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Static Behavior of Sandwich Paneled Steel Beams under Flexural Loads: Finite Element Analysis

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الملخص العربي

في هذه الدراسة تمت دراسة سلوك الكمرات ذات الشطائر ذات الحشو ذو الأشكال المختلفة. تم استخدام برنامج تحليل العناصر المحدودة (ABAQUS). تم استخدام النموذج الذي تم التحقق منه لدراسة تأثير شكل لحشو واتجاه شطائر الحشو على قدرة التحمل القصوي للكمرات ذات الشطائر. أشارت النتائج العددية الحالية إلى أن السعة القصوي للحمل للكمرات الحديده ذات الحشو علي شكل نصف منحني داله الجيب في الاتجاه الطولي يكون أكثر كفاءة من الكمرات الحديده ذات الحشو علي شكل منحني داله الجيب الكامل في نفس الاتجاه وذات الحشو علي شكل جمالون. إن السعة القصوي للحمل للكمرات الحديده ذات الحشو علي شكل نصف منحني داله الجيب في الاتجاه الطولي تحت تاثير حمل الانحناء ذو الثلاث نقاط أكبر من نظيراتها ذات الحشو في الاتجاه العرضي بحوالي 52.8٪.

Abstract

In this study the behavior of sandwich steel beams having different core shapes was studied. The finite element (FE) analysis program (ABAQUS) was used. The verified model was used to study the effect of core shape, panel direction on the load carrying capacity of the sandwich beams. The present numerical results indicated that, the load carrying capacity of the sandwich steel beams have half sin curve core section in the longitudinal direction is more efficient than the sandwich steel beams have full sin curve core section in the same direction and sandwich steel beams have truss core section. The load carrying capacity of the half sin curve core section in the longitudinal direction of sandwich steel beam subjected to 3-point bending is greater than that of the half sin curve core section in the transverse direction of sandwich steel beam by about 52.8 %.

1. Introduction

During the last decades, the use of lightweight core (corrugated core, polymeric foam and honeycomb) besides two face sheets to compose the sandwich structures was widely investigated. The core saves the position of the face sheets of the sandwich beam, increased its buckling, shear and bending resistance [1-3]. The use of sandwich structures becomes familiar in civil and mechanical engineering. Due to the light weight, high stiffness, high strength and energy absorption of sandwich composite structures, it is used in automotive, sporting and aerospace applications [4].

Libove et al. [1] studied the sandwich plates having a corrugated core. Many studies were performed to study the effect of the core materials of the sandwich beams besides the materials of its two facings [5-10]. The buckling and bending behavior of sandwich beams composed of a metal seven-layer and crosswise corrugated core has been analyzed [6]. The analysis assured that, the seven-layer beam experienced higher bending capacity, stiffness and less buckling than the three-layer one [6]. The sandwich structures having re-entrant honeycomb core experienced higher energy absorption with homogeneous stress distribution than that having truss and conventional honeycomb core [10]. Sandwich beams having thin sheets and cores with high mass specified high energy absorptions and loads but suffer from buckling of the sheets [11].

The mechanical behavior of metallic sandwich structures and the affecting factors such as loading rate and temperature was widely studied [12-19]. The beams cores can be shaped from metallic cellular include metallic foams [20–22], corrugated, square, trapezoidal, hexagonal honeycomb and tetrahedral lattices and pyramidal cores [17, 23–29]. From the previous research, the effect of the core shapes and arrangements on the failure loads and modes of the sandwich steel beams and steel slabs was slightly studied. In this paper, the effect of the core shape and core arrangement on the flexural capacity of sandwich steel beams under 3-point bending was numerically studied. A finite element 3D model was performed using the commercial FE program ABAQUS to simulate the sandwich beam with a core having half sin curve, full sin curve and truss core section. The model was verified using an experimental work from previous research. After words, the verified model was used to simulate sandwich beams having steel core with different shapes and configurations. Then the results of all the studied beams were compared to find the best shape and configuration that experienced the highest load carrying capacity.

2. Numerical work

2.1 Finite element model and boundary conditions

The commercial FE program ABAQUS was used to model the entire steel sandwich beams. The 3D eight node solid element, fully integrated (C3D8) was used for all elements [51]. All the simulated sandwich beams were tested in bending under central loads (3PB). A sensitivity analysis was performed to test the convergence of the model and to choose the suitable mesh size to simulate the tested beams. Based on this analysis, mesh size of 5 mm was chosen. The supports and the loading punch were modeled as solid element with steel having high yield and ultimate strengths. Tie contact was used to simulate the contact either between the supports and the beam or between the loading plate and the beam. Also surface to surface contact was used to model the interactions between the core layers and the plates (frictionless and pressure was used in the tangential and normal directions respectively). The load was applied using displacement control by applying displacement to a reference point located on the top of the loading punch in the direction of gravity. The load was calculated from the reactions at the two reference point located at the two supports (steel blocks). A rigid body constraint was used to model the relation between the reference points and the top surface of the loading punch or the bottom of the supports blocks.

2.2. Materials modelling

All elements of the simulated beams and slabs were modelled as elastic plastic steel with strain hardening. A bilinear stress–strain relationship in tension and compression was used to simulate the steel of the beams as shown in Fig. 1.

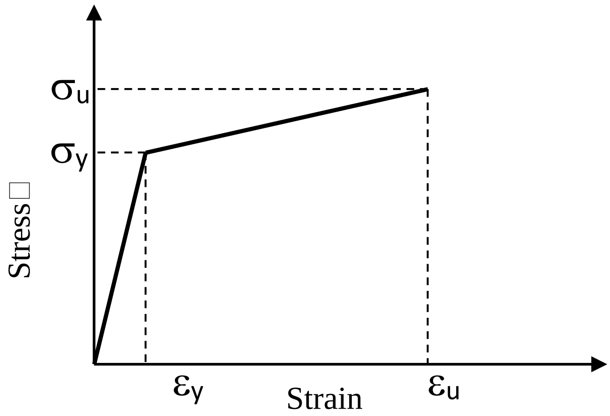
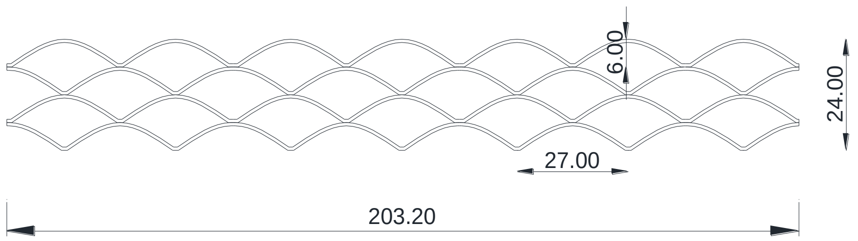


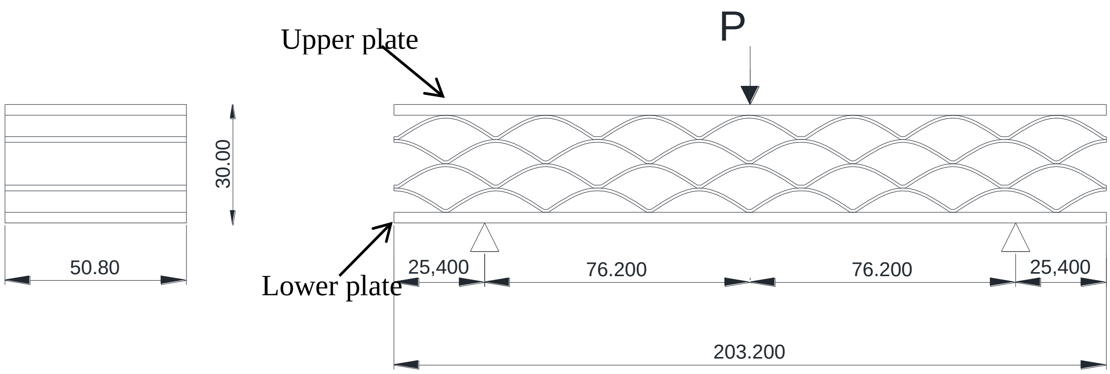
Fig.1 Stress-strain curve of the modeled steel

2.3 Verification of the simulated model

A Sandwich steel beam experimentally studied by Vaidya et al. [20] was used to verify the present model. The core of the simulated sandwich beam was composed of four corrugation sheets welded together to obtain one unit as shown in Fig. 2. The thickness of the each layer was 0.762 mm. The total and loaded span of the beam was 203.2 and 152.4 mm respectively. The upper and lower substrates consisted of two plates having the same thickness of 3.0 mm and width of 50.8 mm. The material properties of the core and substrates (upper and lower) are given in Table 1. The load was applied using a circular bearing plate with a diameter of 38.1 mm. The load was calculated from the reaction at the two reference point located at the two supports as shown in Fig. 3a (Front view). The mesh of the beam is shown in Fig. 3b (3D view).



(A) The corrugation core

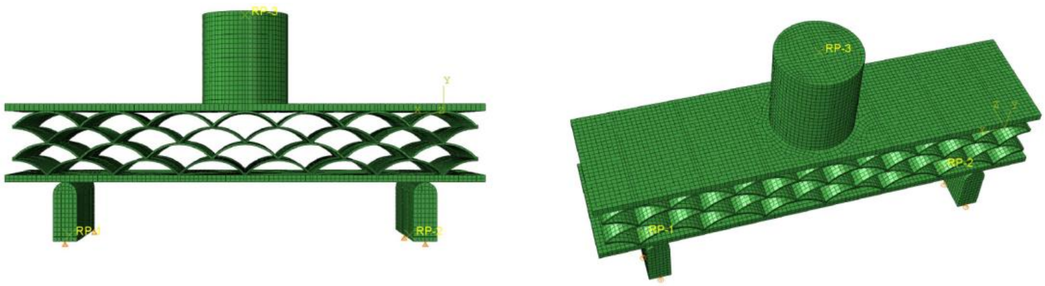


(B)The total beam set up.

Fig. 2: The sandwich steel beam with half sin curve core section

Table 1: The material properties of a sandwich steel paneled beam.

Element	E, GPa	ρ, gm/cm^3	υ	f_y , ,MPa	f_u , MPa
Core	200	0.0787	0.285	210	340
Plates	210	0.0787	0.29	460	520



a) Front view **b) 3D view**

Fig. 3: FE mesh of the simulated sandwich beam.

The numerical results of the load deflection response for the sandwich beam with half sin curve core section were compared with the corresponding experimental data as shown in Fig. 4. A good agreement between the experimental and numerical results is achieved. The ultimate load obtained numerically was 9.19 kN, which was 128 % of that found experimentally. The experimental and numerical difference in results may be accredited to stress-strain relation assumptions of the steel in the FE model (Bilinear curve). The program was stopped due to the distortion buckling of the model (see Fig. 5).

2.4. Parametric study

In the following sections the proposed simulated model will be used to simulate the sandwich beams with different core arrangements. The total height of the beams was kept constant. The dimensions of the top and bottom plates were kept constant (thickness= 3 mm and width = 50.8 mm). The thickness of the core corrugation was also kept constant (0.782 mm). All beams were of the same loading span and boundary conditions.

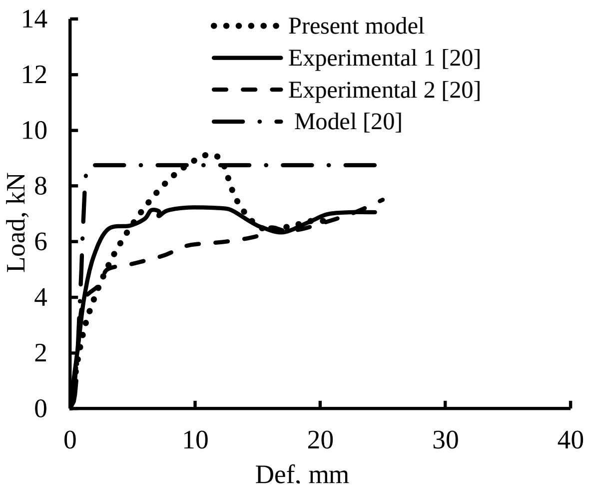
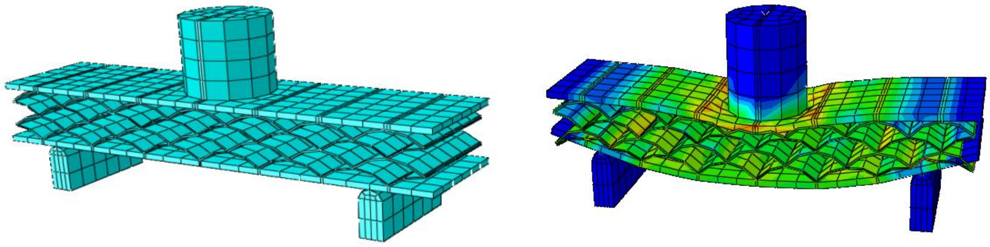


Fig. 4: The load deflection response for the simulated steel sandwich beam.



a) **Before loading** b) **At failure**

Fig. 5: Development of plasticity in sandwich steel beam with half sin curve core sec.

2.5 Simulated beams

The sandwich steel beam with modified core of half sin curve having thickness t_1 and having two steel plates of thickness t for each was the same as the sandwich beam with half sin curve core. The shape and thickness of the corrugated core of the two beams remained constant. The total depth and loaded span of the sandwich beam is also remained constant while the width of the beam was changed. For the sandwich steel beam with modified core of half sin curve, the direction of the core configuration corrugated core of the two beams are listed in Table 2.will be converted to be in the transverse direction, see Fig. 6.

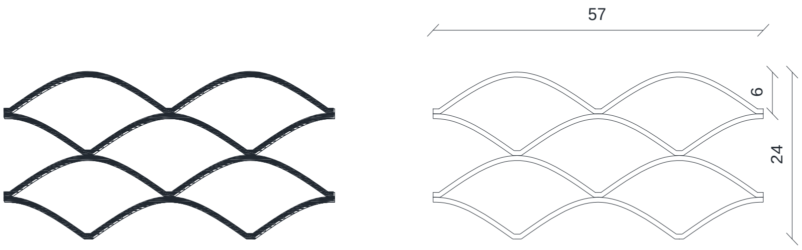


Fig. 6: Sandwich steel beam with half sin curve core in longitudinal dir.

Table 2: Dimension of the half sin curve in longitudinal and transverse direction.

Type of sections	h, mm	t, mm	t_1, mm	b, mm
Half sin curve in traverse direction	24	3	0.782	57
Half sin curve in long. direction	24	3	0.782	57

h= Height of core, t= Thickness of upper and lower plates, t_1= Thickness of the core sheet and b= breath of upper and lower plates.

So, it is a mandatory to study the verified sandwich steel beam with half sin curve core section with new breadth of 57 mm to make fair comparison with the modified beam, Fig.7. The sandwich steel beam was solved with new breadth of 57 mm which is the same breadth of the modified beams. All boundary conditions of the new beam were not changed. All dimensions of the beam section, the material properties of the core configuration and the two skin plates were not also changed with the verified beam, as shown in Table 3.

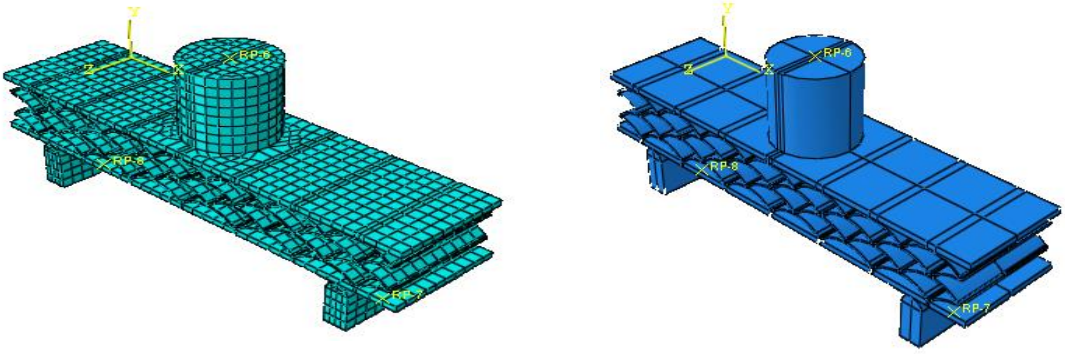
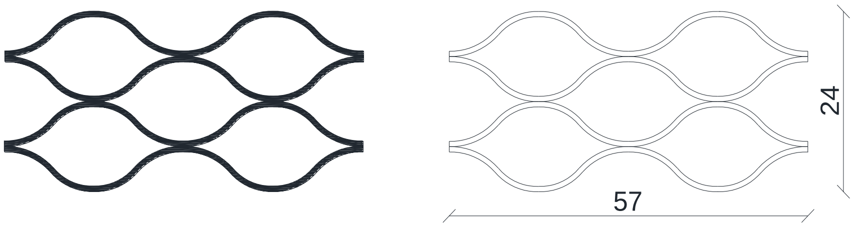


Fig. 7: Sandwich steel beam with half sin curve core in transverse direction with 57mm breadth.

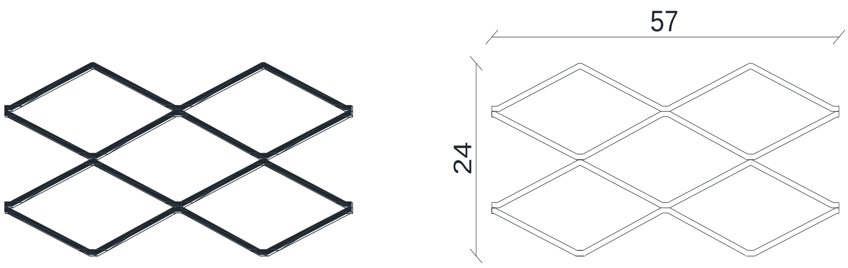
Table 3: Dimensions of the half sin curve in longitudinal and transverse directions.

Core shape	Height mm	upper& lower pl. thickness mm	Core thickness mm	Beam breadth mm
Half sin curve in trans. Dir.(verified)	30	3	0.762	50.8
Half sin curve in long. Dir. (modified)	30	3	0.762	57
Half sin curve in trans. Dir. (calibrated)	30	3	0.762	57

The suggested core shapes are the full sin curve and the truss shape, see Fig. 8. The two beams of new core shapes (the full sin curves, Fig. 8a and the truss shape, Fig. 8b) were of the same core direction as the modified beam with core of half sin curve. The thickness of the corrugated core of the two beams was remained constant. The total depth and span of the sandwich two beams were also remained constant. The dimensions of cores of the full sin curve and the truss shape are listed in Table 2.



(A) Full sin curve core



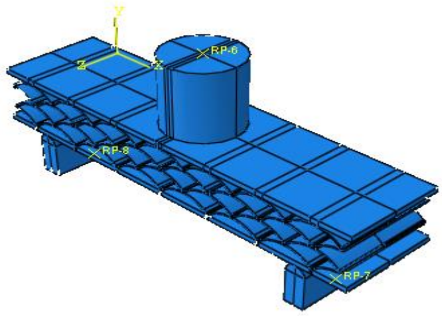
(B).

Fig. 8: The suggested core configuration shapes in the present work

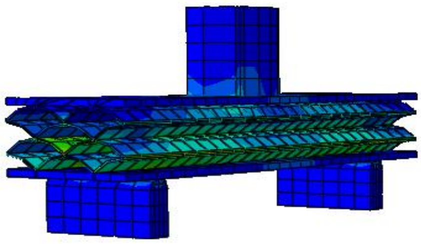
The two configurations (truss core, full sin curve core) studied in the previous section in the longitudinal direction were simulated here by re-arrangement them in the transverse direction. As shown in Fig. 9. This is similar to that of the verified model direction. The core thickness of the two beams with transverse core direction (the full sin curves, Fig. 9a and the truss shape, Fig.9b) was remained constant. The total depth and span of the sandwich two beams were also remained constant. The dimensions of cores of the full sin curve and the truss shape are listed in Table 2.

3. Results and discussion

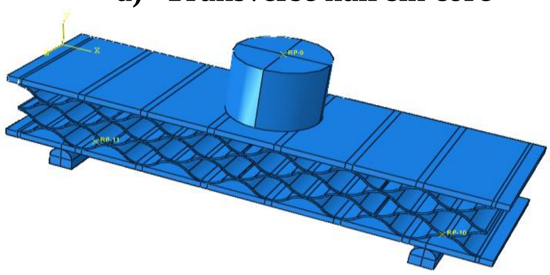
In this section the results obtained will be explained and discussed. The effect of core direction and core shapes on the sandwich beam carrying capacity will also discussed in details. The maximum load carrying capacity and the corresponding deflection of the simulated beams are given in Table 4.



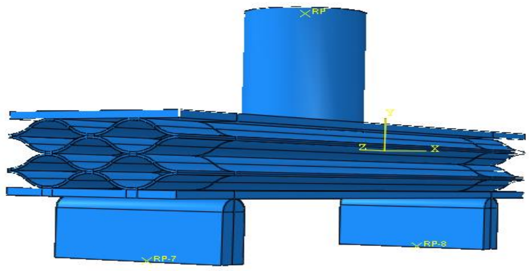
a) Transverse half sin core



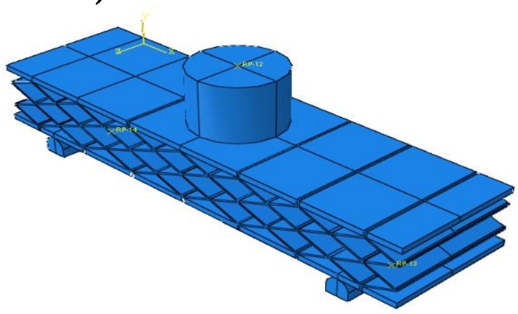
b) Longitudinal half sin core



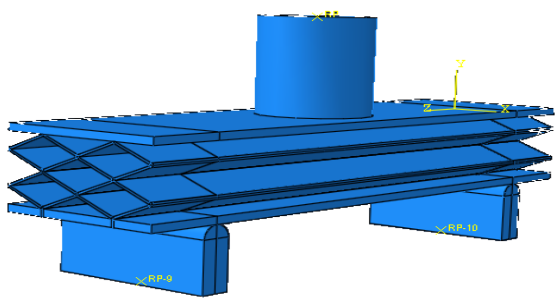
c) Transverse full sin core



d) Longitudinal full sin core



e) Transverse truss core



f) Longitudinal truss core

Fig. 9: Half sin, Full sin and truss cores configurations in transverse and longitudinal direction

Table 4: The load capacity of the beam in longitudinal dir. & transverse dir.

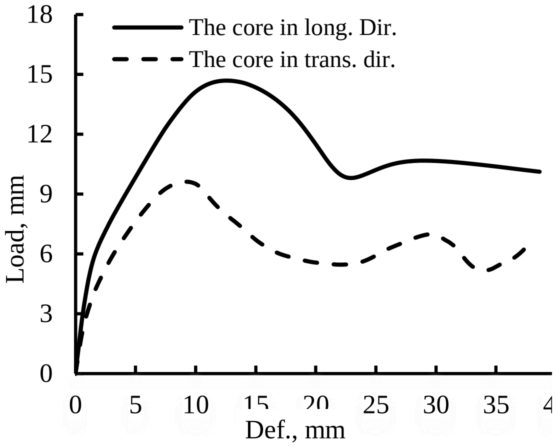
Core shape	Longitudinal dir.		Transverse dir.	
	Max. load (kN)	Def. (mm)	Max. load (kN)	Def. (mm)
Truss	11.765	14.718	8.39	5.5
Full sin curve	12.45	17.11	9.21	4.8
Half sin curve	14.683	17.00	9.612	9.24

3.1 Effect of core direction

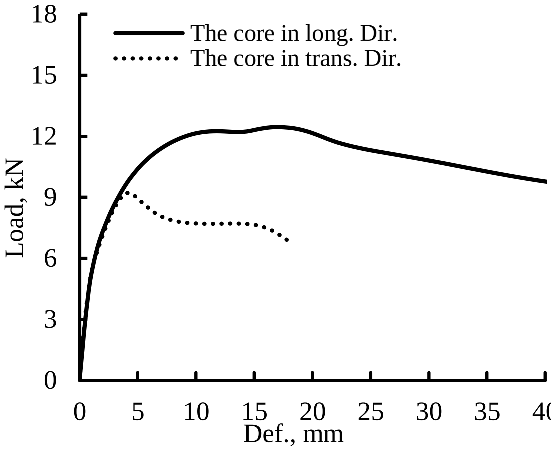
Fig. 10 shows the load–deflection curves response of the sandwich steel beam with different core shapes having transverse and longitudinal directions. The beams had the same material properties and dimensions. From the figure it is observed that, the beam with half sin curve in the longitudinal directions experienced higher maximum load capacity compared with that with core in transverse direction (Fig. 10a). This may be due to the continuous shape of the corrugations in the longitudinal direction the enhanced the beam flexural capacity and reduced the beam deflections. The longitudinal core also may help in bearing a portion of the tensile stresses located in the bottom plate of the beams and then enhanced the beam capacity. The longitudinal core enhanced also the stiffness of the beam as the inertia of the section increased. The maximum load capacity of the transverse core arrangement was 9.6 kN, afterwards the load decreased with low rate with increasing the deflection due the core crushing. Similar trend was observed for the beams with core in the longitudinal direction. The load carrying capacity of the beams with core in the longitudinal direction was about 15 kN, then the load also decreased due to the core deformation. The percentage of enhancement in the load capacity of the beam with longitudinal core was about 52.8 % over that with transverse cores which reveals the great effect of the core direction on the capacity and behavior of the beams with core having half sin curve shape.

The two beams with full sine curve have the same stiffness and dissimilar maximum load capacities (Fig. 10b). The beam with core having full sin curve core in the longitudinal direction experience higher maximum load carrying capacity than that with the same core in the transverse direction. The percentage of enhancement in the load capacity for the beam with core having full sine curve core in the longitudinal direction was about 35.2% over the same beam with core in the transverse direction. As discussed before, the core in the longitudinal direction show higher resistance to the tension and compression stresses than that in the transverse direction as the sheet is continuous in the direction of the stresses and located near top and bottom plates.

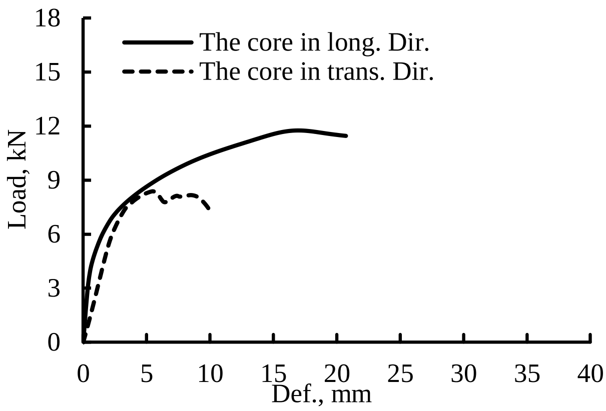
To ensure the great effect of the core direction on the beam carrying capacity, the two beams with truss core in longitudinal and transverse directions were also simulated and tested in flexure. The beam with core in longitudinal direction experienced higher stiffness that the same beam having core in transverse direction (Fig. 10c). Moreover, the beam with core in longitudinal direction experienced higher maximum load capacity that the same beam having core in transverse direction. The percentage of enhancement in the load carrying capacity of the beams with longitudinal truss core was about 40% over that with transverse truss core. These results assured the performance of the core in the longitudinal direction in resisting the loads exerted on.



a) **Half sin curve core**



b) **Full sin curve core**

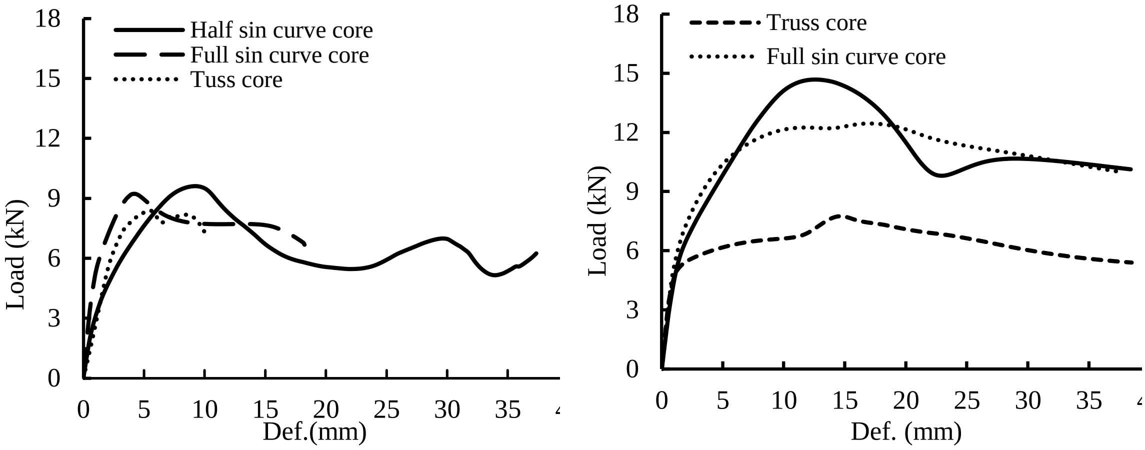


c) **Truss core**

Fig. 10: Effect of the core direction on load- deflection response of the sandwich beam

3.2 Effect of core shape

In this section, the effect of core shape on the behavior and the maximum load carrying capacity of the sandwich beams will be discussed. Fig. 11 shows the load–deflection curves of the sandwich steel beams with half sin curve core, full sin curve core and truss core in longitudinal direction and transverse directions. For the beams having core in the transverse direction the beam with full sin core experienced the higher stiffness than the other beams (Fig. 11a). On contrast the beam with half sin curve experienced the higher maximum loads capacity than the other beams. The same results were also observed for the same beams having core in the longitudinal direction. In general, the deformation of the corrugated beams begins with crushing of the top layer(s), followed by core crushing then plate bending and shear interact to each other (Fig. 12). The failure of all the beams in the longitudinal direction was crushing of the core with a symmetric shape (Fig. 12b,d,f) while for beams in the transverse direction the failure began with buckling of the one of the core panels (Fig. 12a,c,e).



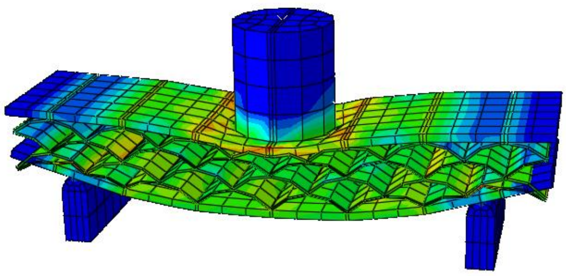
a) The core in the transverse direction **b) The core in the longitudinal direction**

Fig. 11: Load- deflection response of sandwich steel beam with different core shapes.

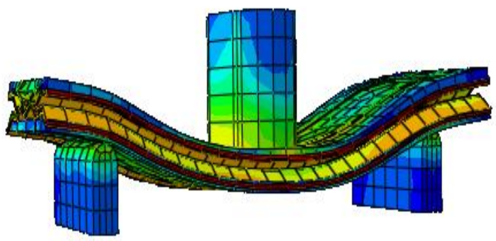
4. Conclusions

The numerical results of the sandwich steel paneled beams carried out in this study, support the following conclusions:

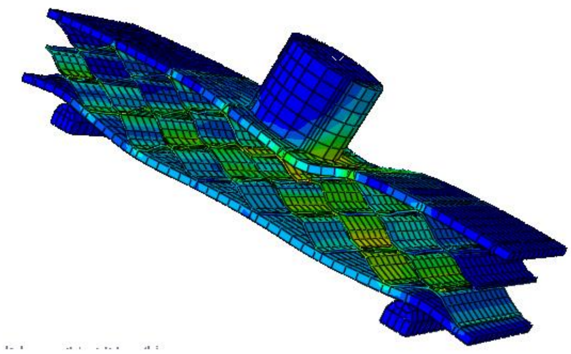
- The load carrying capacity of the sandwich steel beams with half sin curve core section in the longitudinal direction is more efficient than the sandwich steel beams with full sin curve core section and the sandwich steel beams have truss core section.
- The direction of the paneled core which established in the longitudinal axis of the beams have the great effect on increase the load carrying capacity of the sandwich steel beams for the three core types.



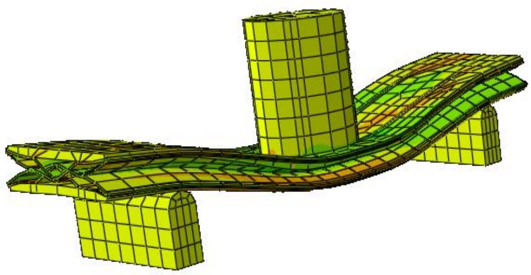
a) Half sin curve core in trans. Dir.



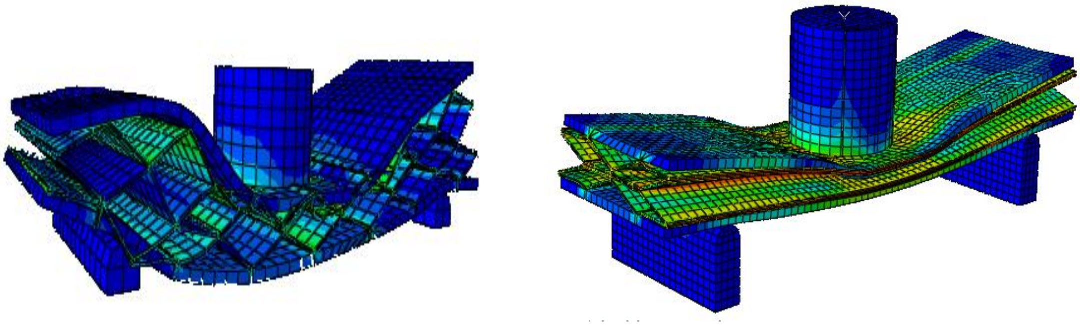
b) Half sin curve core in long. Dir.



c) Full sin curve core in trans. Dir.



d) Full sin curve core in long. Dir.



e) **Truss core in trans. Dir.** **f) Truss curve core in long. Dir.**

Fig. 12: Failure of the modelled beams

- The load capacity of the half sin curve core section in the longitudinal direction of sandwich steel beam subjected to 3-point load is greater than the same of with core section in the transverse direction of sandwich steel beam by about 52.8%. on the other hand The percentage of enhancement in the load carrying capacity of the beams with longitudinal truss core was about 40% over that with transverse truss core while The percentage of enhancement in the load capacity for the beam with core having full sine curve core in the longitudinal direction was about 35.2% over the same beam with core in the transverse direction.

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