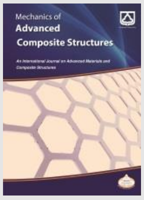
Mechanics of Advanced Composite Structures 10 (2023) 283 – 294

This is an Open Access paper licensed under the Creative Commons License CC-BY 4.0 license.

Semnan University

Mechanics of Advanced Composite Structures

journal homepage: http://MACS.journals.semnan.ac.ir



Experimental Investigation on Quasi-Static Impact Response of Glass/Epoxy Composite Corrugated Core Sandwich Panels

M. Azizi, A. Choopanian Benis, M. Vaezi, M. Jamal-Omidi*

Faculty of Aerospace Engineering, Malek-Ashtar University of Technology, Tehran, Iran

KEYWORDS

Sandwich panel;
Corrugated core;
Glass/epoxy;
Quasi-static impact;
Energy absorption.

ABSTRACT

Composite sandwich structures are vastly utilized in the transportation and aerospace industries as highly effective energy absorbers. This paper aims to study a comparative study on the role of the composite corrugated sheet as a core in sandwich panels under low-velocity loading conditions. In this regard, three types of sandwich structures with different corrugated cores, including three unit cells that have identical mass and mechanical properties, are designed and manufactured. The material system utilized for the face skins and core is woven E-glass/epoxy. Corrugated cores are fabricated using specially designed molds and press techniques and afterward bonded to face sheets for the production of corrugated sandwich panels. In the following, by performing the compression tests on corrugated sandwich panels, the impact response, failure modes, and energy absorption ability for different core shapes are explored. The results reveal that the sandwich panels with the rectangular core have a higher capacity in load carrying and energy absorption than the triangular and arc-shaped cores. It is found that the composite sandwich panels with a rectangular profile increased by 1.14 and 3 times in the SEA compared to the other two types of profiles. It is also observed that the initial mode of failure in these core geometries is buckling of cell walls, and continued loading leads to the fracture of the cell walls (fiber breaking), delamination, and debonding between face sheets and core. The present results provide valuable information on corrugated configurations in the design of sandwich structures and engineering applications.

1. Introduction

Composite sandwich constructions are typically known as a subset of multi-layer structures made of composite which are optimized for expected lifecycle loading conditions [1]. These structures are typically composed of two high-strength panels and a relatively thick, low-density core. Due to their unique features such as lightweight characteristics, noise reduction, high strength, and stiffness, high resistance to corrosion, wearing, vibration, and impact, as well as considerable energy absorption capacity, they are widely utilized in industries of aerospace, marine, construction, and automotive [2, 3].

Sandwich panels are structural members that can be designed to absorb large amounts of impact energy due to their different failure mechanisms. They absorb high-impact energy during the collision in a progressive, controlled, and irreversible way and ensure enhanced structural crashworthiness in a sudden collision [4, 5]. Different shapes and materials are utilized for face layers and cores depending on the application type. The faces are often manufactured of metal or composite materials, and the core can be classified based on its material or architecture. To date, there have been several published studies available regarding crushing responses and energy absorption capacity of sandwich panels in the quasi-static or dynamic loading with different materials and cores such as foams [6, 7], honeycomb [8, 9], truss [10, 11], origami-type [12, 13] and corrugated [14–35].

---

* Corresponding author. Tel.: +98-21-44251196
E-mail address: j_omidi@mut.ac.ir; m.jamalomidi@gmail.com

DOI: 10.22075/macs.2023.28696.1441
Received 2022-10-14; Received in revised form 2023-01-03; Accepted 2023-01-10

© 2023 Published by Semnan University Press. All rights reserved.

Recently, corrugated structures have been considered by many designers due to their unique properties and behavior against mechanical loading. The specific attribute of corrugated constructions is their strongly anisotropic properties; high stiffness transverse to the wave direction in contrast to the compliance along the wave direction [36, 37]. A sandwich panel with a corrugated core is a typical two-dimensional periodic structure with a high flexural, shear, and tensile stiffness-to-weight ratio, high torsion resistance, and loading efficiency means the ratio of the ultimate strength to weight of the structure [14–38]. Another distinctive attribute of a corrugated core is its capability to impart great ventilation characteristics, avoiding humidity retention problems associated with cellular core materials (e.g., polymer foams and honeycombs) [17]. There are several special applications of corrugated panels, such as flexible skin for the wings of morphing airplanes [36, 39] in aerospace engineering, bulkheads, helidecks, accommodation modules [40], and combatant deckhouse structures [41] in marine structures, automobile chassis and bumpers for reducing the impact force on passengers in the automotive industry [42, 43].

Yokozeki et al. [36] proposed corrugated laminates made from carbon fiber-reinforced polymer (CFRP) composites as an ideal material for morphing wing technologies. They performed tensile and flexural tests in the longitudinal and transverse directions to assess the stiffness and strength of corrugated sheets. Furthermore, they analytically established a simple model for predicting the initial stiffness of corrugated composite laminates.

Dayyani et al. [44] designed and investigated two corrugated cores with trapezoidal and rectangular geometry made of glass fiber-reinforced polymer (GFRP) with and without elastomer coating under tensile and flexural loads experimentally and numerically. They used multi-objective optimization to minimize equivalent tensile strength, equivalent bending stiffness, and skin mass and proposed an appropriate corrugated shape for morphing skin application.

The geometric configuration and material properties of the core structure play a significant role in the mechanism of failure and energy absorption capability of corrugated core sandwich panels.

Biagi and Bart-Smith [14] studied the mechanical behavior of corrugated core sandwich beams made of SAE340 stainless steel under in-plane compression. The numerical analysis by ABAQUS finite element (FE) software and analytical approach was performed on beams, and the results were validated via comparison to experimental data. The results illustrated an accurate prediction of the maximum failure load and failure mode for more cases. In addition, the study concluded that the resistance of the corrugated sandwich beams is dependent on local and global boundary conditions. Kılıcaslan et al. [15] experimentally and numerically investigated the low-speed impact behavior of multilayer corrugated sandwich structures consisting of aluminum face sheets, a trapezoidal corrugated aluminum core, and intermediate layers of aluminum sheet. The results appeared that the main deformation mechanisms are due to the buckling/folding of corrugated cores and bending of interlayer and face sheets. In another study, they examined the axial crushing behavior of single and double-layer sandwich panels with corrugated cores made of aluminum alloy by experimental and numerical methods subjected to quasi-static and dynamic rates [16]. They observed the interaction of loading rate and deformation mechanism and reported that the stress of the corrugated core increased in case of loading rate expanded from quasi-static to dynamic.

Rejab and Cantwell [17] examined the compression behavior and following fracture modes in sandwich panels with triangular corrugated cores experimentally and numerically. Three different materials, including aluminum alloy, GFRP, and CFRP, are used to make sandwich panel specimens. They assessed the role of the unit cell numbers and thickness of cell walls on local collapse and overall deformation of structures. The results showed that cores made of composite materials performed significantly better than conventional core constructions like polymer and metal foams.

Hou et al. [18] explored the impact response of sandwich structures made of aluminum alloys with triangular and trapezoidal cores experimentally and using the FE method. They evaluated geometrical factors on the crushing behavior of corrugated cores to find the optimized shape for crashworthiness criteria. In another study, they performed an experimental and numerical analysis on the multi-layered trapezoidal corrugated core sandwich structures made of the aluminum alloy under quasi-static loading [19]. They reported the significant effect of the cell shapes and numbers of core layers on failure modes and energy absorption ability. In a further study, they implemented a crashworthiness analysis of various configurations of multi-layered corrugated sandwich panels [20]. Different configurations were set by defining four factors, the shape of the corrugated core, the arrangement, the variable height, and the variable thickness in every layer.

They eventually obtained the optimal design configuration.

Boonkong et al. [22] studied the energy absorption specification and failure modes of aluminum sandwich panels with the corrugated core experimentally and by means of developing the FE modeling at low velocity. They also explored the crashworthiness behavior of these structures due to the impactor size, the material types of the substrate, and the angle of impact.

Yang et al. [23] presented a novel bio-inspired bidirectional sinusoidal sandwich panel with a corrugated core for evaluating out-of-plane compression considering the anatomy of Odontodactylus Scyllarus. They numerically examined the behavior of aluminum alloy sandwich panels with triangular, rectangular, single sinusoidal, and double sinusoidal cores under planar impact. The results showed that the double sinusoidal core has the highest value of specific energy absorption and the lowest initial peak force. They also demonstrated that energy absorption capability is improved with an increase in the number of waves in double sinusoidal core geometry.

Liu and Turner [24] performed quasi-static and dynamic strain-rate compression tests on the corrugated composite sandwich panels made of carbon fiber/epoxy and reported the rate-dependency behavior for the examined composite cores.

Nouri Damghani and Mohammadzadeh Gonabadi [25] examined the effects of core geometry on energy absorption and impact resistance of corrugated sandwich panels made of aluminum alloy using a drop hammer tester. The results showed the highlighted role of the panel’s height and core geometry in the load-carrying capability of sandwich structures. It was observed that the increase in panel height enhanced energy absorption ability, and the square core has higher impact resistance in comparison to the triangular core.

Rong et al. [26] employed FE analysis to study the influence of the corrugated core with various geometric shapes in the dynamic behavior of sandwich structures under the planar and local impact. The face skins and the core were made of CFRP material and aluminum alloy, respectively. They concluded that geometric shapes have a significant role in energy absorption capability at minor energy levels in the case of local impact. However, for the high energy impact, no significant effect was observed with changes in the geometric shape of the cores. The sandwich panel with a trapezoidal corrugated core dissipates more energy and has good energy absorption capacity regarding the out-of-plane compression. They also, in another study, explored the influence of core materials on the crashworthiness responses of trapezoidal corrugated sandwich panels subjected to the low-velocity local impact experimentally and numerically [27]. The panels were composed of CFRP face skins with aluminum alloy, stainless steel, and CFRP core. The results revealed the significant effect of the core material fracture properties on structural performance and found that the core with stainless steel material improved significantly the ability to absorb energy and load-carrying capacity compared to other ones.

Taghizadeh et al. [29] examined the compression behavior and following failure modes in PVC foam-filled composite sandwich panels with rectangular, trapezoidal, and triangular corrugated cores experimentally. The face skins and the core were manufactured of woven glass/epoxy. The panels were subjected to three different quasi-static compression loading conditions, including concentrated, linear, and planar. They assessed the role of the unit cell numbers and corrugated core geometries on the overall deformation and local collapse of structures. The results showed that three-unit cells rectangular corrugated geometry possessed the best performance than other types of corrugated core geometries. In other studies, they explored the influence of multi-layering in composite sandwich panels with rectangular, trapezoidal, and triangular cores under quasi-static loading including three-point bending and indentation experimentally and numerically [30, 31]. Face sheets and corrugated cores with equal weight fractions were made using ML506 epoxy resin with 15% hardener and an overall volume fraction of 45% for woven glass fibers. They examined parameters such as contact force, energy absorption, and failure mechanisms during the loading processes. They reported that multi-layering of composite sandwich panels not only improved the structural strength in the bending and indentation process but also increased significantly the energy absorption. Also, the results in both loading conditions revealed that panels with rectangular cores performed better compared to the other two shapes, in terms of energy absorption and specific energy.

Yang et al. [32] introduced two types of carbon fiber composite axial and circular corrugated sandwich cylindrical panels (ACSCPs and CCSCPs). They examined the impact behavior of curved panels under low-velocity local impact experimentally and numerically and explored the influences of relative density, impact energy, and impact position on the energy absorption capacity of curved corrugated sandwich shells. The results revealed that ACSCPs have a better crashworthiness performance than CCSCPs.

Mei et al. [34] conducted experimental and numerical quasi-static compression on CFRP X-core sandwich panels and evaluated the compressive mechanical properties and failure modes of X-core profiles fabricated with the different numbers of CFRP prepreg layers. The dominant failure modes on the X-core were fracture and delamination. The results illustrated that CFRP X-core sandwich structures achieve higher compressive properties than conventional cellular materials.

Jamal-Omidi et al. [35] employed Ls-DYNA software to investigate the effects of corrugated cores with square, triangular and sinusoidal shapes on the dynamic response of sandwich panels under vertical and transverse loading conditions. The face sheets and the core were made of woven carbon/epoxy material. They reported that corrugation geometry shapes and the numbers of unit cells play an important role in the crashworthy response and energy absorption performance of sandwich panels.

According to the research performed, it is observed that few studies have focused on evaluating the role of the composite corrugated sheets as a core on the impact response of composite sandwich structures, which is directly associated with structural safety. In this regard, the present study aims to experimentally explore the impact resistance capacity of three groups of woven E-glass fiber/epoxy sandwich panels with rectangular, triangular, and arc-shaped cores under planar compression. Each specimen consists of three unit cells and is made of GFRP with a stacking sequence of $[(0/90)]_{3s}$ for the face sheets and $[(0/90)]_{3t}$ for the cores. The compressive behavior and failure mechanisms of composite corrugated sandwich panels have been examined experimentally in the research process. The results indicate that rectangular corrugated sandwich panel has a better performance and energy absorption ability than the other two types.

2. Experimental Procedure

2.1. Materials and Fabrication Process

In the present study, corrugated core sandwich panels with three different geometries, including rectangular, triangular, and arc-shaped configurations with the same density and mechanical properties, are designed and constructed. The face skins and corrugated cores are made using woven E-glass/epoxy with an average volume fraction of 48%. The tensile and compressive strengths of the examined composite are 230.4 MPa and 158.3 MPa, respectively. The sandwich panels are designed to have the same mass. The face sheets designed in the experiment have an overall dimension of 92 mm × 92 mm for the rectangular core, 97 mm × 97 mm for the triangular core, and 96 mm × 96 mm for the arc-shaped core. Also, the core dimensions for rectangular, triangular, and arc-shaped profiles are about 91 mm × 92 mm, 96 mm × 97 mm, and 95 mm × 96 mm, respectively. The thickness of each face sheet and core for all specimens is 1.0 mm, and 0.5 mm. The corrugated core geometry with different configurations consisting of three unit cells is depicted in Fig. 1. Each face sheet consists of six plies with $[(0/90)]_{3s}$ stacking sequence made by hand lay-up method. To make face sheets, first glass fibers are cut with dimensions of 33 cm ×33 cm and then have been impregnated with the epoxy resin Araldite LY 564 (Huntsman) and Aradur HY 2954 BD hardener with a mix ratio of 10:3. After the stacking sequence is completed, the sheets are vacuumed for 24 h and finally placed at room temperature for 30 h. In the following, face sheets are cut with a Tennsmith cutter machine based on the desired dimensions for each group of specimens.

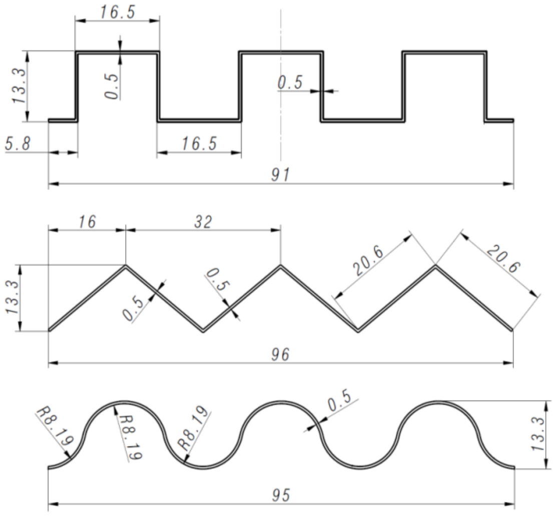


Fig. 1. Dimensions of rectangular, triangular, and arc-shaped profiles (unit: mm)

In this research, special molds have been designed and fabricated to make corrugated cores with rectangular, triangular, and arc-shaped waves. A two-piece Teflon mold was initially made to make a rectangular wave shape, see Fig. 2. The mold is made with high precision on a computer numerical control (CNC) milling machine.

To make a rectangular wave, first, the top and bottom of the die are impregnated with wax (Pasty-Wax 818, Sika) to facilitate the separation of the core from the mold. After drying, the entire inner surface of the molds is covered using two layers of QZ-13 film. Afterward, three plies of resin-impregnated fabrics with $[(0/90)]_{3t}$ stacking sequence are placed on one of the mold jaws. In this work, a ratio of 3:10 (hardener to resin ratio) and 6:10 (resin to fabric weight) is used to manufacture the cores. It should be noted that due to the unique design of the mold, after fixing the jaws, constant pressure is applied to the entire surface of the specimen, and there is no need for a vacuum process. The excess resin is removed from the channels around the mold. The curing operation is performed at room temperature (27 °C) for 30 h.

Fig. 2. Rectangular corrugated mold made of Teflon

(a) Triangular corrugated mold

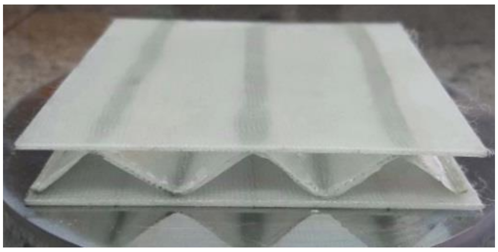
(b) Arc-shaped corrugated mold

Fig. 3. Aluminum molds

After the experiences gained in using Teflon mold, it was decided to replace Teflon with aluminum molds to produce triangular and circular cores. To make aluminum molds, a rectangular cube block is first made using the casting technique, and then the final mold parts are produced by CNC machining. Figure 3 shows aluminum molds designed and manufactured to produce triangular and arc-shaped waves. The manufacture of triangular and arc-shaped waves is performed similarly to the process described for square ones.

Following the manufacturing of the face sheets and cores, they are bonded with epoxy adhesive and cured under constant pressure at room temperature for 48 h. The image of the prepared specimens is shown in Fig. 4. At least three specimens are manufactured for each type. The average mass amounts of the sandwich structures with rectangular, triangular, and arc-shaped corrugated cores are 42.52 gr, 41.35 gr, and 41.89 gr, respectively.

(a) Rectangular corrugation



(b) Triangular corrugation

(c) Arc-shaped corrugation

Fig. 4. Corrugated core sandwich panels

2.2. *Quasi-Static Impact Test*

The corrugated core sandwich panels were examined via compression test in a quasi-static regime through an upper smooth indenter using a universal testing machine (SANTAM STM-150) in accordance with the ASTM standard (C365/C365M-11a). Figure 5 illustrates the test apparatus and a specimen positioned between the platform and the impactor of the machine. As shown in the figure, the specimen is placed on the lower platform, and a uniform compression is then applied at the rate of 2 mm/min. The impact load is measured with the load cell integrated into the impactor of the machine. The load-displacement data is recorded until the specimen is entirely crushed by compression. The photographs of the specimens during the impact process are used to examine their failure mechanisms.

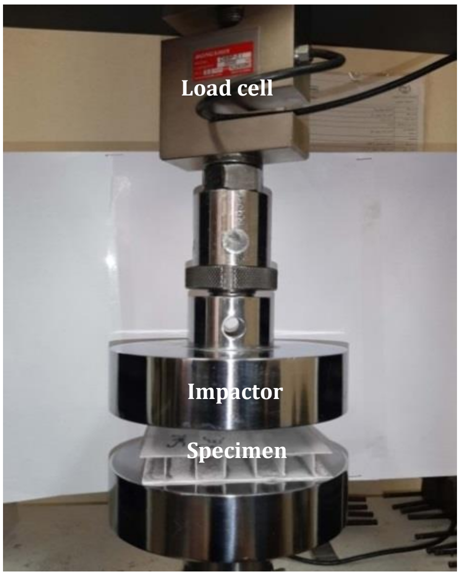


Fig. 5. Compression test setup on composite corrugated core sandwich specimens

3. Results and Discussion

This section discusses the quasi-static impact responses of corrugated sandwich structures achieved via the compression test. In addition, the deformations of specimens are highlighted via illustrated marks to clarify failure mechanisms as a result of compression. Experimental results have shown that the type and shape of the corrugated core significantly influenced the performance of sandwich panels. In the following, their respective mechanical responses are explained separately.

3.1. Compressive Response of Rectangular Corrugated Core

Load-displacement curves following a compression test on a rectangular corrugated core sandwich panel are shown in Fig. 6. It is obvious that the sandwich panel is involved during the compaction in four different phases. The deformed images of the rectangular sandwich specimen corresponding to the regions on the stress-strain curve are represented in Fig. 7. In the linear elastic regime, the region I, the load increases up to the first peak; then, as seen in region II, the buckling of the cells is followed by compressive damage and led to a load drop. It should be noted that the nonlinear deviation at the beginning of the process is associated with the small sliding of the sandwich panel on the lower platform. In region III, the dominant failure modes are fiber breakage in the middle of the cells and delamination near the face sheets. The corrugated core in region IV is entirely crushed, and the core is fully compressed (flattened). In this case, as the face sheets come closer together, the structure acts as a relatively rigid body, thus increasing the force again. Dominant failure mechanisms involved in the crushing process of the rectangular corrugated core sandwich panel are shown in Fig. 8. The test results on the rectangular corrugations show that fiber breaking, delamination, and debonding are the predominant failure modes in this configuration. These damages are also observed by scanning electron microscope (SEM) analysis for this type of structure, as shown in Fig. 9.

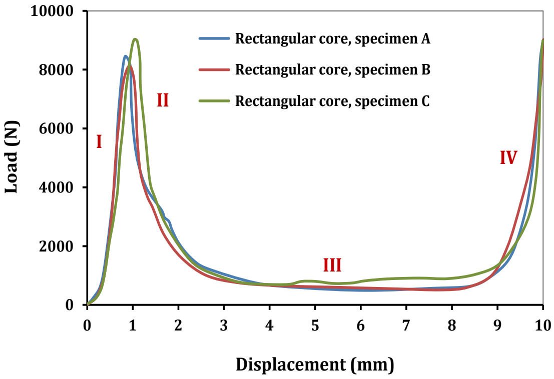


Fig. 6. Compression load-displacement curves for a rectangular corrugated core sandwich panel

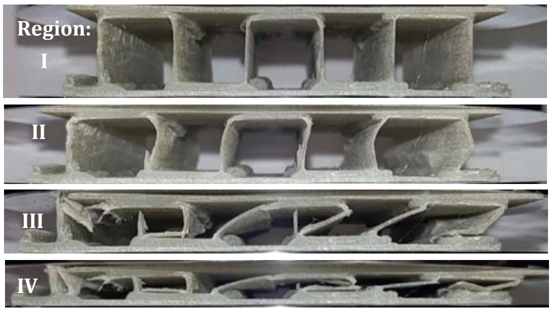


Fig. 7. Image of progressive damage development in rectangular corrugated core sandwich panel

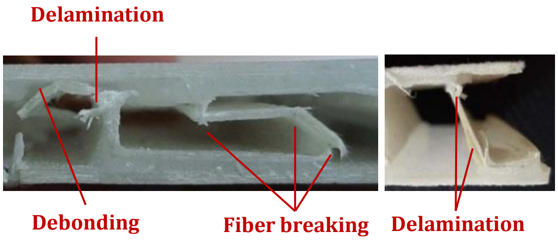


Fig. 8. Failure mode images include delamination, fiber breaking, and debonding after the crushing process

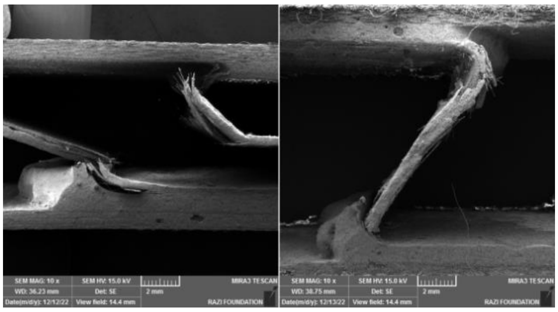


Fig. 9. Damage observed on the rectangular corrugated core sandwich panel established by SEM

3.2. Compressive Response of Triangular Corrugated Core

Load-displacement curves and deformation processes of the triangular corrugated core sandwich panel subjected to planar compression are illustrated in Figs. 10 and 11, respectively. In this case, as before, the behavior has four regions. As shown in Fig. 10, after the linear elastic region, the stress concentration at the sharp edges of the core causes fluctuations, consequently resulting in cracks along the bonding line of the triangular core in the form of tear mode (regions I-II). Fiber breaking of the cell walls is the initial failure mode in this corrugated profile. Also, significant debonding is observed between the core and skin sheets due to a small bonding area. Under this condition, the core shows less resistance, and the energy absorption is reduced.

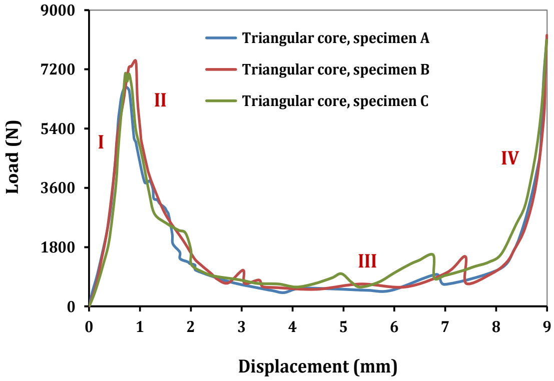


Fig. 10. Compression load-displacement curves for a triangular corrugated core sandwich panel

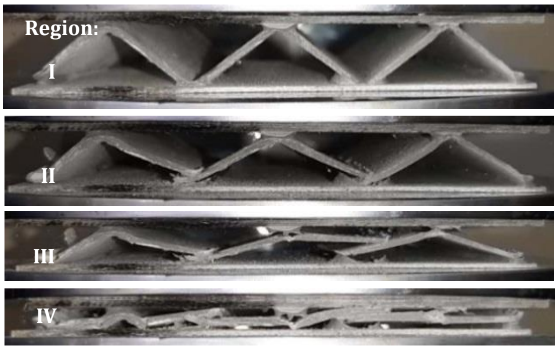


Fig. 11. Image of progressive damage development in triangular corrugated core sandwich panel

The following failure includes fiber breakage, delamination, and debonding between the core and face sheets (regions III-IV), as seen in Fig. 12. Finally, when the cores are pressed so that they come into contact with the surface layers, the cores begin to compress as the pressure load rapidly increases. A comparison of Figs. 6 and 10 shows that the triangular core has less resistance than the rectangular one, resulting in less energy absorption in this construction. A representative image of the damages for this type of structure is shown in Fig. 13 using SEM.

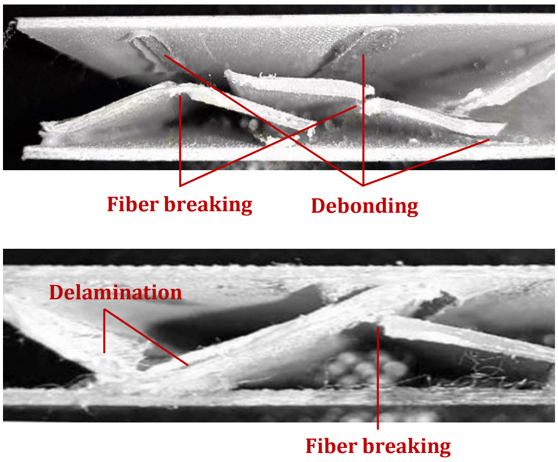


Fig. 12. Failure mode images include debonding, fiber breaking, and delamination after the crushing process

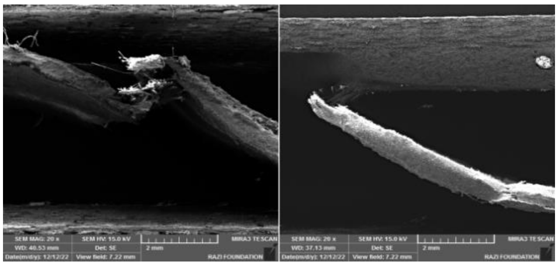


Fig. 13. Damage observed on the triangular corrugated core sandwich panel established by SEM

3.3. Compressive Response of Arc-Shaped Corrugated Core

Load-displacement curves and deformation processes of the arc-shaped corrugated core are exhibited in Figs. 14 and 15, the initial failure starts with fiber breaking in the middle points of cell walls. In this case, like the previous constructions, the arc-shaped corrugated core sandwich panel is involved during compaction in four different phases. As can be observed in the load-displacement diagram, in this case, the initial peak load in the elastic region is less compared to triangular and rectangular cores (region I). This can be attributed to the relatively small bonding area as well as their much lower out-of-plane stiffness than the other two constructions. The results show that a sandwich panel with an arc-shaped corrugated core has much less out-of-plane stiffness compared to triangular and rectangular cores. When the cell wall breaks, the force drops progressively in the image (region II). The following failure includes fiber breaking and delamination (regions III-IV), as seen in Fig. 16. It should be noted that little debonding mode has been observed in the degradation process in this case. When the cores are compressed to contact the face skins, a secondary resistance is created due to densify of cores, which increases the compressive load. Figure 17 displays SEM images of the damages on this type of structure.

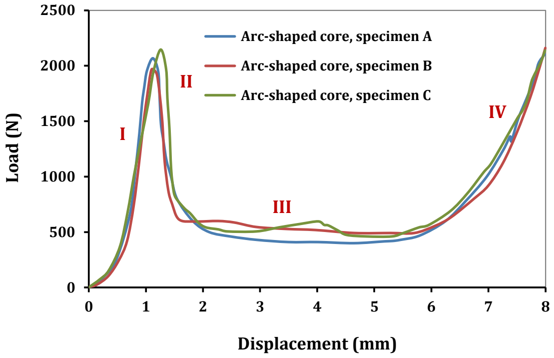


Fig. 14. Compression load-displacement curves for an arc-shaped corrugated core sandwich panel

Fig. 15. Image of progressive damage development in arc-shaped corrugated core sandwich panel

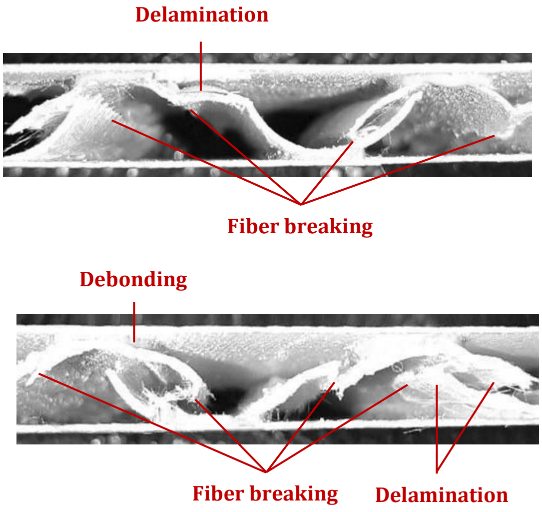


Fig. 16. Failure mode images include fiber breaking, delamination, and debonding after the crushing process

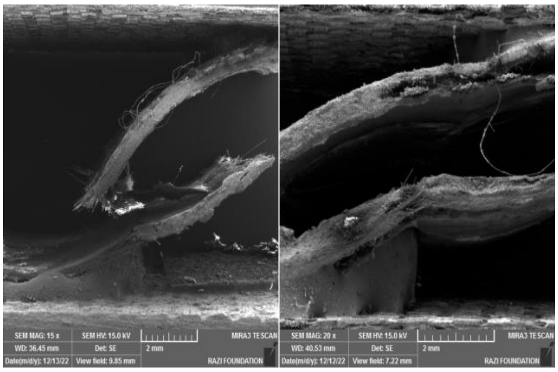


Fig. 17. Damage observed on the arc-shaped core sandwich panel established by SEM

3.4. Energy Absorption Analysis

In order to evaluate the energy absorption capacity of specimens, key parameters including initial crushing load ($F_{Max.}$), total energy absorption (TEA), mean crushing load (F_{Mean}), and specific energy absorption (SEA) are defined. The F_{Max} refers to the initial peak force of the load-displacement response.

The TEA illustrates the total energy absorbed by the specimen during the deformation and equals the area under the force-displacement curve, which can be defined as below:

$$TEA = \int_0^{l_{max}} F(l)dl \tag{1}$$

here, l_{max} is the maximum crushing length.

The mean crushing load, F_{Mean}, is a parameter to evaluate the resistance of a thin-walled structure and can be calculated as below:

$$F_{mean} = \frac{TEA}{l_{max}} \tag{2}$$

The SEA represents the energy absorption capability of a crushed structure, and it is expressed as the energy absorbed per unit mass of a thin-walled structure:

$$SEA = \frac{TEA}{m} \tag{3}$$

where m is the mass of the tested specimen.

In order to comparison of the quasi-static test results obtained from three types of cores, their load-displacement curves are presented in Fig. 18. Also, The results for the $F_{Max.}$, TEA, F_{Mean}, and SEA are summarized in Table 1.

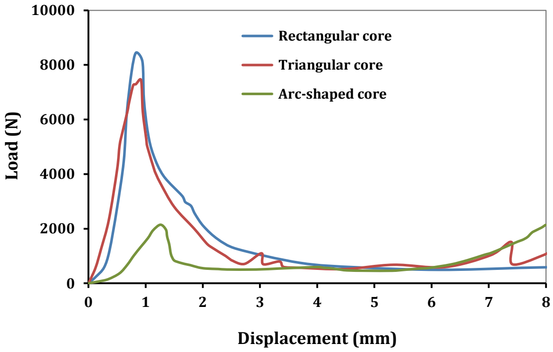


Fig. 18. Comparison of quasi-static planar compressive test results for three corrugated core sandwich panels

The initial crushing load is an important indicator to evaluate safety in the energy absorber design and is directly obtained from the force-displacement response. The energy absorptions are computed as the area under the load-displacement diagram from zero displacements to 6 mm. The reason for choosing this amount of displacement in calculating energy absorption is based on the results of Fig. 18 to evaluate them. As can be seen in the arc-shaped sandwich specimen, the cores begin to densify with a rapidly increasing compression load, beginning at 6 mm.

Table 1. Energy absorption of three specimens with different core geometries

Corrugated sandwich panel		$F_{Max.}$ (kN)	TEA (J)	F_{Mean} (kN)	SEA (J/gr)
Rectangular core	A	8.45	10.80	1.80	0.2576
	B	8.13	10.12	1.69	0.2414
	C	9.03	11.20	1.87	0.2672
Triangular core	A	6.67	8.87	1.48	0.2115
	B	7.44	9.90	1.65	0.2361
	C	7.08	9.48	1.58	0.2261
Arc-shaped core	A	2.07	3.37	0.56	0.0804
	B	1.97	3.56	0.59	0.0849
	C	2.15	3.82	0.64	0.0911

$l_{Crush\ length}$ =6 mm

The SEA is computed by dividing the energy absorption by the mass of the specimen. Here, the mass is calculated based on the average mass of three types of cores (41.92 gr). The initial crushing loads by the rectangular corrugated core were higher, 1.21 and 4.14 times than triangular and arc-shaped cores, respectively. Also, the triangular corrugated core shows an increase of 3.42 times compared to arc-shaped cores. Furthermore, it is observed that the rectangular corrugated core supports the SEA higher than two types of corrugations, especially compared to arc-shaped corrugated cores (3 times). In order to more intuitively compare the mechanical response of the three core types, the histogram of $F_{Max.}$ and SEA average is presented in Fig. 19. The results indicate that the rectangular profile plays an influential role in assessing the crashworthiness ability of corrugated sandwich structures. This conclusion is consistent with the available results of Taghizadeh et al. [29-31] regarding the better performance of the rectangular geometry compared to the trapezoidal and triangular shapes in corrugated sandwich panels.

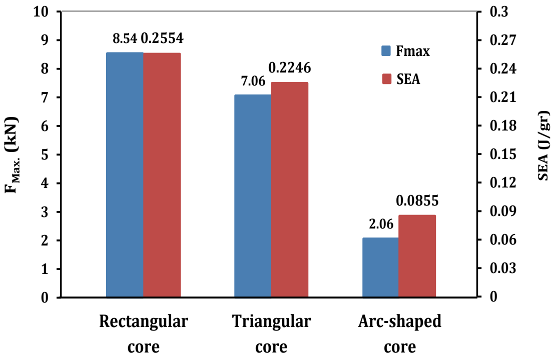


Fig. 19. Histogram comparing the mechanical performance including $F_{Max.}$ and SEA (within a crushing length of 6 mm)

4. Conclusion

Sandwich composite structures are extensively utilized in engineering applications due to their lightweight and high strength-to-weight ratio. In recent years, many researchers have been attracted to the use of these structures with the aim of creating crash-worthy structures. In this study, the quasi-static impact test is performed on three corrugated core sandwich structures with rectangular, triangular, and arc-shaped profiles in order to assess their impact resistance, local failure, and overall deformation. For this purpose, sandwich panels with different corrugated cores consisting of three unit cells with the same height, weight, and materials are designed. Woven E-glass fiber-reinforced polymer is used in the study. The corrugated core specimens are fabricated using specially designed molds and press techniques, following the shape of rectangular, triangular, and arc-shaped configurations. For the planar impact, it is found from the diagrams of response vs. displacement that the peak load, $F_{Max.}$, and SEA increase in structure with a rectangular core more than the other two structures, which can significantly assist engineers in designing energy-absorbing structures and their final decision in achieving a more efficient design. The results revealed that when the thicknesses of face skins and core, height, density, and the number of unit cells are kept constant, the core cell configuration significantly influences the planar impact responses. The SEA with rectangular cores exhibits an average amount of 0.2554 J/gr, which is approximately 1.14 and 3.0 times higher than triangular and arc-shaped profiles. Also, a 2.63 times increase in SEA on sandwich panels with a triangular core is observed compared to an arc-shaped core. The lower crashworthiness of sandwich panels with arc-shaped cores can be attributed to their less out-of-plane stiffness under planar compression. Failure modes in the specimens have shown that the dominant initial damage is due to instabilities as the cell walls started to buckle; beyond this buckling threshold, the panels deformed, resulting in the formation of fiber breaking, delamination, and debonding. Moreover, significant debonding is observed in the sandwich panels with the triangular core because of the smaller bonding area between the face skins and the core. Generally, rectangular corrugated sandwich panels exhibit better performance in crashworthiness due to their high stiffness, ultimate strength, and easy fabrication. They are the proper choice for selection as energy absorbers among the three kinds of sandwich panels. Further, corrugated profiles can be a more suitable alternative as cores in sandwich structures compared to conventional core constructions like honeycombs and polymer and metal foams.

Nomenclature

ACSCPs	Axial corrugated sandwich cylindrical panels
CFRP	Carbon fiber-reinforced polymer
CCSCPs	Circular corrugated sandwich cylindrical panels
CNC	Computer numerical control
FE	Finite element
GFRP	Glass fiber-reinforced polymer
SEA	Specific energy absorption
TEA	Total energy absorption
$F_{Max.}$	Initial crushing load
F_{Mean}	Mean crushing load

Acknowledgments

Not applicable.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

References

[1] Birman, V. and Kardomateas, G.A., 2018. Review of current trends in research and applications of sandwich structures. *Composites Part B: Engineering*, 142, pp.221–240.

[2] Usta, F., Türkmen, H.S. and Scarpa, F., 2021. Low-velocity impact resistance of composite sandwich panels with various types of auxetic and non-auxetic core structures. *Thin-Walled Structures*, Vol. 163, pp.107738.

[3] Shu, C., Zhao, S. and Hou, S., 2018. Crashworthiness analysis of two-layered corrugated sandwich panels under crushing loading. *Thin-Walled Structures*, 133, pp.42–51.

[4] Torre, L. and Kenny, J.M., 2000. Impact testing and simulation of composite sandwich structures for civil transportation. *Composite Structures*, 50, pp.257–267.

[5] Tarlochan, F., Hamouda, A.M.S., Mahdi, E. and Sahari, B.B., 2007. Composite sandwich structures for crashworthiness applications. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 221, pp.121–130.

[6] Huo, X., Liu, H., Luo, Q., Sun, G. and Li, Q., 2020. On low-velocity impact response of foam-core sandwich panels. International Journal of Mechanical Sciences, 181, pp.105681.

[7] Zniker, H., El Kouifat, M.K., Feddal, I., Bouzakraoui, S. and Ouaki, B., 2022. Comparative study of quasi-static indentation (QSI) response of composites used in maritime transport. *Materials Today: Proceedings*. https://doi.org/10. 1016 /j.matpr.2022.09.488

[8] Palomba, G., Epasto, G., Crupi, V. and Guglielmino, E., 2018. Single and double-layer honeycomb sandwich panels under impact loading. *International Journal of Impact Engineering*, 121, pp.77–90.

[9] He, W., Yao, L., Meng, X., Sun, G., Xie, D. and Liu, J., 2019. Effect of structural parameters on low-velocity impact behavior of aluminum honeycomb sandwich structures with CFRP face sheets. *Thin-Walled Structures*, 137, pp.411–432.

[10] Liu, J., Pattofatto, S., Fang, D., Lu, F. and Zhao, H., 2015. Impact strength enhancement of aluminum tetrahedral lattice truss core structures. *International Journal of Impact Engineering*, 79, pp. 3–13.

[11] Ullah, I., Brandt, M. and Feih, S., 2016. Failure and energy absorption characteristics of advanced 3D truss core structures. *Materials & Design*, 92, pp.937–948.

[12] Li, Z., Chen, W., Hao, H., Cui, J. and Shi, Y., 2019. Experimental study of multi-layer folded truncated structures under dynamic crushing. *International Journal of Impact Engineering*, 131, pp.111–122.

[13] Fathers, R.K., Gattas, J.M. and You, Z., 2015. Quasi-static crushing of eggbox, cube, and modified cube fold core sandwich structures. *International Journal of Mechanical Sciences*, 101, pp.421–428.

[14] Biagi, R. and Bart-Smith, H., 2012. In-plane column response of metallic corrugated core sandwich panels. *International Journal of Solids and Structures*, 49, pp.3901–3914.

[15] Kılıçaslan, C., Güden, M., Odaci, İ.K. and Taşdemirci, A., 2013. The impact responses and the finite element modeling of a layered trapezoidal corrugated aluminum core and aluminum sheet interlayer sandwich

structures. *Materials & Design*, 46, pp.121–133.

[16] Kılıçaslan, C., Odaci, İ.K. and Güden, M., 2016. Single-and double-layer aluminum corrugated core sandwiches under quasi-static and dynamic loadings. *Journal of Sandwich Structures and Materials*, 18, pp.667–692.

[17] Rejab, M.R.M. and Cantwel, W.J., 2013. The mechanical behaviour of corrugated-core sandwich panels. *Composites Part B: Engineering*, 47, pp.267–277.

[18] Hou, S., Zhao, S., Ren, L., Han, X. and Li, Q., 2013. Crashworthiness optimization of corrugated sandwich panels. *Materials & Design*, 51, pp.1071–1084.

[19] Hou, S., Shu, C., Zhao, S., Liu, T., Han, X. and Li, Q., 2015. Experimental and numerical studies on multi-layered corrugated sandwich panels under crushing loading. *Composite Structures*, 126, pp.371–385.

[20] Shu, C., Hou, S., Zhang, Y.X. and Luo, Y., 2021. Crashworthiness analysis and optimization of different configurations multi-layered corrugated sandwich panels under crush loading. *Journal of Sandwich Structures & Materials*, 23, pp.2901–2922.

[21] St-Pierre, L., Fleck, N.A. and Deshpande, V.S., 2015. The dynamic indentation response of sandwich panels with a corrugated or Y-frame core. *International Journal of Mechanical Sciences*, 92, pp.279–289.

[22] Boonkong, T., Shen, Y.O., Guan, Z.W. and Cantwell, W.J., 2016. The low-velocity impact response of curvilinear-core sandwich structures. *International Journal of Impact Engineering*, 93, pp.28–38.

[23] Yang, X., Ma, J., Shi, Y., Sun, Y. and Yang, J., 2017. Crashworthiness investigation of the bio-inspired bi-directionally corrugated core sandwich panel under quasi-static crushing load. *Materials & Design*, 135, pp.275–290.

[24] Liu, T. and Turner, P., 2017. Dynamic compressive response of wrapped carbon fibre composite corrugated cores. *Composite Structures*, 165, pp.266–272.

[25] Nouri Damghani, M. and Mohammadzadeh Gonabadi, A., 2017. Numerical and experimental study of energy absorption in aluminum corrugated core sandwich panels by drop hammer test. *Mechanics, Materials Science & Engineering*, 8, pp.52–60.

[26] Rong, Y., Liu, J., Luo, W. and He, W., 2018. Effects of geometric configurations of corrugated cores on the local impact and planar compression of sandwich panels. *Composites Part B: Engineering*, 152, pp.324–335.

[27] Rong, Y., Luo, W., Liu, J., Shen, Z. and He, W., 2020. Effect of core materials on the low-velocity impact behaviour of trapezoidal corrugated sandwich panels. *International Journal of Crashworthiness*, 25, pp.505–516.

[28] Jackson, K.E. and Fasanella, E.L., 2018. 8.15 Design, testing, and simulation of crashworthy composite airframe structures at NASA langley tesearch center. *Comprehensive Composite Materials II*, 8, pp.286–307.

[29] Taghizadeh, S.A., Farrokhabadi, A., Liaghat, G., Pedram, E., Malekinejad, H., Mohammadi, S.F. and Ahmadi, H., 2019. Characterization of compressive behavior of PVC foam infilled composite sandwich panels with different corrugated core shapes. *Thin-Walled Structures*, 135, pp.160–172.

[30] Farrokhabadi, A., Taghizadeh, S.A., Madadi, H., Norouzi, H. and Ataei, A., 2020. Experimental and numerical analysis of novel multi-layer sandwich panels under three point bending load. *Composite Structures*, 250, p.112631.

[31] Taghizadeh, S.A., Naghdinasab, M., Madadi, H. and Farrokhabadi, A., 2021. Investigation of novel multi-layer sandwich panels under quasi-static indentation loading using experimental and numerical analyses. *Thin-Walled Structures*, 160, p.107326.

[32] Yang, J.S., Zhang, W.M., Yang, F., Chen, S.Y., Schmidt, R., Schröder, K.U., Ma, L. and Wu, L.Z., 2020. Low-velocity impact behavior of carbon fibre composite curved corrugated sandwich shells. *Composite Structures*, 238, pp.112027.

[33] Hamidin, F., Farrokhabadi, A. and Ahmadi, H., 2021. The effect of core shape on the bending response of sandwich panels with filled and unfilled sine and square corrugated cores. *Journal of Failure Analysis and Prevention*, 21, pp.537–546.

[34] Mei, J., Tan, P.J., Bosi, F., Zhang, T., Liu, J. Y., Wang, B. and Huang, W., 2021. Fabrication and mechanical characterization of CFRP X-core sandwich panels. *Thin-Walled Structures*, 158, pp.107144.

[35] Jamal-Omidi, M., Zabihpoor, M., Vaezi, M. and Benis, A.C., 2022. Numerical Investigation on the Effect of Composite Corrugated Cores in Lightweight Sandwich Panels under Planar Impact Loading. *International Journal of Integrated Engineering*, 14, pp.63–76.

[36] Yokozeki, T., Takeda, S.I., Ogasawara, T. and Ishikawa, T., 2006. Mechanical properties of corrugated composites for candidate materials of flexible wing structures. *Composites Part A: Applied Science and Manufacturing*, 37, pp.1578–1586.

[37] Khalkhali, A., Narimanzadeh, N., Khakshournia, S. and Amiri, S., 2014. Optimal design of sandwich panels using multi-objective genetic algorithm and finite element method. *International Journal of Engineering, Transactions C: Aspects*, 27, pp.395–402.

[38] Mallick, P.K. and Boorle, R., 2014. Sandwich panels with corrugated core-A lightweighting concept with improved stiffness (No. 2014-01-0808). *SAE Technical Paper*.

[39] Dayyani, I., Khodaparast, H.H., Woods, B.K. and Friswell, M.I., 2015. The design of a coated composite corrugated skin for the camber morphing airfoil. *Journal of Intelligent Material Systems and Structures*, 26, pp.1592–1608.

[40] Konstantinou, E.A., 1996. *Adhesively bonded steel sandwich structures for marine applications* (Doctoral dissertation, University of Glasgow, United Kingdom).

[41] Liang, C.C., Yang, M.F. and Wu, P.W., 2001. Optimum design of metallic corrugated core sandwich panels subjected to blast loads. *Ocean Engineering*, 28, pp.825–861.

[42] Donga, A., 2011. *Application of sandwich beam in Automobile front bumper for frontal crash analysis* (Doctoral dissertation, Wichita State University).

[43] Milton, S. and Grove, S.M., 1997. Composite sandwich panel manufacturing concepts for a lightweight vehicle chassis (ACMC, University of Plymouth).

[44] Dayyani, I., Ziaei-Rad, S. and Salehi, H., 2012. Numerical and experimental investigations on mechanical behavior of composite corrugated core. Applied Composite Materials, 19, pp.705–721.