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Evaluation of Sandwich Panels Strengthened by Different Corrugated Aluminum Cores Under Flexural and Compressive Loadings

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ABSTRACT

The developed design of sandwich structure and the appropriate selection of its core materials and geometries proven its efficient applications in lightweight structures. This study aims to quantify the best core geometries and positions that can carry a higher stiffness without weight compromising. To do so, the flexural strength applying four-point bending test, compressive strength and stiffness of aluminum (Al) facesheets strengthened by two different aluminum corrugated square and triangle cores, oriented in flatwise and edgewise positions, i.e., flatwise square (FS), edgewise square (ES), flatwise triangle (FT), and edgewise triangle (ET). The results indicated the sandwich panels with ET core had the highest flexural strength of 28 MPa at lower deflections, and the lowest strength of 13 MPa for panels with FT cores. The highest compressive strength of 81 MPa and the highest specific strength of 516 MPa/Kg were obtained with ES core sandwich panels co MPa red to 21 MPa and 120 MPa/Kg for panels with FT core. For all cases, the deformation occurred near surface buckling and core crushing. The sandwich panels with ET and ES cores showing a higher load-carrying capacity under the bending load due to the standing direction of the stiff Al struts, while the sandwich structures with FT and FS cores have totally slipped, bent and destroyed at lower loads. This study provides advice for the development of sandwich structures with various core geometries/orientations used in a range of engineering applications.

1. INTRODUCTION

The lightweight sandwich structures have been widely used in various engineering applications like automotive, marine, and aerospace industries for their reasonable fabrication cost, high strength to weight ratio (specific strength) and stiffness [1]. The sandwich structures are made of the outer skins (facesheets) with a thickness of 0.25 mm to 3 mm, adhesively bonded to a lightweight interior core material with a density of 16 to 480 kg/m^3. The performance of sandwich structure mainly depends on the skins, the core, and the skin/core interface (film adhesive) as well as their constituent materials and geometrical dimensions [2]. The skins carry the tension and compression flexural loads and the cores carry the shear loads [3]. Increasing the core's thickness induces a higher stiffness with a little weight gain, and this has urged the researchers to further investigate the sandwich strength/stiffness using different skin materials (e.g., aluminum, carbon, composites, aramid and glass) and various core materials (e.g., metallic: aluminum or steel and nonmetallic: honeycomb glass, aramid or carbon fabric; balsa wood, cell foams, and syntactic) [4, 5]. Doubling thickness of the M-shaped composite core sandwich resulted in a significant increase in the specific flexural strength and the compressive stiffness [6]. Thinner Al foam core (5 mm) sandwich structure deformed due to skin wrinkling, core cracking and core crushing whereas the thicker core structures (20mm) deformed due to the core indentation and core shear cracking [7]. Effect of using different skin sandwich materials on the compressive and bending behavior were also evaluated such as carbon fiber/polymer (CFRP) [8], high-strength ceramic tile [9] and hybrid kevlar/carbon/silica epoxy nanocomposite [10]. Others studies involved the role of varying sandwich core geometries on the strength/stiffness with an efficient weight were published [11-13]. The sandwich structures with an open cell composite X-core indicated a higher specific bending strength than that for the competing cell-core structure [14]. Bartolozzi et al. [15] carried out the static and dynamic behavior for a sandwich structure with a sinusoidal core. A short span and long span stainless steel Y-core beams were fabricated to investigate their three-point bending strength [16]. Short span panel was found to be a stronger than the long span which failed due to buckling. The sandwich structure with pyramidal cores revealed that optimizing the core geometry can induce an optimal bending and compressive behavior [17]. The corrugated metallic cores have proven a good shock resistant and withstand heavy loads and thus widely employed in the efficient lightweight building and construction structures, aerospace and automobile structures [18]. The sandwich structure consisting of stainless steel (SS) skin/square SS honeycomb-corrugated core showed a higher bending load/stiffness [19]. Interestingly, aluminum metal was manufactured in different shapes/geometries as skins and/or core for an efficient sandwich structure for its good strength/stiffness, availability, and has a good formability and corrosion resistance [20]. The quasi-static compressive and bending performance for aluminum corrugated core sandwich was evaluated, and the energy absorbers due to the core configuration tends to decrease the force oscillation [21]. Sun et al. [22] studied toughness of aluminum foam core sandwiched between two CFRP composite facesheets, while Bakir et al. [23] studied the lap shear, the impact and tensile behavior of aluminum foam facesheets adhered to polyester foam core. Flattening sandwich panels with a hexagon-shaped aluminum core with local-orthogonal-tight given 400% higher specific energy absorption than the cores without local-orthogonal-tight for the good matching between the high stiffness skins and low stiffness core [24].

Nevertheless, to date still no study explaining the in-plane compressive and flexural strength of metallic aluminum (Al) skins/corrugated core sandwich structure. This study aims to evaluate the mechanical strengths/stiffness for Al facesheets/Al core sandwich panels. The aluminum core has been used in two different corrugated geometries (square and triangle) and aligned in horizontal (flatwise) and vertical (edgewise) arrangements in order to determine the best sandwich structure that can carry the highest compressive and flexural strengths in relations to weight, structural core geometry and orientation.

2. EXPERIMENTAL PROCEDURE

2.1. Materials used

Lightweight aluminum (Al) thin sheets having properties showing in Table 1 were used as sandwich structure facesheets and corrugated cores.

Table 1. Mechanical properties of Al sheet used in the study

Material	Density	Hardness	Yield Strength	Tensile Strength	Elongation at Break
Aluminum sheet	2.72 g/cm^3	28HRC	109 MPa	145 MPa	8%

2.2. Fabrication of corrugated cores and sandwich panels

Two different corrugated Al core geometries, are square and triangle with a 20 mm thickness were fabricated (bent) using a cold-forming machine. Dimensions of the fabricated square and triangle frames and ribs are shown in Figure 1.

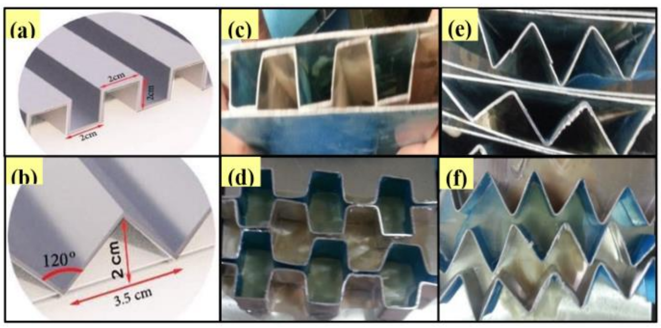

Figure 1. The corrugated square and tringle cores (a & b); flatwise square (FS) and edgewise square (ES) (c & d); and flatwise triangle (FT) and edgewise triangle (ET) (e & f)

The fabricated shapes were oriented in different arrangements, are horizontal (flatwise or in-plane) and vertical (edgewise or out-of-plane). To obtain an overall of four corrugated sandwich structure sections, are flatwise square (FS), flatwise tringle (FT), edgewise square (ES), and edgewise triangle (ET) (Figure 1). Alongside, two aluminum skins (top and bottom facing sheets) were also cut to wrap up the Al cores with 0.8 mm thickness (standard gauge 8) each face.

2.3 Sandwich panel assembly

Figure 2 illustrates the preparation process of two different corrugated Al skins/Al core sandwich panels (square and tringle), oriented in flatwise and edgewise cores alignment. The Al corrugated core is sandwiched between the upper and lower Al facesheets via a secondary bonding using an epoxy adhesive. The dimensions of the assembled corrugated square sandwich panels for the compressive test are 21.6 mm thickness, 15 cm width and length, and the same dimensions for the rectangular panels for the bending test except the length is 30 cm length. Aspect ratio of about 14:1, and the facings of 4% of the panel's depth were considered.

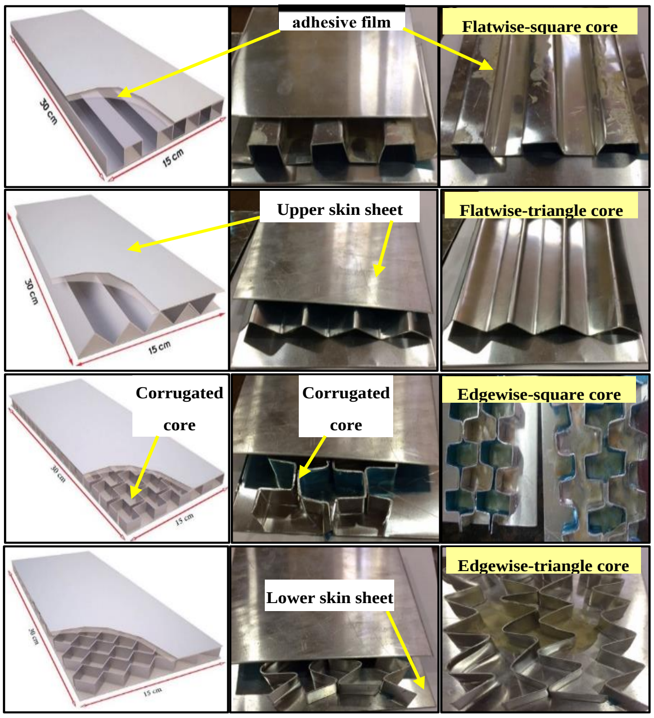

Figure 2. The four corrugated aluminum core arrangements: Flatwise Square (FS), Flatwise Triangle (FT), Edgewise Square (ES), and Edgewise Triangle (ET)

2.4 Testing strategy

Rockwell C hardness and density tests as well as the tensile properties for Al facesheets were performed according to ASTM B557 standard-for cast and wrought aluminum-to determine the main characteristics of the chosen aluminum metal. The obtained results are listed in Table 1 and have been further discussed within the results and discussion. The in-plane compressive testing for four sandwich structure (FS, FT, ES, and ET) panels was performed using a screw-driven 500kN test machine Figure 3(a) according to ASTM C365 standard. The load control of 1kN/sec rate at a quasi-static strain rate was applied until the failure of the core was observed. For the test, sandwich specimens of 150 mm×150 mm×22 mm were placed between two rigid steel plates in the testing machine Figure 3(b-c), and the force was ramped up until failure where the maximum compressive load limited to 1500 N to prevent undesired over compression of the panel. At least five tests were repeated for each sandwich panel, and the compressive strength was computed by dividing the failure load on the sectional area.

Four-point bending test of the fabricated Al skins/Al core sandwich panels was conducted as per ASTM C393 standard. After placing the specimens (150 mm×300 mm×22 mm) under a couple of steel cylinder in the testing machine Figure 3(d) and Figure 3(e), the force was ramped up until failure has occurred. Five specimens for each sandwich panel were tested and the bending strength was computed applying Eq. (1).

$$\sigma_f = \frac{FL}{bd^2} \tag{1}$$

where, σ_f is flexural strength (MPa), F is the applied force (N), L is a load support span, and b is width of the specimen (150 mm), and d is the specimen depth (21.6 mm).

Stiffness of the sandwich structure (k) that indicates the resistance of a body for deformation was calculated to determine the stiffness-to-weight and strength-to-weight ratios in relation to the core's geometry and position.

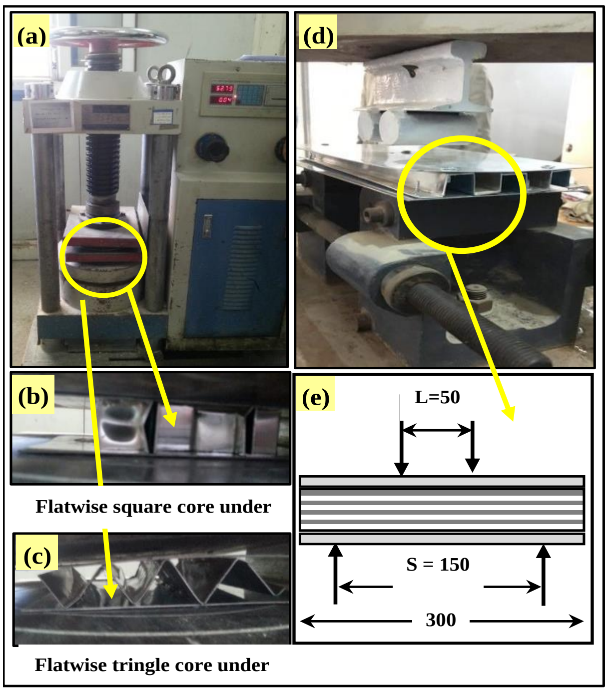

Figure 3. (a) the compression machine; (b & c) the FS and FT cores under compression; (d) the universal testing machine; and (e) four-point bending configuration

3. RESULTS AND DISCUSSION

3.1 Tensile properties and characterization of aluminum facesheets

The tensile properties of aluminum sheet used in the study were determined as shown in Table 1. The load-displacement curve of the tensile test for the aluminum sheet is shown in Figure 4. Results indicated that the obtained yield strength and the tensile strength of 109 MPa (16 ksi) and 145 MPa (21 ksi), respectively of an ultimate load reached 2310N and cross-sectional area of 0.8mm thin and 20mm width. These strength and durability are in conformance with Al alloy 6063 specifications stating in ASTM-B221 standard.

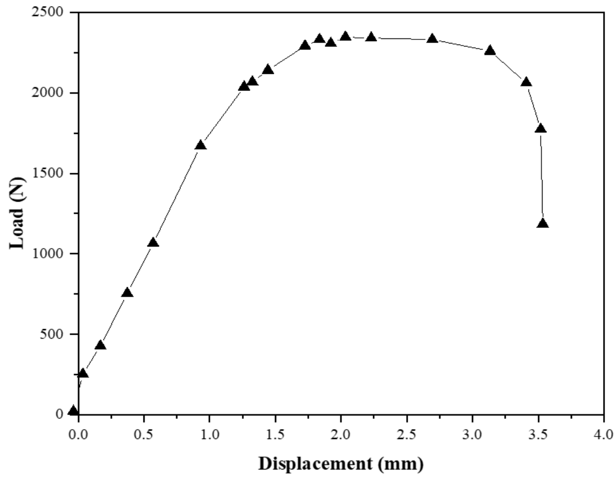

Figure 4. The load-displacement curve for aluminum facesheets

3.2 In-plane compression behavior of corrugated sandwich structures

Results of the in-plane compression testing for the four fabricated corrugated sandwich FS, FT, ES, and ET structures are given in Table 2. In general, it can be clearly observed that the mechanical strength/stiffness of the sandwich panels are core shape-dependence where the sandwich structure with edgewise square (ES) core had the highest compressive strength of 81 MPa while the lowest compressive of 21 MPa for the corresponding sandwich with flatwise tringle (FT). Similarly, the specific strength (strength/weight ratio) and the specific stiffness (stiffness/weight ratio) reached the maximal values of 516 kN.m/Kg and 92.3 MPa/Kg and the minimal values of 120 kN.m/Kg and 8.2 MPa/Kg for the ES and FT sandwich panels, respectively. This is attributed for capability of the ES core section to resist buckling since they deflected in 5 mm only compared to the FT core section that showed the highest deflection of 10 mm. The corrugated FT cores suffered a severe tearing stress followed by crushed cracking rather than buckling failure Figure 5. while the ES cores collapsed in the mid-height collapse mode Figure 3(b) under the applied compression load.

From the figure, it can be also observed that the core tearing (or shearing) and crushing appeared at any position along the FT frame and rib. This finding can be attributed to the impact of tringle sharp corner radii and fillets (oblique struts at 60° angle) which is unable to withstand the increased compressive load and would fail in Euler buckling failure mode. This matter was already pointed out during the fabrication but could not be overcome although making triangles with 120° angles Figure 1(b). In terms of the lower compressive strengths for the corrugated FS core sections, the drop load occurred due to the rib deformation as well as the web crippling failure. From Figure 5(b) images 1-4, it can be observed that the core materials deform in other failure modes such as local buckling of the struts, shear buckling, fracture of the struts and large bending deformation of the struts, which is likely to impel the struts to destroy near their mid-span position. The vertical struts for the FS core geometry have undergone compressive load. According to Jing et al. [25], the failure modes occurred for sandwich panel with open-cell aluminum cores subjected to a comparison and punching stress, are skin wrinkle, core shearing, inelastic deformation and interfacial failure.

On the other side, the higher compressive strengths for the panels with the corrugated ES core (81 MPa) and ET core (77 MPa) and thereof the higher stiffness values (14.5 and 13.5 KN/m), and specific strengths (516 and 497 MPa/Kg), respectively Figure 5(c-d), images 1-4 can be ascribed for the edge free effect and uniform loads on the panel frames and the edge closeouts. The majority of bulkheads numbers in the edgewise orientation regardless the core geometry along with the standing direction of the stiff aluminum struts also contributed to reduce (or prevent) the face crushing, rib or near surface buckling, core cracking/crushing, rib broken and thereof allowing the load to be maintained, improved the load-carrying capacity and enhanced the strength/stiffness of the structure. The lower slenderness ratio (the length to thickness ratio) of the edgewise alignment also restricted the load distribution. This is in agreement with the results of Fotsing et al. [26] that revealed the lower and higher compressive strengths are due to the core discontinuity or the core modifications so in order to avoid early buckling/crushing failure, narrower cells/bulkheads of the metallic core can be highly recommended.

Interestingly, it is important to mention here that reticulated of adhesive skin-to-core-surface was not adequate enough to withstand the applied mechanical loads, and it is necessary to prepare the aluminum surface properly and suitable adhesive bond (layer) including an appropriate oxide layer is required in order to carry the stresses applied at the interface between the oxide and the adhesive [1].

Table 2. Compressive strengths and stiffness for four sandwich structures with different cores geometries/positions

Sandwich Structure Core	Weight (g)*	Compressive Strength (MPa)	Stiffness (KN/m)	Strength/ Weight Ratio (MPa/Kg) (Specific Strength)	Stiffness/Weight Ratio (KN.m/Kg) (Specific Stiffness)
Flatwise square (FS)	187	26±3	3.6	139	19.3
Flatwise triangle (FT)	175	21±1.8	1.44	120	8.2
Edgewise square (ES)	157	81±2.6	14.5	516	92.3
Edgewise triangle (ET)	155	77±4.5	13.7	497	88.4

*The weight given is the average of five samples with 150×150 mm^2 dimension

Figure 5. Compression failure modes for four sandwich structures (a) FS, (b) FT, (c) ES, and (d) ET cores at different stages under load

3.3 Flexural strength and behavior of corrugated sandwich panels

The four-point bending strengths for the fabricated corrugated FS, FT, ES, and ET cores sandwich structures are given in Table 3. The flexural strength of the sandwich panel is obviously a core shape-dependence where the panels with the edgewise cores directions exhibited a higher flexural strength. The sandwich panels with edgewise triangle (ET) core had the maximal flexural strength of 28 MPa and specific strength of 90 MPa/Kg at 26mm deflection while the sandwich panels with flatwise triangle (FT) cores had the minimal strength and specific strength of 13 MPa and 37 MPa/Kg, respectively given the same deflection. The highest bending strength of the sandwich structure with the corrugated edgewise triangle (ET) core is attributed for their high load-carrying capacity due to the standing direction of the stiff aluminum struts, and the lowest strength of the flatwise triangle attributed for the drop load with the deformation of triangle rib. These findings are in agreement with Khalili et al. [27] which established the maximum bending strength and the energy absorption contributed with 26.5% deflection and improved strength by 13% after the failure in bending for the edgewise cores sandwich structure. Herein, we found an improvement in the flexural strengths by 4% and 115% for the edgewise square and edgewise tringle cores panels versus the flatwise square and flatwise tringle cores panels, respectively.

The force-displacement curves for the sandwich structures with FS and FT cores and structures with ES and ET cores under bending load at different deflections (6.5 mm, 13 mm, 20 mm, and 26 mm) are plotted in Figures 6 and 7, respectively. From Figure 6(a-b), one can clearly observe that the flatwise triangle and flatwise square cores panels have totally slipped, bent and destroyed under relatively lower bending loads. The flatwise square cores showed a load up to 11295 N Figure 6(a) and a deflection of 26 mm inset images in Figure 6(a), while the flatwise tringle cores reached the same deflection at less than 5500 N. Under further bending load, the sandwich panels with flatwise cores will continue to fold in an unstable manner since the load is confined over a small area during this folding process. Buckling of the panel has also led to debonding of the upper skin from the core and bent failure of the core as illustrated in Figure 8(a-c) at 26 mm deflection.

According to Xiang et al. [28], the deformation of top facesheets is localized around the central region of the panel. To maintain a better mechanical response with a great potential application of such sandwich panels, either thicker core cells/ribs are used or rectangular grid cores like leaf texture were suggested for their good stiffness, energy absorption and damage performance at intersection, rib, and center locations [29].

Table 3. Bending strengths for four corrugated sandwich panels

Sandwich Structure Core	Weight (g)*	Bending Strength (MPa) at Maximum Deflection of 26 mm	Specific Strength (MPa/Kg)
Flatwise square (FS)	374	24±3	64
Flatwise triangle (FT)	350	13±1.5	37
Edgewise square (ES)	314	25±2	80
Edgewise triangle (ET)	310	28±2.5	90

*The weight given is the average of five samples with a dimension of 300×150 mm^2

On the other side, the edgewise triangle and edgewise square cores sandwich structures have sustained under the applied direct bending load, resulting in higher loads at higher deflections as shown in Figure 7(a-b). However, the bending load at the upper skin is high in relation to its thickness which tended to occurrence of the deformation due to the near surface or facesheets crushing. To reinforce the thinner facesheets and enhance the energy-absorption and the flexural strength for corrugated structure, a number of horizontal stiffeners in various positions and thicknesses were used [30]. Otherwise, to support the facing before bending happens, the sandwich panel should be designed with a stiff corrugated core without compromising the weight index along with a strong interface between the facesheets and the core. Herein, albeit of stiff edgewise square and tringle aluminum cores were designed and used, poor fixation between the core and the faces was noticed and this has caused shear flow in the interface and slipped rather than bent. Therefore, a good bonding (or special fixation) between the core and the faces should be perfectly carried out before processing the test. From Figure 7(a-b), it can be also noticed that both the edgewise square and edgewise tringle cores experienced relatively higher loads under bending of 11350 N and 12900 N with a maximum deflection of 26 mm, respectively. To reiterate, the standing stiff arrangement of square and tringle aluminum cores contributed to reduce the core cells folding, and this was supported by the inset images of the deflected edgewise square and tringle cores only in Figure 7(a-b) as well as the deformed sandwich panels at different deflections illustrated in Figure 8(a-c).

To further support this evidence, Zhou et al. [31] studied different Miura-based folded cores and found that the curved lines showed the highest quasi-static compression and bending strengths. Among various Miura-type fold-cores geometries i.e., cube and egg-box, and cube-strip studied, the diamond strip exhibited the best capability of energy absorption and higher quasi-static bending performance [32]. Corrugated sinusoidal tubes including outer circular, middle lateral, and inner circular tubes exhibited their stability under compression [33].

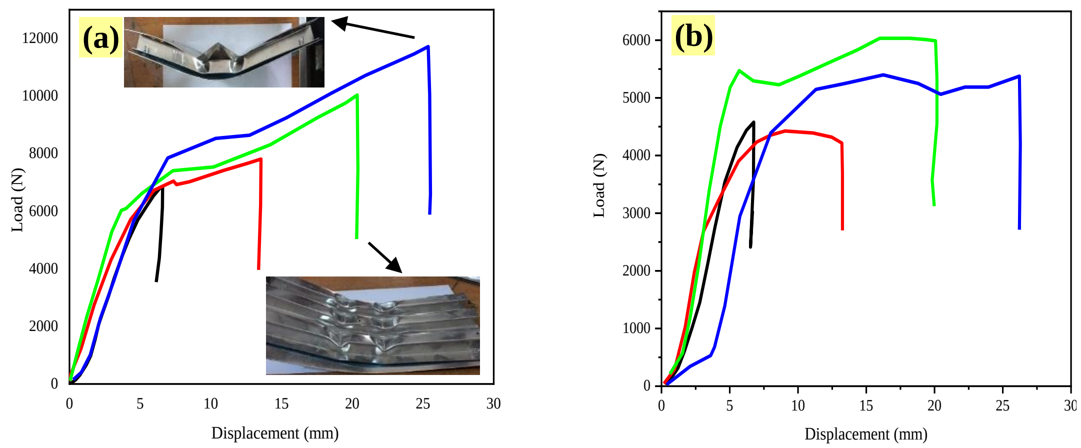

Figure 6. The load-displacement curves for sandwich panels with: (a) FS (deflected panels, insets), and (b) FT cores under bending at different deflections

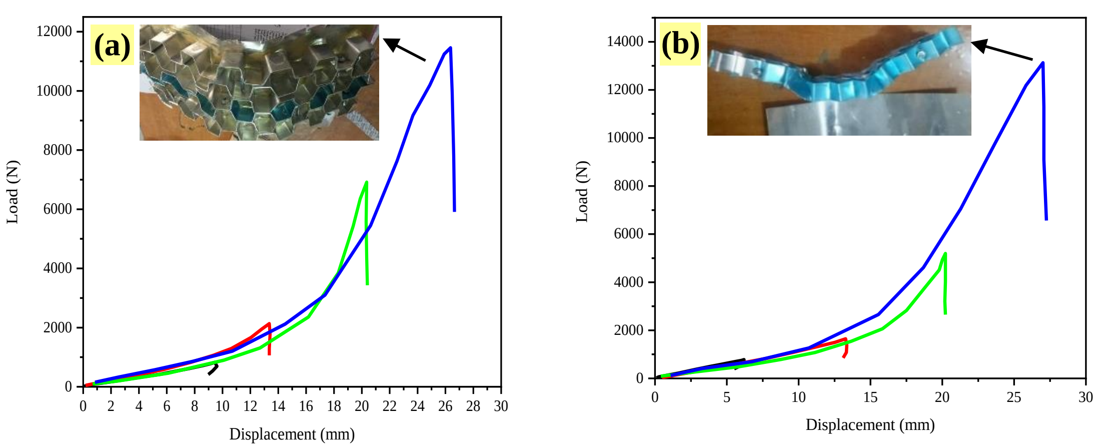

Figure 7. The load-displacement curves for sandwich panels with: (a) ES, and (b) ET cores under bending at different deflections (deflected panels, insets)

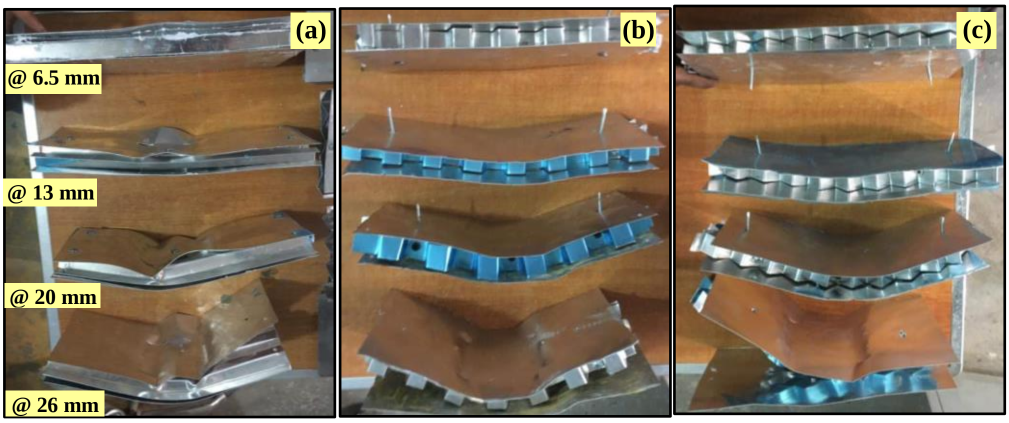

Figure 8. Deformed panels after bending at different deflections (6.5, 13, 20, 26 mm) with: (a) FS, (b) ES, and (c) ET

4. CONCLUSIONS

In this study, four aluminum facesheets/aluminum cores sandwich structures configurations of two corrugated square and tringle core geometries, oriented in two flatwise and edgewise directions were fabricated. It was found that the mechanical strengths of the sandwich structures are core directional and geometrical dependent where the highest strengths, stiffness and specific strength (strength to weigh ratio) were found for the panels with edgewise square (ES) and edgewise triangle (ET) cores and the lowest values for panels with flatwise square (FS) and flatwise triangle (FT) cores. This was ascribed for the capability of the ES core section to resist buckling due to the higher bulkheads' numbers in the edgewise orientation as well as the standing direction of the stiff aluminum struts which contributed to reduce the face crushing, rib or near surface buckling, core crushing, rib broken. While, the drop load occurred in the corrugated flatwise square FS and flatwise triangle FT cores due to the crushed cracking along the frame and rib, ribbon deformation and web crippling failure. This experimental study can be a basic guideline for further validations and investigations into the development of sandwich structures with various core geometries and orientations.

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