due to local indentation at the center, delamination of face sheets and face sheet debonding from the core toward the edges. When the applied compressive strength is more than the out-of-plane compressive strength, local indentation occurs. The high bending moments in the loading conditions caused the face sheets to delaminate from the core structure. Due to the increased surface area in the modified honeycomb cores, there was increased bond strength between the face sheet and core material. This resulted in reduced deflection angles of face sheets in modified honeycomb cores at the end of three-point bend testing. It was observed that the face sheets deflected to an angle of about 9° in the traditional specimens, and 4.5° in the modified specimens. The improved deflection behavior of face sheets in the modified specimens can be attributed to the increased adhesive strength of the sandwich specimen provided by the increased surface area. The specimens after the end of testing can be seen in Figure 6.

TABLE 3 Edgewise compression test results.

Core type	Ultimate edgewise strength (MPa)	Sample coefficient of variation (%)
Traditional	528.8 ± 7.2	1.3
Modified	653.7 ± 9.1	1.4

4.2 | Edgewise compression test

Edgewise compression testing was performed on the sandwich specimens according to the ASTM C364 standard. The representative load–displacement curves from the experimental testing can be found in Figure 7. It can be observed that both the traditional and modified honeycomb sandwich structure experienced similar load–displacement behavior unit failure. Both the specimens behaved similarly in the elastic deformation region. The traditional specimens failed after a peak load of about 69 kN. The modified specimens reached a peak load of about 85 kN before failure. The minor increase in load after failure in the modified specimens can be attributed to the sequential crushing on the facets included in the design of modified honeycombs to increase the surface area of the structure. The ultimate edgewise compressive strength of the specimens was calculated from the experimental data (Equation 4) to quantitatively assess the difference between the traditional and modified honeycomb sandwich structures.

$$\sigma = \frac{P_{\max}}{w(2t_{\mathrm{fs}})} \tag{4}$$

where σ is the ultimate edgewise compressive strength in MPa, $P_{\max}$ is the maximum force in N of the edgewise

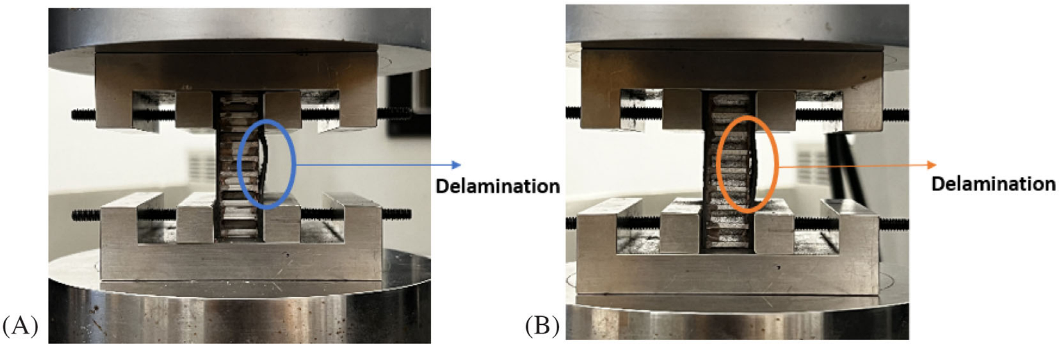


FIGURE 8 Failure of edgewise compression test specimens. (A) Traditional specimen. (B) Modified specimen.

compression force-displacement curve, *w* is the specimen width in mm, and t_{fs} is the one face sheet thickness.

The results from the edgewise compression test are tabulated in the Table 3. It can be seen that the ultimate edgewise compressive strength increased by 19.1% when the modified honeycomb core was used instead of a traditional honeycomb core. Despite an increase in weight by about 2.5% with minor changes to the design, the load carrying capacity of the sandwich structure increased by 19.1%. When a sandwich column is subjected to edgewise compression, the compressive load is applied perpendicular to the face sheets, causing the column to buckle. The failure mode of the column is dependent on its geometrical size, which includes the thickness of the face sheets and the height of the column. For relatively thin face sheets and short column heights, the failure mode is typically local buckling, where the face sheets deform in a wrinkled or crumpled pattern. This type of failure occurs when the compressive stress exceeds the material's yield stress, causing the face sheets to buckle in a small region. For thicker face sheets and taller column heights, the failure mode is typically global buckling, where the entire column buckles in a uniform pattern. This type of failure occurs when the compressive stress exceeds the critical buckling stress of the column, causing the column to buckle over its entire length. In general, as the thickness of the face sheets and the height of the column increase, the critical buckling stress decreases, making the column more susceptible to global buckling. Lei et al. observed similar failure modes of failure in sandwich columns subjected to edgewise compressive loads.[33] The failure mode in all specimens was consistent with the accepted failure mode stipulated in the ASTM C364 standard. Failure was initiated due to core compressive damage which caused the face sheets to buckle and delaminate from the core. The specimens at the end of testing and corresponding failure modes can be seen in the Figure 8. Visual inspection of the specimens after testing revealed increased delamination in the traditional specimens compared to that of the modified honeycomb core specimens.

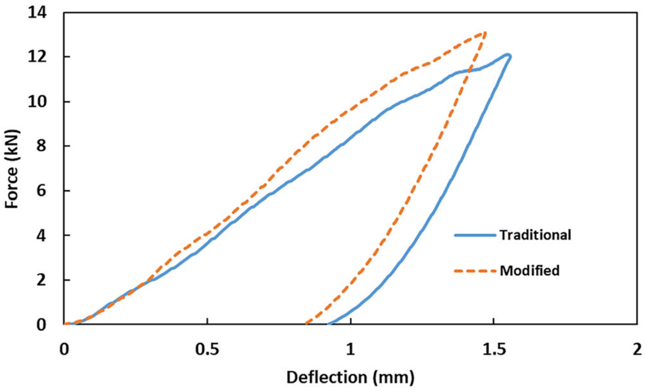


FIGURE 9 Force–deflection plot.

4.3 | Impact test

Impact testing was performed on the sandwich specimens according to ASTM D7766. The representative force——deflection and energy-time plots from the experimental testing can be seen in Figures 9 and 10 respectively. The experimental data were recorded from testing of the sandwich structure under an impact loading of 9.3 J. The closed force–deflection plot indicates

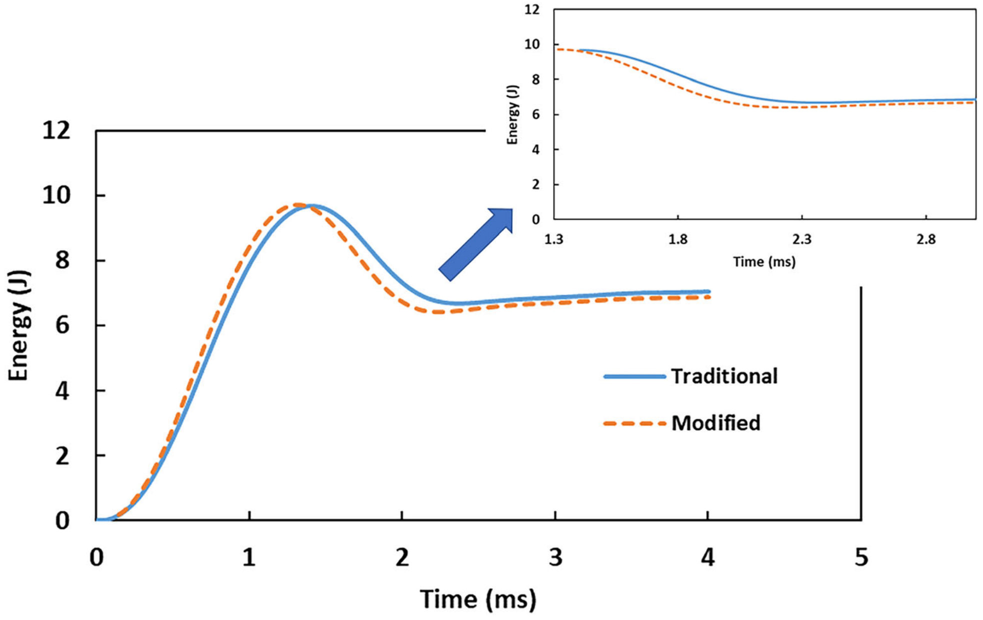


FIGURE 10 Energy–time plot.

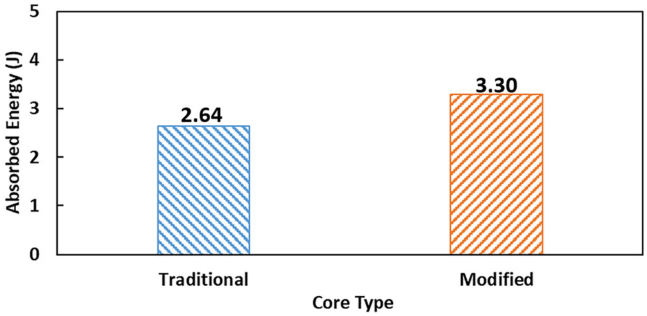


FIGURE 11 Comparison chart of absorbed energy.

TABLE 4 Impact test results.

Core type	Peak force (kN)	Absorbed energy (J)	Ratio of absorbed and impact energy
Traditional	12.11	2.64	0.28
Modified	13.17	3.3	0.35

that the impactor did not perforate the sandwich panel. Both the sandwich structures behaved similarly under the impact loading but varied in terms of the peak force received and energy absorbed during the impact event. During impact loading of the sandwich structure, it undergoes elastoplastic deformation accompanied by damage. A sandwich structure with low elastic energy under impact loading has a good energy-absorbing structure as it causes less damage to the impactor. From Figure 10 it can be seen that the modified honeycomb sandwich structure has lower energy at the end of the impact event indicating it is a better energy absorber.

Figure 11 shows the absorbed energy plots for both the traditional and modified sandwich structure. From the plot, it is evident that the absorbed energy increased when the modified honeycomb core was used instead of the traditional honeycomb core. To quantitatively evaluate the performance of the sandwich structures, the ratio of the absorbed energy and the impact energy was calculated. This ratio is generally used to evaluate the energy-absorbing characteristics of sandwich structures with different cores. This has a range of 0–1 (where, 0 indicates the impactor receives all the kinetic energy back, and 1 indicates that the sandwich structure absorbed all the energy). Sandwich panels with a higher ratio of absorbed energy to impact energy are suitable for energy absorbing applications.

The results from the impact tests are tabulated in Table 4. From the table, it is evident that the energy absorbing capacity of the sandwich structure increased by 20% when the traditional honeycomb core was replaced by the modified honeycomb core. The peak load during the impact event increased by 8% when the modified honeycomb core was use. The plots comparing the peak load and the ratio of absorbed energy to impacted energy for the respective cores can be found in Figure 12.

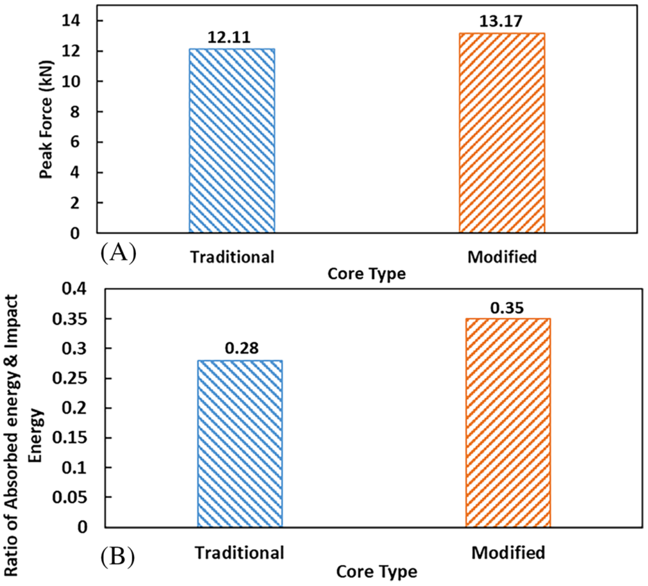


FIGURE 12 Comparison charts. (A) Peak force during impact. (B) Ratio of absorbed and impact energy.

5 | CONCLUSIONS

In this work, the mechanical performance of a modified honeycomb structure was compared to that of a traditional honeycomb core in sandwich applications. Both the core structures were additively manufactured through the L-PBF process using the A6061 RAM-2 aluminum alloy. The sandwich structures were made from IM7/Cycom 5320-1 carbon/epoxy face sheets bonded with an FM-309-1 adhesive system. To characterize the performance of the sandwich structure, three-point bend, edgewise compression, and impact tests were performed. Three-point bend results show that the core ultimate shear strength increased by 12.6% when the modified honeycomb core was used. The displacement to failure also increased by 11% for the modified honeycomb core. The edgewise compression test indicated that the ultimate edgewise compressive strength increased by 19.1% when the modified honeycomb core was used instead of a traditional honeycomb core. Impact results show that the peak load during the impact event increased by 8% when a modified honeycomb core was used. The energy absorbed also increased by 20% when the modified honeycomb core was used instead of a traditional honeycomb core. In conclusion, with a minor design change, the performance of the honeycomb sandwich structure was improved significantly. These increased surface area honeycombs are a good replacement to address the delamination issues faced by traditional honeycombs in sandwich applications.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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