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Crush behavior of sandwich panel with corrugated strip egg box core

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ABSTRACT

This research investigates the amount of energy absorption in a sandwich panel with a corrugated core of an egg-box with two different dimensions. Sandwich panels with different core shapes are widely used in the transportation industry due to their lightweight, and many studies have been conducted on their properties, one of which is the study of energy absorption. Investigating the amount of energy absorption in these types of cores will help increase the safety of the passengers. In this research, the cores with the ratio of the angle of the leg to the base of 30 degrees (T30) and 40 degrees (T40) are made through sheet cutting and bending and are connected to each other using spot welding. ST 37 steel sheet is used for the core and surface. The samples are subjected to a quasi-static uniform load. The force-displacement curves are obtained and the peak force value, energy absorption rate, specific energy absorption, and energy absorption efficiency are calculated from the crushing behavior of the sample. It was found that the angle ratio affects the amount of energy absorption. The amount of energy absorption in T40 is about 1.5 times that of the T30 model.

Keywords: energy absorption, egg-box core, corrugated sandwich sheet, crushing behavior

1. Introduction

Due to their high strength and energy absorption capacity, sandwich panels are used in many industries, including transportation, military, and packaging. These panels are made of two thin outer shells, known as faceplates, and a core in the middle. In the mechanical applications of sandwich panels, the faceplates are usually responsible for transferring the force to the core and bearing bending moments, while the core takes part in supporting shear forces. The faceplates are often flat plates made of steel or laminated composites, while the core can be made of different materials and with different geometries. For example, the core can be made of foam, cellular structure, truss, corrugated sheet, etc. The shape of the core structure can affect the mechanical properties of the sandwich panels and many researchers have proposed different shapes for the core structure to improve the mechanical properties of sandwich panels [1].

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Nomenclature

F	crushing force
m	mass of specimen
L	length of the trapezoidal corrugation's leg
a	length of the trapezoidal corrugation's base
α	angle between the trapezoidal corrugation's leg and base
ds	amount of displacement integral parameter
EA	Energy Absorption
SEA	Specific Energy Absorption (energy absorbed per unit mass of the structure)
IPF	Initial Peak Crushing Force
MCF	Mean Crushing Force
CFE	Crushing Force Efficiency

One of the most common forms of cores in steel sandwich panels is a corrugated sheet. The corrugated core profile can have simple geometric shapes such as trapezoidal and rectangular, or more complex shapes like circular or sinusoidal. One of the distinctive features of corrugated cores is that their profile has a prismatic shape that repeats in a specific direction. On the other hand, the bidirectional corrugated panels are made of a repetition of a cellular shape in two orthogonal directions. These corrugated structures have the same stiffness and strength in both directions.

The sandwich structures have also a high energy absorption capacity to the mass ratio which makes them a good alternative as energy absorbers in transportation applications [2]. Energy absorbers are sacrificial structural elements that act upon impact. In other words, an energy absorber is a system that can convert all or part of the kinetic energy into another form of energy to reduce the crushing force transmitted to the structure. The energy absorption mechanism in an energy absorption system depends on the geometry, material, and loading condition.

One of the methods to evaluate the energy absorption capacity in structures is to use a quasi-static compression test, in which the structure is subjected to a slowly varying compressive load until the complete collapse. During the test, the crushing force is measured and the crushing force-displacement diagram is extracted. The amount of absorbed energy during the crushing process indicates the energy absorption capacity of the structure.

Many research pieces have been conducted on the mechanical performance of sandwich structures, and now, the focus of some researchers has been drawn to investigate the effect of sandwich panel geometry on their energy absorption capacity using experimental and numerical methods [3]. For instance, Leekitwattana et al. [4] investigated the transverse shear stiffness of a new bidirectional strip corrugated sandwich structure by combining the force-distortion relationship and the modified stiffness matrix method. Huo et al. [5] also investigated the effect of configuration and number of layers of a multilayered corrugated sandwich panel on their crushing mechanism under a quasi-static compressive load using numerical and experimental methods and found that the impact capability of a corrugated sandwich is closely related to cell width, wall thickness, and core height. Côté et al. [6] showed that the corrugated core structure provides much higher shear strength in the longitudinal direction, compared to the honeycomb and square diamond cores. Dharmasena et al. [7] studied the dynamic crushing response of laminated corrugated sandwich panels under impact loads. They found that multi-layered sandwich structures significantly reduce the intensity of impact loads. Radford et al. [8] investigated the responses of corrugated, pyramidal, bulk triangular aluminum foam core sandwich panels subjected to shock loading. They found that corrugated foam and metal sandwich panels exhibit the highest impact strength, while the pyramid core is the weakest among them. Tilbrook et al. [9] studied the dynamic out-of-plane compressive response of stainless-steel corrugated sandwich cores and Y frames for different impact velocities. The results showed that the plastic wave effects on the core structures lead to high surface stresses, while the low surface stresses remain almost constant. Lu et al. [10] investigated the compressive response and failure mechanisms of a corrugated sandwich panel by use of a combined theoretical and experimental approach. In this work, the corrugated specimens were modeled by the use of the curved beam elements and surface contact elements. The elastoplastic material was tuned with a bi-linear constitutive model which satisfied the J2-flow theory and assigned to the finite element model. The effects of boundary conditions, geometrical parameters, material properties, and geometrical imperfections on the compressive strength of corrugated boards were studied. As a result, they found out that the panel has the highest compression strength when the initially sinusoidal corrugated core deforms into a square wave pattern. Moreover, it was shown that the stress–strain curves of the corrugated panel had an undulating behavior in compression, which reflects the initiation, spreading, and arrest of the localized plastic collapse mechanisms. Rejab and Cantwell [11] investigated a series of experimental and numerical analyses on the compression response and subsequent failure modes of the corrugated core sandwich panels which were made of three different materials: aluminum alloy, glass fiber reinforced plastic, and carbon fiber reinforced plastic. Particular attention in this work was paid to the effect of the number of unit cells and the thickness of the cell walls in determining the overall deformation and local collapse behavior of the panel. They realized that the buckling of the cell walls was the first failure mode in these corrugated structures and increasing the compression loading will result in the localized delamination as well as debonding between the skins and the core. The experimental results were compared to finite element and analytical solutions. The predictions offered by the numerical models were in good agreement. However, the analytical model overestimated the load-bearing capability of the corrugations due to the fact that the model assumed a perfect bonding between the apex of the corrugated core and the skin and neglected the effect of initial imperfections along the cell walls. Kooistra et al. [12] analyzed the transverse compression and collapse mechanisms of a second-order hierarchical corrugated sandwich panel. In contrast to a first-order corrugated sandwich panel which exhibits two competing collapse modes of elastic buckling and plastic yielding, they showed that the second-order corrugated panel has six competing modes of failure: elastic buckling and yielding of the larger and smaller struts, shear buckling of the larger struts, and wrinkling of the face sheets of the larger struts. Farrokhabdai et al. [13] investigated the mechanical behavior of a multi-layered composite sandwich panel with a multi-layer corrugated core subjected to quasi-static three-point bending experimentally and numerically. Parameters such as contact force, energy absorption, and specific absorbed energy (unit mass energy) were studied for different corrugated core geometries (rectangular, trapezoidal, and triangular) during the loading and failure process. Experimental investigations on the laser - welded triangular corrugated core sandwich panels and equivalent solid plates subjected to air blast loading were the subject of the study by Zhang et al. [14]. Mechanical behavior of multilayered sandwich panels of wood veneer and a core of cork agglomerates was tested in perpendicular compression and tensile, longitudinal compression, three and four-point bending and shear, and load–displacement curves patterns and cracking fractures were analyzed by Lakreb et al. [15]. Akhmet et al. studied the stress distribution at the adhesive joints of the corrugated sandwich structure subjected to three - point bending using the cohesive zone model [16]. They employed FEA and conducted experiments to assess the effects of parameters such as adhesive layer thickness and adhesive joint width on the stress distribution. Experimental investigation of the static behavior of corrugated plywood core bonded between plywood face sheets was performed by Kavermann and Bhattacharyya [17] via three and four-point bending tests. Energy absorption characteristics of composite corrugated core sandwich panels by considering varied core geometries under quasi-static out-of-plane loading conditions were presented experimentally by Taghizadeh et al. [18]. Jiang et al. designed and employed the horizontal stiffener with the aim of reinforcing flexural performances of corrugated core sandwich composite structures [19]. Several stiffeners with different thicknesses, positions, and numbers have been studied via FE simulation. The effect of the number of layers and core configurations of multi - layered thermoplastic composite corrugated sandwich panels were experimentally and numerically investigated by Chen et al. [20]. They performed quasi - static compressive tests and characterized the failure deformation modes of these structures. Zurnaci et al. [21] compared the compressive performance of metal sandwich panels with a corrugated core in 2 models of integrated corrugated and cut corrugated under quasi-static compressive load with experimental testing and found that geometry plays a key role in compressive performance. They also found that the cut corrugated core performed better.

Many researchers have investigated the effect of the core geometries on energy absorption and crushing behaviors of sandwich panels. They concluded that the shape of the core plays a key role in that matter. In this paper, the crushing behavior and energy absorption capacity of two sandwich panels with egg box cores made of corrugated strips are compared. Both specimens are made using metal sheet work and are tested using quasi-static compressive load till crushing.

2. Research Method

In this paper, the crushing behavior of a sandwich panel with an egg-box core consisting of trapezoidal cross-corrugated sheets is evaluated experimentally. The core of the studied sandwich panel has four egg-box cells. An upper view of a nine-cell core of the studied sandwich panel is shown in Fig. 1. The corrugated core profile of the specimens and their dimensions are shown in Fig. 2 and Table 1, respectively. Two specimens with different heights are studied in this research.

The samples are made of 0.5 mm-thick ST37 steel sheets, using the sheet metal work method and spot welding. The properties of ST 37 steel are presented in Table 2. The basic compartments of the core are produced by cutting steel sheets and bending them to the required shape. The basic compartments are assembled into the egg-box core shape and spot-welded together and to the faceplates. The spot weld process is shown in Fig. 3.

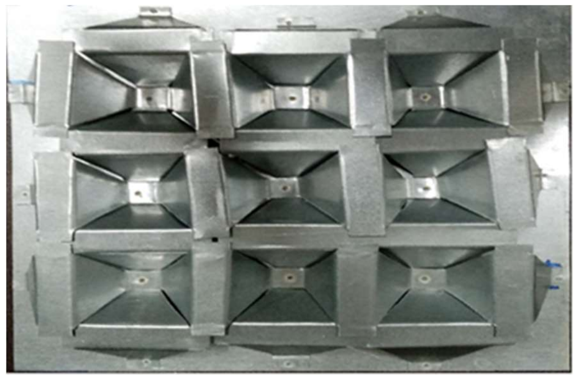

Fig. 1. Top view of the studied egg-box core

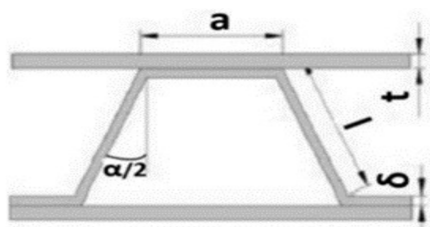

Fig. 2. The schematic shape of the trapezoidal corrugate profile

Table 1. The specimens' dimensions.

Specimen	$\frac{\alpha}{2}$ (°)	L (mm)	a (mm)
T30	30	43.3	20
T40	40	31	20

Fig. 3. Spot welding the basic compartments of the core

Table 2. Mechanical properties of ST37 steel

Young module (GPa)	Poisson's ratio	Yield Stress (MPa)	Ultimate Stress (MPa)	Elangation (%)
200	0.3	250	400	20

Afterward, the samples are subjected to a quasi-static crushing test using the Santam STD-600 universal compression testing machine (Fig. 4). As the specimens' width is larger than the test machine's jaws' width, two thick panels are used to even out the pressure on the test specimens. These plates are placed on the top and bottom of the specimens as shown in Fig. 5. Due to the large distance between the upper and lower of the universal testing device's jaws, a cruciform steel piece (Fig. 4) and a circular metal plate with a thickness of 5 cm (Fig. 5) are used to compensate for this distance.

The samples are placed between the two jaws of the compression testing machine and the upper jaw moves down with a constant speed of 5 mm/s, the test speed is chosen to ensure the quasi-static condition. The amount of force applied by the device at any moment is measured by the load cell. In this way, the crushing force-displacement diagram has been extracted for these sandwich panels.

Fig. 4. Santam STD-600 compression testing machine

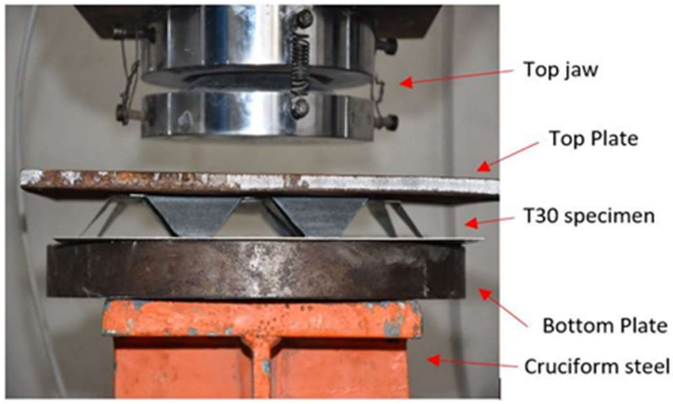

Fig. 5. Sandwich panel test details

3. Energy Absorption Evaluation

To evaluate the energy absorption capability of the studied sandwich panels in the compression test, the crushing force-displacement diagram is extracted. Many researchers have proposed different parameters to evaluate the crashworthiness of the energy absorber structures. Among them, the amount of absorbed energy (EA), energy absorbed per unit mass of the structure (SEA), Initial Peak Crushing Force (IPF), Mean Crushing Force (MCF), and Crushing Force Efficiency (CFE) are more common in the literature and can be calculated using the data extracted by compression test. EA is equal to the area under the crushing force-displacement diagram, i.e.:

$$EA = \int_{0}^{D_{\max}} F.ds \tag{1}$$

Where F and EA are the crushing force and the amount of absorbed energy, respectively; ds is the amount of displacement integral parameter which changes from zero to $D_{\max}$, the deformation at the start of the densification region.

SEA is another measure to evaluate a structure's energy absorption capability and is equal to:

$$SEA = \frac{EA}{m} \tag{2}$$

where m is the mass of the energy absorber.

Other parameters, that are used to evaluate the crashworthiness of structures, are the IPF and MCF. IPF is the highest force required to initiate the buckling of the structure in thin-walled structures after reaching this point the amount of the crushing force will decrease and the force at this point is a local maximum of the crushing force-displacement diagram. It is demanded to minimize IPF as in energy absorbers used in vehicles, reducing the amount of crushing force applied to the structure during the collision can improve the safety of the passengers. Although the designers aim for lower IPF, they try to maximize the amount of force applied during the whole course of the collision, in order to maximize the absorbed energy.

$$MCF = \frac{EA}{D_{\max}} \tag{3}$$

In the energy absorber structures, the bigger the Mean Crushing Force (MCF), the more the crashworthiness. Thus, the ratio between the MCF and IPF in some structures can show the crushing force efficiency.

$$CFE = \frac{MCF}{IPF} \tag{4}$$

An ideal design would have a CFE value of 1 by maintaining the maximum initial crushing force throughout its length; so that it is the same as the average crushing force [22].

4. Results and Discussion

In this research, the fabricated specimens are subjected to a quasi-static compressive test and the crushing force-displacement diagram is extracted, which is shown in Fig. 6 for both T30 and T40 specimens. The energy-absorbing structures are efficient until the start of the densification region, where the load starts to increase abruptly. It is clear that these structures do not behave like thin-walled tube structures, and IPF is not the maximum load applied to the structure during the crushing.

The force-displacement diagram for the specimens is presented until the densification region. It can be concluded from Fig. 6 that until the first buckling, both specimens behave the same and almost in a linear manner, but the T30 specimen buckling load is 63.2% higher than the T40. T40's free-to-deform length is bigger and thus its buckling load is smaller. It should also be noted that due to the initial imperfection caused by manufacturing errors, the first part of the diagram is not linear.

After the force reduction caused by the first buckling, the crushing force is increased for both specimens. While the force of the T40 structure is relatively constant after the first buckling, The T30 experiences the second maximum load at the point (f=9.8, x=11.3). As the T30 specimen height is smaller than the other specimen, its effective crushing length is also smaller.

In Fig. 7, the first and second buckling shapes of the T40 sample are presented, respectively. It is clear that the right part of the structure buckled first. The side walls of the studied specimens are prone to buckle due to the lack of transverse supports. The perfect design of the structure is symmetric which means that all side walls have the same buckling risk. While the manufactured specimen is curved as shown in Fig. 7-a. This will cause the load transfer first to the right side wall in Fig. 7-a. The left side wall will then buckle when the left part of the lower plate gradually comes in contact with the lower test machine's jaw due to the deformation of the specimen as in Fig. 7.

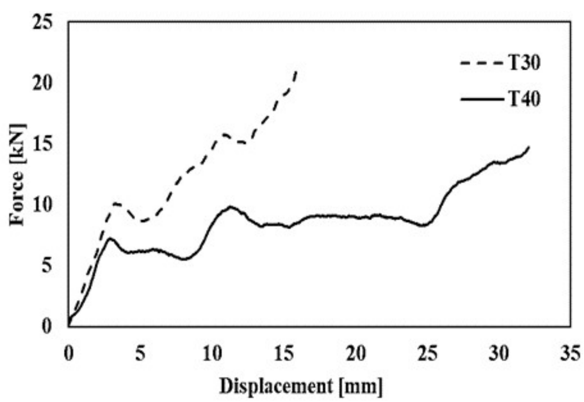

Fig. 6. Force-displacement diagram for T30 and T40 specimens

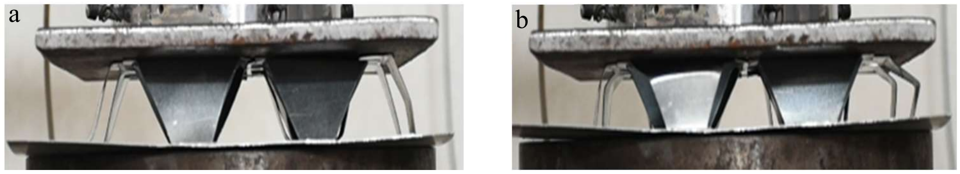

Fig. 7. (a) First buckling of the T40 specimen ; (b) second buckling of the T40 specimen

In the T40 specimen, the left side wall initially is bent, and the other core's side walls buckles afterward. The buckling shape of the edges is accordion-like in two half-wave modes. In such a manner, the left part of the core undergoes a larger deformation, and other parts deform less due to the initial imperfection in the structure. The T30 specimen crushing modes are the same as T40. Its buckling initiates from the left side wall and then progresses to other parts of the core. At the end of the test, the T30 model experiences less deviation to the left as compared to the T40 (Fig. 8 and Fig. 9). In both samples, the connection of the core to the bottom plate (made by spot welding) remains intact and does not fail.

Fig. 8. The Model T40 at the end of the test

Fig. 9. The Model T30 at the end of the test

Using Eqs. (1) and (2) and (3) and (4), IPF, CFE, and EA indices are calculated for the above-mentioned specimens and presented in Table 3. In the force-displacement diagram, the first maximum crushing force shows the first behavior of the panel against the compressive load. As loading begins, the compressive load increases linearly until the core of the sandwich panel begins to buckle and both specimens experience an initial peak load followed by a decrease in force with increasing displacement. In the T40 sandwich panel, the elastic behavior is initially linear until the force reaches the first peak force at P=7.2 kN; then the amount of compressive force on the sheet remains constant. After that, the second peak force occurs at P=9.8 kN; and the resistance of the sample decreases and the panel is condensed and the amount of force increases suddenly. The amount of energy absorption in this case is equal to 88.5 J. In the T30 sandwich panel, the initial peak load occurs at P=10 kN and then the load will increase and reach the second peak load P=15.5 kN. The buckling shape of the part is shown in Fig. 8. In this case, the amount of energy absorption will be equal to 133.2 J.

Table 3. Crashworthiness indices of T30 and T40

	IPF (kN)	EA (kN)	SEA (J/kg)	CFE
T30	9.8	88.538	177.076	0.806
T40	15.5	133.227	226.454	0.682

5. Conclusion

In this study, a corrugated core configuration is proposed to improve the compressive performance of metal sandwich panels. The sandwich panel with different angles of the leg relative to the core is made by sheet cutting and spot welding process, and the quasi-static compression tests of the sandwich panels are conducted. The compression behaviors are then investigated experimentally. Finally, after the experimental investigations, the comparison of their compressive performance results is done in detail. According to the force-displacement diagram and Table 3, the amount of energy absorption, peak force, specific energy absorption, and energy efficiency in the core mode with an angle of 40 degrees are calculated to be about 1.5 times that of the core mode with an angle of 30 degrees. This means that a sandwich panel with a base angle of 40 degrees can absorb more energy, withstand more force, and be more efficient than a panel with a base angle of 30 degrees. The reason is that increasing the leg angle increases the bending stiffness of the core, which makes it more resistant to buckling and deformation. This is because increasing the leg angle increases the flexural stiffness of the core, which makes it more resistant to buckling and deformation. The results showed that the use of a corrugated core configuration with an optimal base angle can increase the compressive performance of metal sandwich panels. This can be useful for applications that require lightweight and strong structures, such as aerospace engineering, civil engineering, and automotive engineering. For example, corrugated core sandwich panels can be used in aircraft fuselages, bridge decks, and car doors.

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