Journal of Stress Analysis
Vol. 6, No. 2, Autumn − Winter 2021-22, 123-130

Bu-Ali Sina University

ORIGINAL RESEARCH PAPER

Experimental and Numerical Crushing Behavior of Sandwich Structures with Two-layered Bi-directional Corrugated Core and Single-layered Bi-directional Interconnected Corrugated Core

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Article info

Article history:
Received 09 January 2022
Received in revised form
03 February 2022
Accepted 09 March 2022

Keywords:
Mechanical energy absorption
Crushing
Quasi-static compression
Two-layered bi-directional corrugated core
Single-layered bi-directional interconnected corrugated core

Abstract

This paper investigates the quasi-static compressive strength of two sandwich structure designs in which cores consist of trapezoidal corrugated panels. In one design, the core consists of a steel cross-corrugated two-layered structure, while in the other design, the core consists of a single layer of bidirectional interconnected corrugated core made of ST37 steel sheets. To investigate the energy absorption capacity of these sandwich structures quasi-static compression is performed numerically and experimentally. First, from each design, a test specimen is constructed and tested under quasi-static compressive load. Following that, the finite element models of the designs are constructed and their crushing process is simulated and the FEM method results were compared with the test results and the FE model is verified. After verification of the numerical model, for each design, three different trapezoidal wave profiles are modeled and, the mechanical behavior of the other bidirectional interconnected corrugated cores is evaluated numerically. The results showed that the maximum force and energy absorption capacity of the sandwich structures with the single-layered bi-directional interconnected corrugated core is higher than the strength and energy absorption capacity of their counterparts with the same weight in the two-layered bi-directional corrugated core group with the same weight. It was also found that, in the single-layered bi-directional interconnected corrugated core group, the failure mode is plasticity near the welding joints, while for the single-layered bi-directional interconnected corrugated core, the failure mode is plastic buckling of the corrugated core under compressive load and some local plastic deformation in the connection of the layers.

1. Introduction

The sandwich structures are typically made of a low-density core and two outer faceplates. Sandwich structures are significantly versatile since their core can be made of different materials with various structures such as foam, honeycomb, corrugated plates, or nature-inspired structures. On the other hand, these structures have high energy absorption capacity, thus they are used in various industries from packaging to the military.

Basic quantities to evaluate the mechanical qual-

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http://dx.doi.org/10.22084/JRSTAN.2022.26073.1206
ISSN: 2588-2597

ity of sandwich structures generally include the maximum force and the specific energy absorption capacity under flexural and compressive loads. In addition, stiffness and deformation range can be considered acceptable mechanical criteria for evaluating the energy absorption capacity of a structure. Sandwich panels are exposed to many loading conditions during their lifetime. One of which is the out-of-plane compression. The energy absorption capacity of the sandwich structures under out-of-plane compressive loads is assessed using a quasi-static compression test.

The results of a typical quasi-static compression test can be expressed by a force-displacement diagram. According to this diagram, as the compressive force on the structure increases, the deformation of the structure also increases until the maximum force is reached and, in this case, the load-bearing capacity of the structure decreases abruptly. After that, the load may have an alternating increasing and decreasing trend, or it may stay quite unchanged for a long period of deformation.

Due to the increasing use of sandwich structures in various industries, many studies have studied investigated new sandwich structures with better mechanical performance under defined loading conditions. Sandwich structures with truss or kagome core can absorb mechanical energy despite their low weight and have been studied extensively. Sun and Gao [1], Wang et al. [2], and Xu et al. [3] designed composite sandwich panels with truss cores and studied their performance under quasi-static loads experimentally and numerically. To investigate the buckling and post-buckling of such structures, Sebaey and Mahdi [4] numerically analyzed the buckling and post-buckling behavior of a composite sandwich structure with a truss core under biaxial compressive load and presented a new design for sandwich structures designs with a kagome truss core.

Sandwich structures with truss cores can also be made in multilayer designs, and their mechanical energy absorption capacity can be increased. Xiong et al. [5] investigated the compressive strength and impact strength of a two-layered composite sandwich structure with a truss core. By comparing structures made of carbon fiber and glass fiber, they concluded that structures made of carbon fiber were capable of absorbing more energy. Li et al. [6] also investigated the compressive strength of a multilayer composite sandwich structure with a pyramidal truss core and compared the mechanical properties of such structures with a foam-filled core and without foam. Their research showed that foam-filled sandwich structures have a higher energy absorption capacity.

Sandwich structures with a corrugated core are another type of sandwich structure in which the core is a sheet that is shaped into a corrugated or honeycomb core. Various designs of sandwich structures with corrugated cores have been studied. The energy absorption of this group of sandwich structures has been studied under different static or dynamic loads. In sandwich structures, the faceplates may be flat or curved. Mamalis et al. [7] investigated the failure behavior and energy absorption properties of composite tubular components of sandwich structures with corrugated cores and cylindrical faceplates under quasi-static compressive axial loading. Chen et al. [8] investigated the strength of a cylindrical structure with a honeycomb core under quasi-static load.

Huo et al. [9] studied the sandwich structure with flat faceplates, triangular and trapezoidal corrugated cores under quasi-static loading using both experimental and numerical methods and presented the optimal parameters for both sandwich structures. To increase the resistance of composite sandwich structures against the delamination of lateral shells and cores, Jin et al. [10] and Abedzade Atar et al.[11] proposed a new sandwich structure, in which the corrugated core and faceplates were woven together.

Rejab and Cantwell [12] compared the differences in strength, fracture modes, and mechanical behavior of aluminum sandwich structures, glass fiber-reinforced plastics, and carbon-fiber-reinforced plastics with corrugated cores under quasi-static transverse compressive loads. Hu et al. [13] studied the mechanical behavior of a composite sandwich structure with a core composed of interwoven corrugated strips. They tested the structure under quasi-static shear, in-plane compression, and flexural loads. Heimbs et al. [14] investigated the crushing strength of a sandwich structure with an origami corrugated core made of carbon fiber and aramid.

Sebaey and Mahdi [15] investigated the energy absorption, maximum force, and mean crushing force for a unit cell core of a composite sandwich structure with a lattice design with and without foam and proposed a structure with higher maximum force and energy absorption. Using a composite made of natural fibers, Li et al. [16] designed a composite sandwich structure with a core of interwoven corrugated sheets and evaluated its mechanical behavior under out-of-plane compressive loads. Zhao et al. [17] proposed a new core structure consisting of corrugated panels with a wave profile perpendicular to the faceplates made of Ti-6Al-4V and investigated its behavior under quasi-static transverse force. Che et al. [18] proposed a new design for a multilayer steel sandwich structure with a bidirectionally corrugated core and studied its behavior under compressive load. Due to the more uniform load transformation between core and faceplates during the crash process, it was concluded that the structure has high efficiency for energy absorption. Kilicaslan et al. [19] also investigated the crushing of a sandwich structure with a single layer and multilayer discontinuous corrugated core. Taghizadeh et al. [20] improved the behavior of composite multilayer sandwich structures against low-speed impact using different core layouts and different flexural stiffnesses in layers.

Zhang et al. [21] investigated the strength of sandwich structures with honeycomb cores and increased the impact strength by placing reinforcing tubes inside the honeycomb core. Li et al. [22] proposed another design of sandwich structures in which the core can be described by an interconnected combination of interlocking orthogonal corrugated cores. Using a rapid prototyping method, they fabricated an integrated polymer specimen with a trapezoidal wave profile. Finally, they evaluated the mechanical behavior of the fabricated sample.

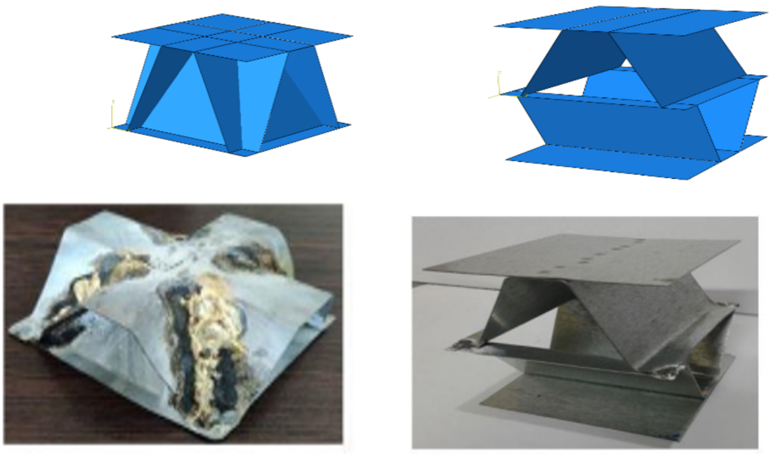
Reviewing the research literature, it can be observed that many parts of research have been dedicated to designing and improving the energy absorption of sandwich structures. Depending on the subject, they proposed new geometries or suitable materials for structures. Since the change in the choice of material of the components, as well as the way of connection between them, affects the mechanical behavior of the sandwich structure, the design proposed by Li et al. [22] can be revised. Accordingly, based on the geometry introduced by Li et al. [22], a new metal sandwich structure is designed that can be made using conventional sheet metal work. In the new design, not only is the core materials changed to steel but also the connections between its substructures are welded joints. The mentioned structure can be constructed by integrating a set of formed sheets metal work [23, 24].

2. Materials and Methods

Based on the geometric description, the studied sandwich structures are as follows:

- B-type: A sandwich panel with a single-layered bi-directional interconnected trapezoidal corrugated core (Fig. 1a).
- M-type: A sandwich panel with a two-layered bi-directional trapezoidal corrugated core (Fig. 1b).

Three cores with the different dimensions were considered for the core corrugation profile. The dimensions of both sandwich panels' cores are described in Table 1.

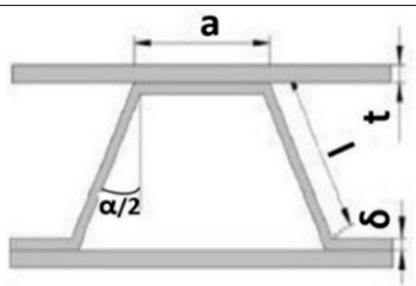


B-type sandwich structure M-type sandwich structure

Fig. 1. Two studied sandwich panels.

Table 1
Sandwich panels' cores dimensions

$\frac{\alpha}{2}$ (°)	l (mm)	a (mm)	Specimen
30	43.3	20	B30 M30
45	31	20	B45 M45
60	25	20	B60 M60



All the core pieces and faceplates of the sandwich structures were made of ST37 structural steel sheets of 0.5mm thickness. The M30 specimen was made by bending metal sheets to a corrugated shape and joining the pieces through spot welding. The pieces that made the B30 sandwich structure is shown in Fig. 2 and its building process can be described as follows:

1) Expanded two-dimensional forms that can be folded to shape the different parts of the cores are prepared on a 1:1 scale.

2) Based on these sketches, the 0.5mm steel sheets are cut and bent according to the desired trapezoidal wave profile.

3) The core consists of a continuous corrugated panel as the base and 3 pieces that are mounted on the base as reinforcements. The 3 reinforcements are placed along each other to form a piecewise corrugated panel perpendicular to the base corrugated panel which is continuous.

4) After placing all the pieces together to shape a bidirectional corrugated core, first the pieces are connected by spot welding and the position of the parts is stabilized. Finally, the whole set is integrated using the brass welding method.

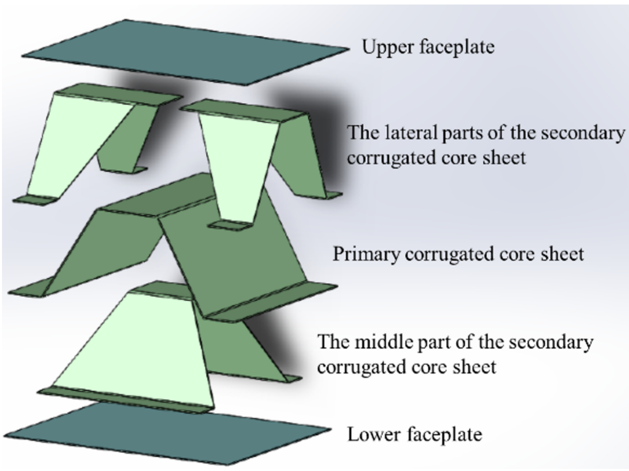


Fig. 2. The B30 specimen pieces.

The M30 and B30 samples were subjected to out-of-plane compressive quasi-static loading at ambient temperature and the force-displacement diagrams were derived. In this research, the SANTAM STD600 compression testing device was used. In which, the upper platen of the device moved downwards at a speed of 5mm/min, and the applied force was recorded using a load cell.

Although the compressive behavior of the structures can be studied using experimental methods, the advances in the numerical methods, especially in the FE methods, enable us to investigate the crushing phenomenon at a relatively low cost. Thus, to study more designs, studied samples were modeled on ABAQUS Commercial Finite Element Software. As the thickness of specimens was relatively small, these structures can be modeled using shell elements. Therefore, the element type S3, which is a shell element with 3 nodes, was used for the core, so the core with irregular shape could be meshed, while the element type S4R which is a shell element with 4 node was used to map mesh the square faceplate. The two platens of the compressive test machine were modelled using rigid boxes, one of which was fixed at the bottom and the other was moving downward. The contact between the platens and the model was defined as frictionless.

The problem was solved using the displacement-controlled method. The displacement was applied to a rigid block above the upper faceplate in the direction perpendicular to the faceplates at a speed of 5mm/min. A fixed rigid block was also placed below the lower faceplate. The contacts between pieces, self-contacts, and contact between parts were defined to be frictionless and the material was assumed to be perfectly elastoplastic. The Young modulus and the strength of the plate sheets were obtained from tension test. The elastic modulus was obtained to be 204GPa and the yield strength was equal to 216MPa. The tensile test specimens were made based on ASME standard and cut using wire cut and are shown in Fig. 3.

Fig. 3. The tensile test specimens.

3. Results and Discussion

To validate the proposed FE model, the corresponding FEM results were compared with those of the experiments. The B30 and M30 specimens were tested under a compressive quasi-static load. The force-displacement diagrams for B30 and M30 crushing tests were obtained and the results were compared with the FE results in Figs. 4 and 5. As shown in these Figures, the numerical method can well estimate the crushing behavior for both structures.

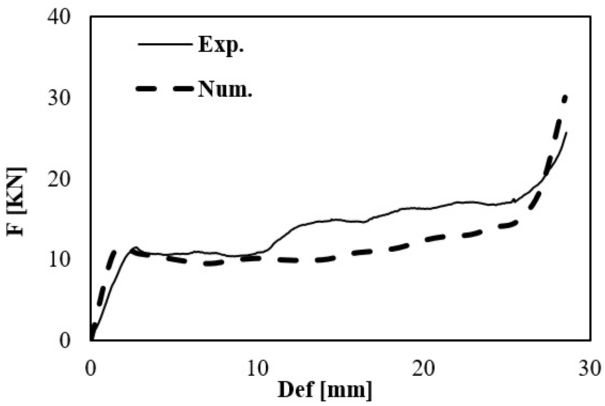


Fig. 4. The force-displacement of the B30 specimen.

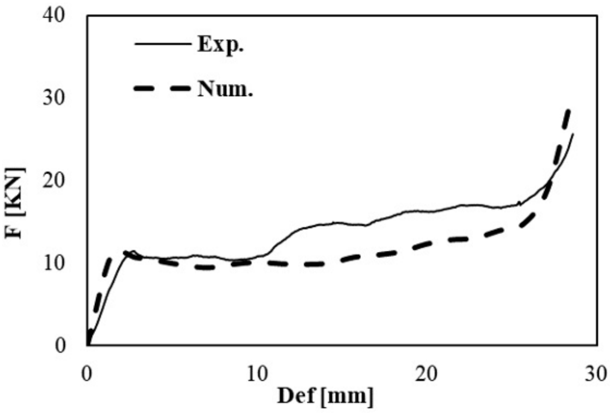


Fig. 5. The force-displacement of the M30 specimen.

Fig. 6 also shows the comparison between the deformations calculated in the numerical method and the deformations of the experiments for the first sample. In this figure, the distribution of plastic strains calculated in the numerical method can also be seen. It is clear that in this sample, up to 10mm displacement, the force measured in the experiment and in numerical analysis are well matched. After this deformation, the value measured in the experiment is greater than the calculated value. It should be noted that the failure in this sample begins with the plasticization of the area around the joints of two corrugated core sheets, which are connected by welding. In this area, due to bronze welding, the amount of hardness and strength is locally higher than the model under study and it seems that the error in this analysis is inevitable.

Fig. 7 shows the comparison between the deformation in the experiment and the deformations calculated in the numerical method for the M30 specimen as well as the plastic strain distribution calculated by the numerical method. In the crushing phenomenon of multilayer structures, usually, the weaker layer collapses first and the amount of force increases to the maximum force that this layer can withstand. After that, the force decreases until the next weakest layer starts to collapse. The damage continues in the same way until the last stage of the crushing phenomenon in which all layers failed. If the layers are similar, one of the layers will collapse due to the stress distribution and the force transmission process, and then the next layers will collapse, respectively. In the M30 specimen, the upper corrugated panel's bases buckled first. But due to the fact that the load transfers through layers, in the lower corrugated panel's bases, there was also a local plastic deformation. After that, the force increased to the maximum strength of the lower layer and then decreased.

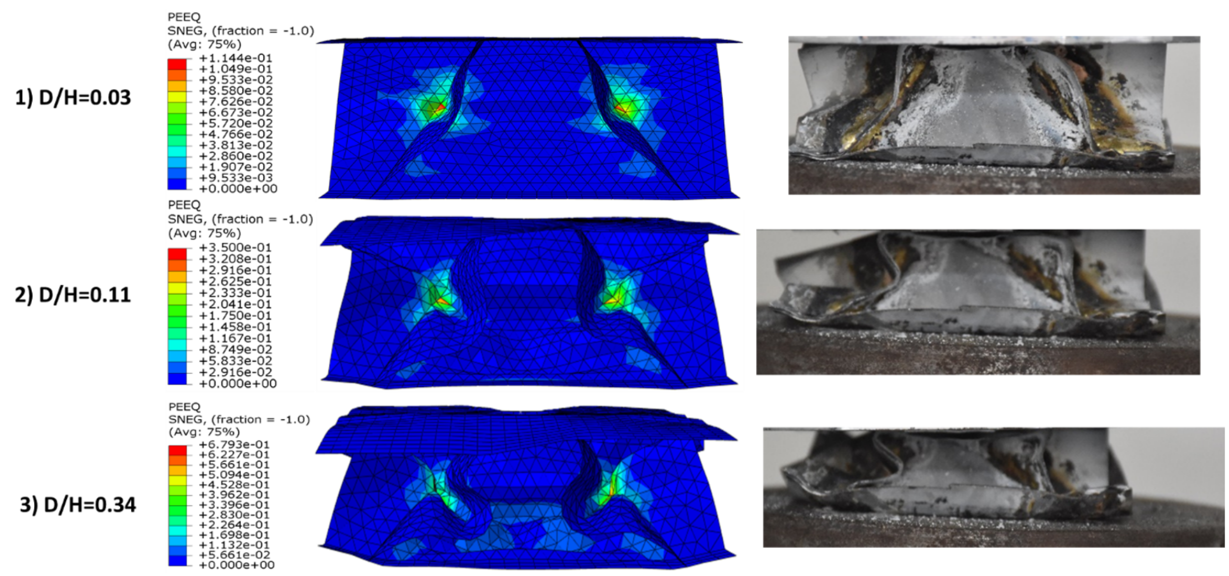


Fig. 6. The displacement and plastic strain contour for B30 specimen.

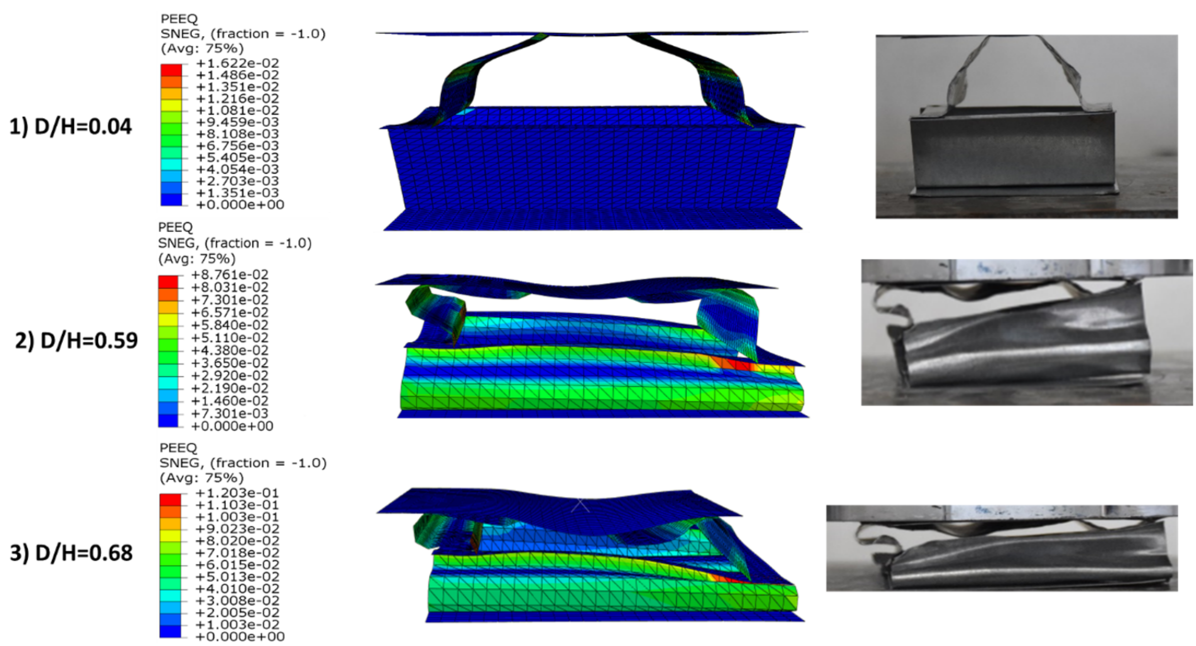


Fig. 7. The displacement and plastic strain contour for M30 specimen.

Figs. 8 and 9 illustrate the force-displacement curves for B and M-type specimens. It should be noted that the horizontal axis in these diagrams is the D/H, in which D is displacement and the H is the height of the specimen. From Table 1, it can be deduced that the height of M30, M45 and M60 are not equal. The M30 specimen's height is the highest and the height of M60 specimen is the lowest. For the B-type specimens, the force-displacement diagrams are very similar and the B30 has the largest maximum force. While the M-type specimens have quite different trends in their force-displacement curves.

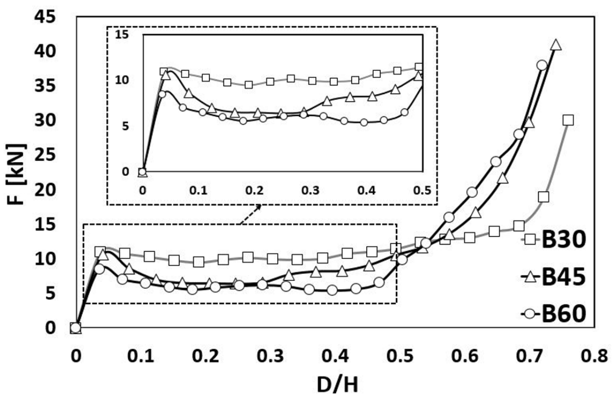


Fig. 8. The force-displacement for the B-type specimens.

In the former structures, the collapse mode is plasticity and its progression to the other area. On the other hand, the latter structures' collapse mode is buckling which depends on the geometrical dimensions. Thus, in the M -type, the shortest specimens will have the higher buckling force and hence the upper maximum force. In both diagrams, a sudden load increase occurred at the last stage of the crushing. This is the end of the crushing phenomenon. For using these structures as a passive energy absorption system, this crushing stage will be avoided, to limit the applied forces to the structures. Also for passive energy absorption system.

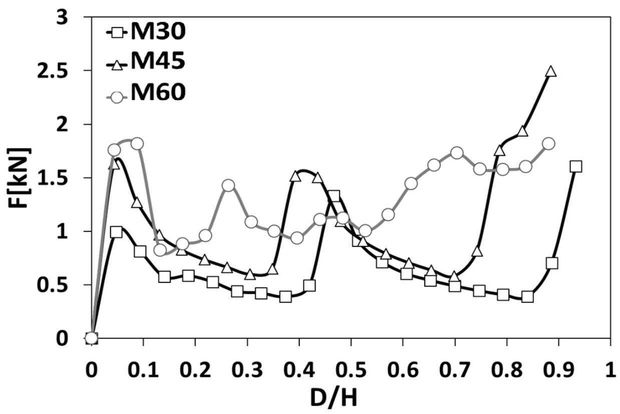


Fig. 9. The force-displacement for the M-type specimens.

The absorbed energy is calculated using the FEM results, by calculating the total area under the force-displacement curve and is presented in Table 2. The absorbed energy depends on the forces and the total displacement of the sandwich panel. The B30 and M30 are the highest specimens and during the crushing test have the highest deformation range, thus they both have a higher energy absorption capacity. On the other hand, the shortest specimens, that are B60 and M60, have the lowest energy absorption capacity, although M60 has the largest maximum force. In comparison to the absorbed energy, it should be noted that the corresponding specimens in M group and the B group have the same weights.

Table 2
Absorbed energy during crushing.

B60	B45	B30	
102.5	207.6	355.1	Absorbed Energy (J)
M60	M45	M30	
27.1	40.4	46.8	Absorbed Energy (J)

4. Conclusions

In this paper, the crushing behavior and energy absorption of unit cells of two sandwich structures with different core arrangements made of steel sheets were studied, experimentally and numerically. The test specimens consisted of a single-layered bi-directional interconnected corrugated core and two-layered bi-directional corrugated core. First, specimens were tested under out-of-plane compression and the force displacement diagram for both specimens were extracted. Afterwards, the numerical method's results were compared to the test results and good agreements between test and numerical simulation was achieved. Then the results for other specimens were derived numerically. Using a single-layered bi-directional interconnected corrugated core instead of a two-layered bi-directional corrugated core in order to increase the energy absorption and strength of the structure under quasi-static out-of-plane load was an efficient method that increases the peak loads, absorbed energy. The plateau region in the force-displacement diagram of the single-layered bi-directional interconnected corrugated core was also another good mechanical behavior. It should be that both designs had the same weight, while the former height was also smaller and was operationally beneficial. The results of this research revealed that this novel steel sandwich structure design could enhance the mechanical performance of corrugated steel sandwich structures dramatically.

For the sandwich panel with a two-layered bi-directional corrugated core, the failure mode was buckling of the core layers under compressive load, and the failure occurred layer by layer. Consequently, the force diagram had an alternating increasing and decreasing trend. Due to the major failure mode, which was buckling, these structures' strength depends on the geometry, and the bigger their height is, the more their maximum force is. While the energy absorption capacity of the structure depends on load and deformation range, and the mean force range for all specimens in that category is almost the same, so the energy absorption increases by the height of the sandwich structure.

Furthermore, for the sandwich panel with a single-layered bi-directional interconnected corrugated core the failure mode was plasticity in the welding joints and near them and the plastic region and plastic deformation increased until the final phase of the crushing. The applied crushing force of this structure was quite the same for all specimens, while the energy absorption however depends on the deformation range and changed dramatically.

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