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Behavior study of the steel plate girder with a cellular honeycomb web

Keywords: finite element analysis, steel plate girder, honeycomb web, corrugated web, shear strength, web failure, shear stress, numerical analysis

Introduction

Steel plate girders with corrugated webs can enhance their shear strength against web buckling and circumvent steel's mass reduction issues (De'nan & Hashim, 2013). The purpose of this study is to investigate the shear behavior and failure mode of hollow honeycomb steel plate web girders (HWsG) numerically and to compare the finite element (FE) research with the authors' experimental programs that were carried out by Shaffaf and Ammash (2022). Various researchers have examined the shear buckling behavior of the corrugated steel plate web. Under concentrated load, Ammash and Dashi (2022) studied the shear behavior of inclined and vertical corrugated steel plate web girders. They created fourteen specimens with varying modes, angles, and depths of web corrugation. Compared to the flat web, they obtained an increase in ultimate load of inclined corrugated web shear

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resistance of 49–79% for 300 mm depth and 49.3–103.0%. Ammash and Kadhim (2022) calculated the shear behavior of a concrete-filled core sandwich corrugated steel plate web girder. The authors constructed and tested sixteen specimens of simply supported girders under concentrated load. The composite core sandwich web girders demonstrated a 29–36% increase in the web shear compared to the flat web. The trapezoidal corrugated web was utilized to fabricate eight-steel plate web girders by Nie, Zhu, Tao and Tang (2013). The ANSYS was chosen as the software to be used for this investigation. A concentration was applied to all eight models in the middle of the span. According to the findings of the calculations, the load-carrying capacity values of the trapezoidal corrugated web recorders are greater than those of the flat web. Abbas, Ibrahim and Korashy (2019) presented an experimental thesis and numerical analysis with multiple parameters, including the web depth, width, corrugation angle, and plate thickness. They concluded that corrugation angles could improve web shear resistance. Pasternak and Kubieniec (2010), Hassanein, Salem and Mohmoud (2018) investigated the shear behavior of trapezoidal and sinusoidal webs subjected to two concentrated loads. They gained on the progression of steel web strength. Leblouba, Barakat and Al-Saadon (2018) evaluated the web geometry and shear web strength properties of nine plate girder specimens with trapezoidal corrugated web until failure. They concluded that the width of the corrugated web has a negative relationship with shear strength. Ammash and Al-Bader (2021) investigated the shear behavior of core sandwich corrugated steel plate web I-section girders experimentally and numerically. They constructed ten steel plate girders with simple support and tested them under a midspan concentrated load. Three different trapezoidal, triangular, and rectangular corrugated steel web patterns were manufactured, with differences in corrugation widths (20 mm, 40 mm and 60 mm) and corrugation angles (90° and 45°). The results demonstrated that the trapezoidal corrugated web had a higher ultimate load value than flat web and other web modes by a ratio of 28%. Shaffaf and Ammash (2022) investigated the shear behavior of honeycomb steel web girders through an experimental study. Twelve honeycomb web girders with simple support were tested under a concentrated midspan load. The girders were divided into three groups: 60 mm, 80 mm and 100 mm thick honeycomb webs. The steel plate thickness of honeycomb web (HW) was 0.70 mm, 600 mm, 1,200 mm and 1,800 mm lengths were fabricated for each HW specimen. The experimental test results demonstrated that the 60 mm honeycomb corrugation width provided a higher ultimate load than the flat web. Figure 1 depicts the specimen's deformed shape.

FIGURE 1. Deformation shape of steel plate honeycomb web girders: A – girder with 60 mm HW corrugation width and 600 mm length (HW60L_1); B – girder with 60 mm HW corrugation width and 1,200 mm length (HW60L_2); C – girder with 60 mm HW corrugation width and 1,800 mm length (HW60L_3); D – girder with 80 mm corrugation width and 600 mm length (HW80L_1); E – honeycomb girder with 80 mm corrugation width and 1,200 mm length (HW80L_2); F – girder with 80 mm corrugation width and 1,800 mm length (HW80L_3); G – girder with 100 mm HW corrugation width and 600 mm length (HW100L_1); H – girder with 100 mm web corrugation width and 1,200 mm length (HW100L_2); I – honeycomb girder with 100 mm HW corrugation width and 1,800 mm length (HW100L_3)

Source: own work adopted from Shaffaf and Ammash (2022).

Material and methods

This paper is distinguished by a numerical investigation and numerically comparing the test results of the previous experimental work by Shaffaf and Ammash (2022) with the finite element analysis results of the current study. Shaffaf and Ammash (2022) constructed twelve simply supported girders with honeycomb web steel plates

(HSW) and tested them with a concentrated midspan load. Twelve simply supported girders were tested at the University of Al-Qadisiyah Structures Laboratory, and the results were recorded. In this paper, honeycomb web specimens were modelled with a three-dimensional analysis (3D), reduced integration, and shell elements (3D-S4R) in Abaqus software with six degrees of freedom per node and simulated with exactly the same mechanical properties and details of the corresponding material of the steel plate that had been used in the experimental study. The details including dimensions, properties, loading method, and boundary conditions of all specimens of simply supported ends. Experimentally, the mechanical properties and the tensile test method was conducted in accordance with the American Institute of Steel Construction specifications (American Institute of Steel Construction [AISC], 2016). All steel plate girder specimens have the same web depth (300 mm), while the steel plate thicknesses for the flat and honeycomb webs are 2 mm and 0.70 mm, respectively. The width of the flange was 200 mm, while the thickness and width of the constant flange were 6 mm and 200 mm, respectively. The girder length of each group varies among 600 mm, 1,200 mm and 1,800 mm. The twelve specimens were divided into four groups: flat, honeycomb steel web with a 60 mm corrugation width (HW60), honeycomb steel web with a 80 mm corrugation width (HW80), and with a 100 mm corrugation width of the honeycomb web (HW100). Each group was fabricated with aspect ratios of 1%, 2% and 3% for three 600 mm, 1,200 mm and 1,800 mm, respectively. All specimens were tested with a concentrated midspan load. Furthermore, the boundary conditions were simulated in the Abaqus software using the load option to prevent displacements and rotations in all directions [$X(U_1)$, $Y(U_2)$ and $Z(U_3)$] at the pin-supported end, while at the roller-supported end, rotations and displacements were prevented in the X and Y directions [$X(U_1)$ and $Y(U_2) = 0$]. The finite element meshing size of all simulated simply supported girders was 10 mm. The 10 mm mesh size gives a very close load displacement curve compared with the experimental test results. The details of the finite element models (FEM) for the honeycomb web steel plate girder model are shown in Figure 2.

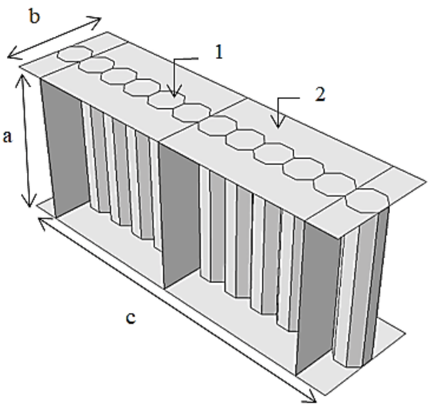

FIGURE 2. Finite element model of steel plate honeycomb steel web girder: a – web depth; b – flange width; c – girder length; 1 – honeycomb steel web; 2 – steel web

Source: Ammash and Shaffaf (2022).

Results and discussion

This section will discuss the validation of the FE analysis results obtained from Shaffaf and Ammash (2022) experimental test results. Table 1 compares twelve steel plate I-girders with two web modes (flat web and honeycomb web) that are simply supported. Figures 3 and 4 depict the comparison between load and deflection. Figure 5 illustrates two varieties of shear web buckling failure (global and interactive shear buckling). The corrugated web geometry can influence the shear buckling mode. The global buckling is almost all of the web failure that occurs at the web panel with the flat mode due to the applied shear stress. Global buckling was only observed at the web panel of the flat web girder, whereas intermediate buckling or interactive shear buckling was observed at most honeycomb web corrugations (Fig. 5B). Also, Figure 3A illustrates a good correlation between the two studies' load-carrying capacities (the experimental and present FEM study). The results indicate a slight increase in the shear buckling strength of the HW specimens, particularly $HW60L_1$, which recorded a higher ultimate load than FWL_1 and other HW corrugations (80 mm and 100 mm) due to an increase in the slenderness ratio of cross-section of the honey-

TABLE 1. Comparison between Shaffaf and Ammash (2022) experimental test results and the finite element analysis of the present research

Girder	Ultimate load (Pu, ex) [kN]	Ultimate load (Pu, FE) [kN]	$\frac{Pu,FE\_Pu,ex}{Pu,ex}$ [%]	Failure mode
FWL_1	132	137.0	3.6	global buckling
FWL_2	110	108.7	–1.2	global buckling
FWL_3	105	110.6	5.3	global buckling
$HW60L_1$	142	129.5	–8.8	interactive buckling
$HW60L_2$	116	118.9	2.5	interactive buckling
$HW60L_3$	110	114.0	3.6	interactive buckling
$HW80L_1$	126	126.0	0.0	interactive buckling
$HW80L_2$	118	121.0	2.5	interactive buckling
$HW80L_3$	98	102.0	4.0	interactive buckling
$HW100L_1$	93	97.12	4.5	interactive buckling
$HW100L_2$	80	81.3	1.6	interactive buckling
$HW100L_3$	72	69.5	0.0	interactive buckling

L_1, L_2, L_3 refers to 600 mm, 1,200 mm and 1,800 mm, respectively.

Source: own work adopted from Shaffaf and Ammash (2022).

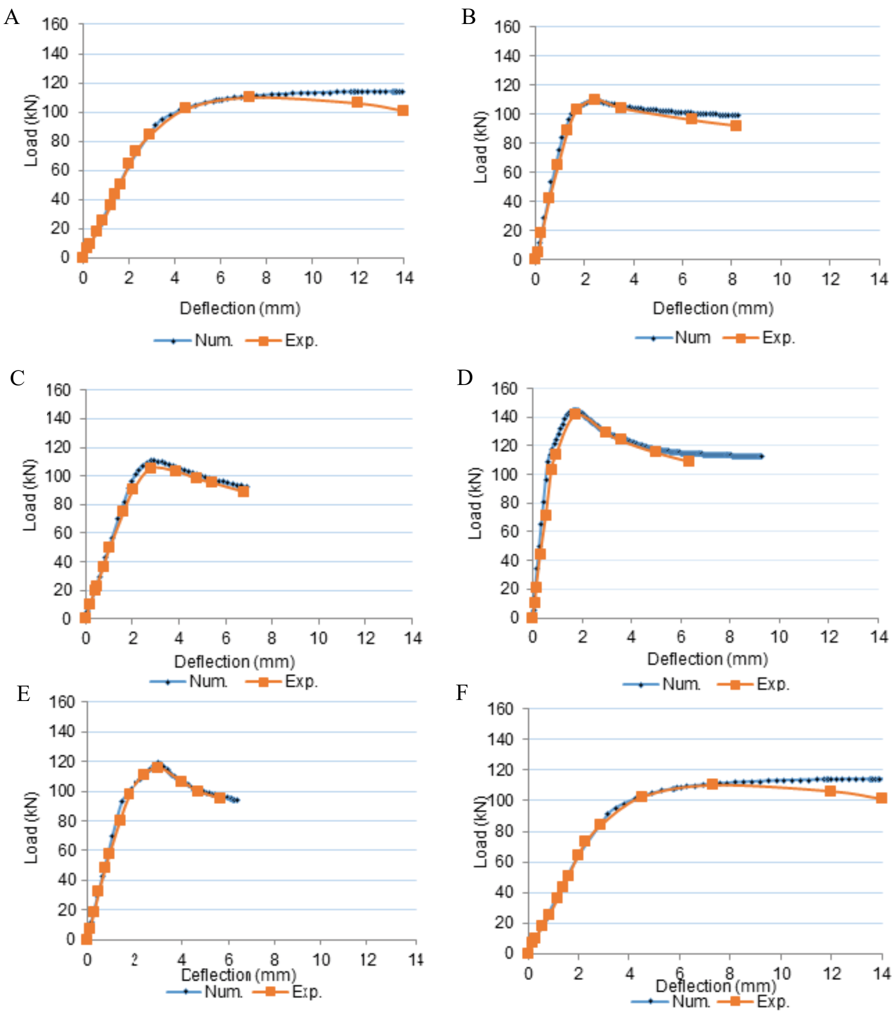

FIGURE 3. Comparison of the load–deflection curves between the experimental test results of Shaffaf and Ammash (2022) and finite element investigation of the current research: A – FWL_1 specimens; B – FWL_2 specimens; C – FWL_3 specimens; D – $HW60L_1$ specimens; E – $HW60L_2$ specimens; F – $HW60L_3$ specimens

Source: own work adopted from Shaffaf and Ammash (2022).

comb web as corrugation dimension increases. Furthermore, when the corrugation dimension of the honeycomb web decreases, the moment of inertia of the minor axis or Y axis increase, because the inside empty spacing between the hollow honeycomb cell decreases which can reduce the web shear strength. Table 1 illustrates the maximum difference of the load carrying capacity between the numerical and experimental results was 8.8% from the comparison results of honeycomb steel web

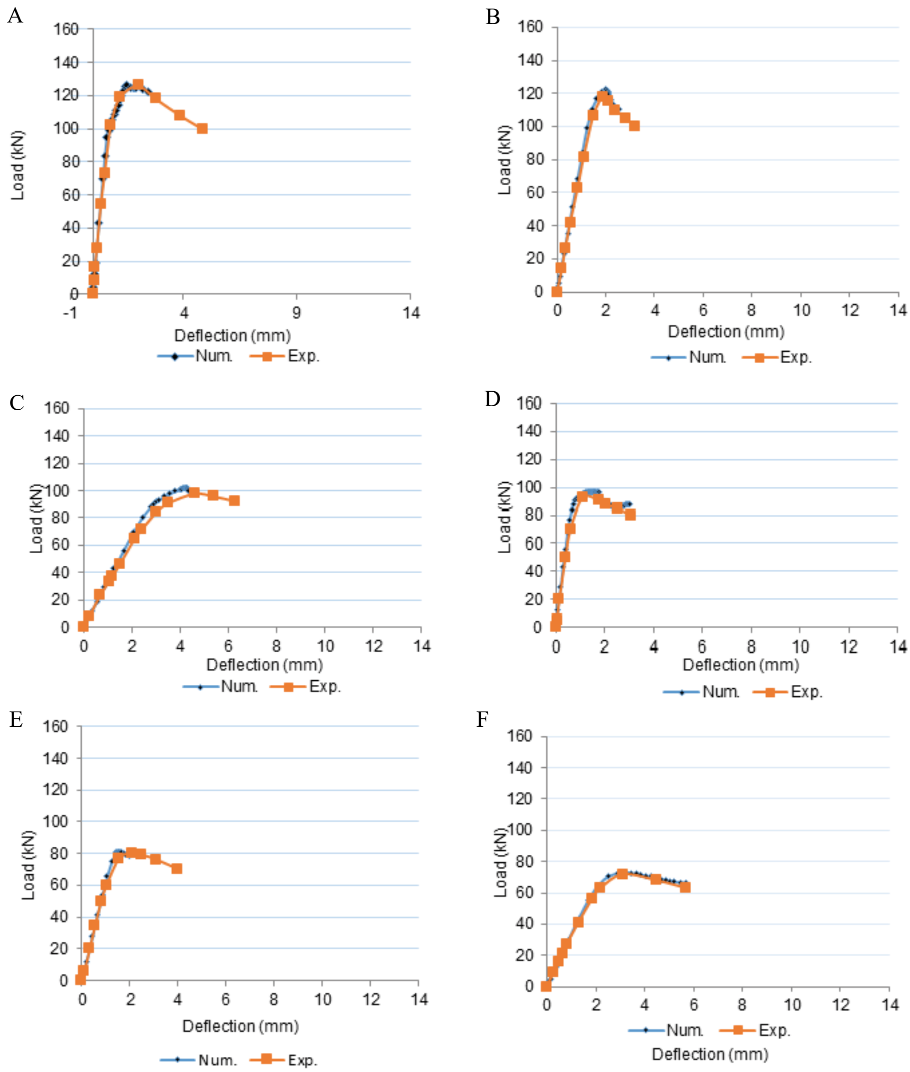

FIGURE 4. Comparison of the load–deflection curves between the experimental test results of Shaffaf and Ammash (2022) and finite element investigation of the current research: A – $HW80L_1$ specimens; B – $HW80L_2$ specimens; C – $HW80L_3$ specimens; D – $HW100L_1$ specimens; E – $HW100L_2$ specimens; F – $HW100L_2$ specimens

Source: own work adopted from Shaffaf and Ammash (2022).

with 60 mm thick ($HW60L_1$). This ratio indicates that the current simulated models of the flat web and the honeycomb web I-girder specimens is able to estimate shear behavior, buckling modes, ultimate load and maximum midspan deflection of all plate girder in this paper.

Figures 3A, 3B and 3C illustrate the load carrying capacity of the flat steel web girders with 600 mm, 1,200 mm and 1,800 mm length, respectively. The FWL_1 specimen recorded 132 kN. This value is greater than other specimens of flat web FWL_2 and FWL_3 due to increasing in the shear span to depth ratio from 1 to 2% and 3% for FWL_1, FWL_2 and FWL_3, respectively. The aspect ratio (a/d) has inverse relation with the web shear strength. The load carrying capacity verse maximum middle displacement that is illustrated in Figure 3 indicates the appropriate comparison between the experimental test results and FE investigation of this paper.

Figure 3D shows the FE results and the experimental test result of honeycomb web plate girder 60 mm thick. The increase in the load carrying capacity and decrease in the maximum displacement of girder midspan was clearly noticed. The $HW60L_1$ specimens recorded an enhancement in the web shear strength, which reaches the 8% development compared with same weight of the flat web girder. This slight increase was due to using extremely thin web thickness of about 0.70 mm. The steel plate thickness has a great effect on the web shear strength. However, reducing the dimension web corrugations can contribute to enhancing the buckling resistance due to increasing the moment of inertia of the Y axis (I_y).

While the decrease in the ultimate load of $HW60L_2$ and $HW60L_3$ obviously appeared as illustrated in Figures 3E and 3F. This decrease was a result of increasing the spacing between the intermediate stiffeners to the web depth ratio. When the shear span to depth ratio increases, the tension field action that developed between inside web panel also decreases. The tension field action can resist the diagonal tension.

Figures 4A, 4B and 4C show the elastic buckling load values: 102 kN, 106 kN and 84 kN, while the ultimate loads: 126 kN, 118 kN and 98 kN and the linear vertical displacement of midspan; 2.00 mm, 1.90 mm and 4.60 mm for $HW80L_1$, $HW80L_2$ and $HW60L_3$, respectively. Figure 4 shows the difference in load carrying capacity when the aspect ratio increased from 1%, 2% and 3%. The ultimate load decreased when the aspect ratio increased. In the failure mode, intermediate buckling failure was noticed at all these categories of honeycomb steel plate web specimens.

As Figures 4D, 4E and 4F state, three tested specimens of honeycomb web steel plate I-girder specimens: $HW100L_1$, $HW100L_2$ and $HW100L_3$ with a/d equal to 1%, 2% and 3%. The thickness of the steel plate was 0.70 mm, which it is a constant for all honeycomb web pattern. The test results of the load carrying capacity of honeycomb steel plate web with a/d equal to 1.0% $HW100L_1$ was 93 kN while the other honeycomb specimens with corresponding aspect ratio values; 2% and 3% were (80 kN and 72 kN) for $HW100L_2$ and $HW100L_3$ specimens, respectively. Noticeably, these specimens recorded less value in the shear strength and midspan deflection compared with other specimens of honeycomb steel web with fold dimensions equal to 60 mm and 80 mm. The maximum deflections were 1.10 mm, 2.10 mm and 3.10 mm. What is more, the local buckling and intermediate shear web buckling failure was obtained.

For the honeycomb web steel plate girders with *a*/*d* equal to 3% or with 1,800 mm length, the maximum percentage decreases in the shear strength of honeycomb web value of 31.4% from test results of the $HW100L_3$. While the maximum percentage decreases in the midspan vertical deflection value of 62% from the test results of the honeycomb web $HW60L_3$. As noticed, dimension folds, plate thickness of honeycomb web, and aspect ratio have an important influence on the ultimate load and deflection.

A

B

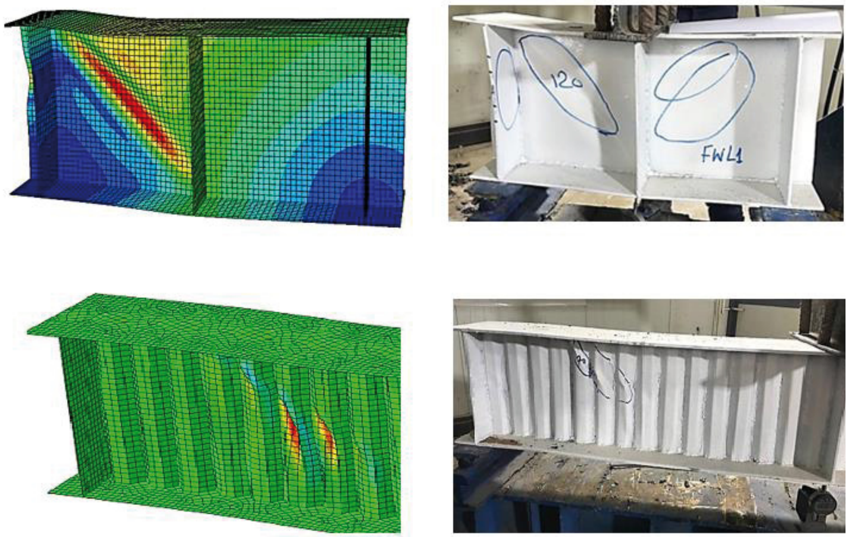

FIGURE 5. Comparison of shear buckling failure between Shaffaf and Ammash (2022) experimental study and present finite element model buckling for girders with flat and honeycomb steel plate web: A – global buckling mode of flat web girder with 600 mm length FWL_1; B – intermediate buckling of honeycomb web girder with 60 mm thick and 1,800 mm length $HW60L_3$

Source: own work adopted from Shaffaf and Ammash (2022).

Slenderness ratio of honeycomb web and aspect ratio

This paper uses the numerical analysis to investigate the effect of the web slenderness ratio on the shear buckling strength. Fifteen I-section specimens of simply supported steel plate web girders were manufactured using the honeycomb corrugated steel plate web in the FE, Abaqus/CAE software. These specimens were separated into five distinct groups. Each has a unique honeycomb corrugated steel web dimension of 20 mm, 40 mm, 60 mm, 80 mm and 100 mm, and each group consists of three specimens with lengths of 600 mm, 1,200 mm and 1,800 mm, or aspect ratios of 1%, 2% and 3%.

Figure 6 depicts the relationship between the ultimate strength and slenderness ratio of the web (b/t_w) of 600 mm long honeycomb web specimens (HWL_1). Figure 6 demonstrates that the honeycomb web with a 20 mm fold dimension and a b/t_w of 29% had the highest load capacity value compared to other fold dimensions (40 mm, 60 mm, 80 mm and 100 mm). Figure 7 depicts the shear strength change versus slenderness ratio of 1,200 mm long honeycomb web girders (HWL_2). As shown in Figure 7, as the ratio of web slenderness decreases, the shear strength against shear web buckling failure increases. Hence, in the structural web design of steel plate girders in steel constructions, increasing the web corrugation will be ineffective and may increase cost, mass, and shear strength without providing any benefit.

In addition, Figure 8 illustrates the honeycomb web girder with 1,800 mm long HWL_3 and its negative relationship with load carrying capacity or shear strength and b/t_w. As the ratio of web slenderness increases, shear strength decreases. So, it can be concluded that, for a constant steel plate thickness, when the corrugated dimensions of the web are reduced, the steel plate will behave like a thick plate that resists shear stress with a high yield strength, as opposed to a thin plate that resists shear stress with a lower yield strength. The shear span also influences the shear

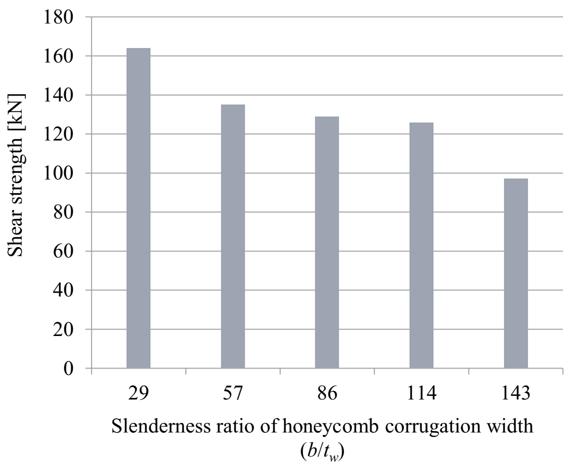

FIGURE 6. Shear strength verse slenderness ratio of honeycomb web cross-section for the HWL_1 specimen with various corrugation dimension: 60 mm, 80 mm and 100 mm and with 600 mm length

Source: Ammash and Shaffaf (2022).

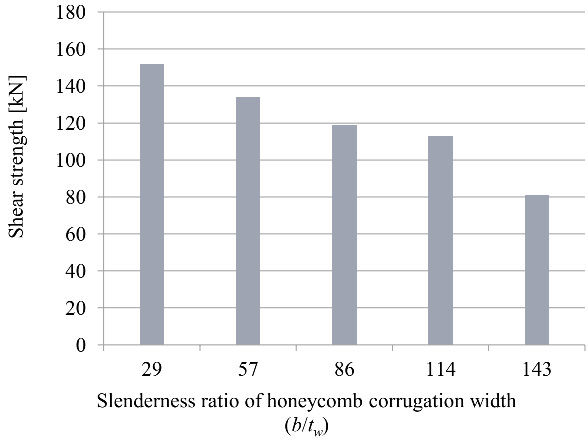

FIGURE 7. Shear strength verse slenderness ratio of honeycomb web cross-section for the HWL_2 specimen various corrugation dimension: 60 mm, 80 mm and 100 mm and with 1,200 mm length

Source: Ammash and Shaffaf (2023).

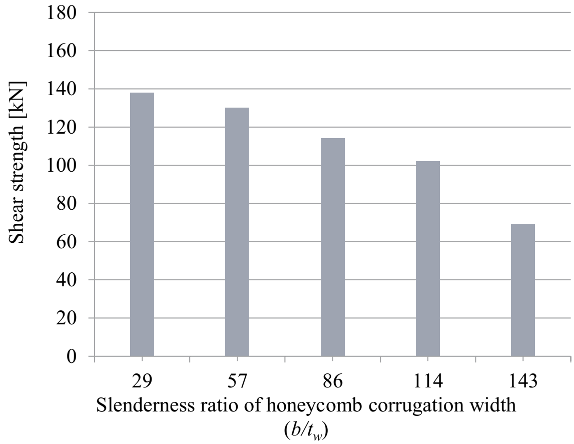

FIGURE 8. Shear strength verse slenderness ratio of honeycomb web cross-section for HWL_3 specimen various corrugation dimension: 60 mm, 80 mm and 100 mm and with 1,800 mm length

Source: Ammash and Shaffaf (2022).

strength-to-depth or a/d. The shear buckling strength decreases as the distance between the intermediate stiffeners and the effective depth increases (Abdullah, Muhaisin & Ammash, 2022). In this numerical analysis, Figure 9 depicts the relationships between the shear strength results of twelve honeycomb and plain web FE girder models and a/d values.

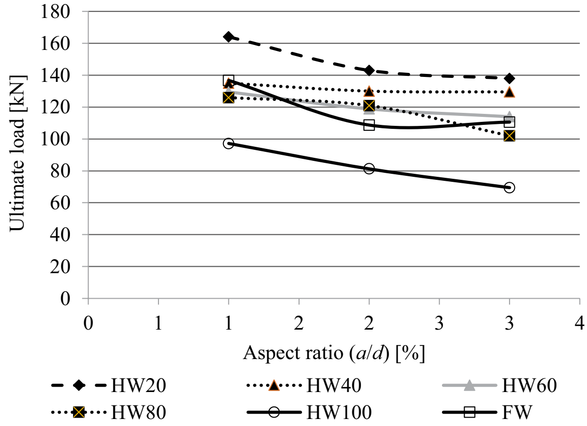

FIGURE 9. Ultimate load verse shear span to depth ratio (*a*/*d*) for all plate girder specimens flat web and honeycomb web

Source: Ammash and Shaffaf (2022).

Effect of honeycomb steel plate web thickness

Regarding the effect of thickness on the buckling strength, shear buckling in the steel honeycomb web is directly proportional to the thickness. The positive relationship between the increased steel web thickness and shear buckling strength holds true for flat and curved webs. Under a concentrated load, Figure 10 depicts the load-carrying capacity of the flat and honeycomb corrugations plate web with a thickness ranging from 1 to 4 mm.

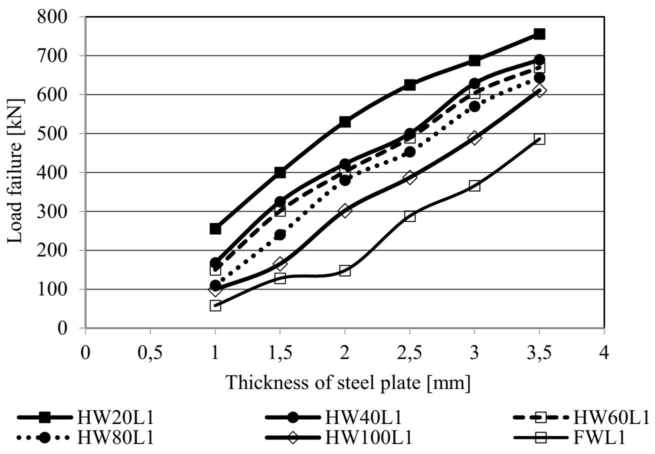

FIGURE 10. Variation in the shear web buckling resistance of the flat web and the honeycomb web specimens which have 600 mm length verse the thickness of steel plate (t_w)

Source: Ammash and Shaffaf (2022).

Types of shear failure

When a simply supported girder is subjected to a concentrated load, a maximum vertical shear force will develop at each support and be opposed by the web of both panels. Due to the intermediate stiffeners at each simply supported edge and under concentrated load, tension field action carried by the width of the web subpanels at a 45° angle against the shear web buckling failure diagonal will withstand the applied shear stress. Increasing the inside spacing between intermediate stiffeners can effectively reduce the shear buckling strength. Consequently, the web subpanel will fail gradually under local, global, or middle shear buckling. Theoretically, the inelastic shear buckling failure is controlled if the web is designed with thin dimensions, wide corrugation width, and compact flange. Failure is primarily determined by web shear buckling or pure shear (Fig. 11A). Steel plate with a small corrugation dimension (20 mm) while maintaining other parameters (flanges thicknesses, width, web depth, and thickness) has improved critical shear strength (τ_{cr}) to the yield strength (τ_y) against the slenderness ratio (b/t_w) and exhibits an elastic behavior that significantly enhances the web shear strength compared to other corrugation dimensions (40 mm, 60 mm, 80 mm, and 100 mm). Shear stress includes a component for flexural failure. It is known as flexural shear, as shown in Figure 11B.

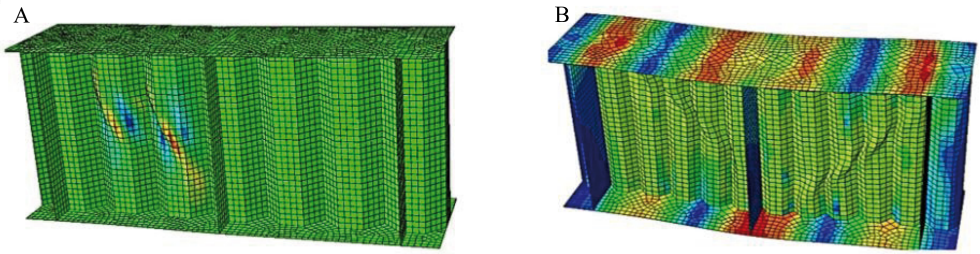

FIGURE 11. The failure of the honeycomb steel plate web girder: A – shear buckling failure of the girder with 60 mm corrugation dimension and 600 mm length; B – flexural-shear failure of the girder with 20 mm corrugation dimension and 600 mm length

Source: Ammash and Shaffaf (2022).

Conclusions

This paper numerically investigates the shear behavior and failure modes, flexural failure and buckling web shear failure of the specimen flat web and the honeycomb web patterns. This innovative honeycomb web (corrugated web) system typically has high shear strength and less midspan vertical displacement compared with fat web mode.

There are two numerical analyses carried out in the present paper. The first step is the elastic or the linear shear buckling. The second step is the non-linear or inelastic buckling which was adopted to simulate the post shear buckling behavior of all plate girder specimens under the effect of one concentrated load applied at midspan of girders. From the numerical and experimental comparison of the present study, it is possible to conclude the following:

- The shear buckling resistance of the honeycomb web plate girder was significantly higher than that of the flat web, particularly at a thickness of 60 mm.
- The dimensions of the corrugated honeycomb web can adversely affect the critical shear stress.
- Girders with 20 mm thick honeycomb steel plates provided greater ultimate load and less midspan deflection than girders with larger corrugation web dimensions.
- Due to the increase in the web slenderness ratio, shear strength decreased as honeycomb web dimensions increased.
- The load-carrying capacity of the steel web can be enhanced by increasing the thickness of the steel plate.
- The ultimate load increased from 8 to 30% when the width of the corrugated honeycomb web was reduced from 60 to 20 mm.
- The shear web strength of honeycomb web increased from 60 to 450% when steel plate thickness was increased from 1 to 4 mm.
- According to the Euler equation, as the honeycomb web's moment of inertia increases, the corrugated web's critical buckling load increases. Thus, when the corrugation dimension decreases, the moment of inertia of the X axis (I_x) increases, and then the shear strength of the corrugated steel web increases.
- Shear strength is negatively affected by the slenderness ratio of the corrugation dimension.

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Summary

Behavior study of the steel plate girder with a cellular honeycomb web. Based on the experimental test results of the authors, this investigation is concerned with the finite element analysis to examine and compare the load values and failure modes of the authors' results. This research was conducted using the Abaqus software. The experimental work included the fabrication of twelve plate girders with honeycomb and flat web plate corrugation patterns, which were then tested under a single concentrated load at the midspan. According to the corrugation dimension or outer honeycomb web thickness, the honeycomb steel plate web girder is divided into three groups (60 mm, 80 mm and 100 mm). The specimens also involved plate girders with a flat web. The specimens were created with three lengths (600 mm, 1,200 mm and 1,800 mm). The Abaqus software was used in finite element models to simulate the concentrated load. The numerical results demonstrated that the 60 mm thick honeycomb web provides a greater load-bearing capacity and shear strength than other girders. The 20 mm honeycomb corrugation on the steel plate girder indicates the increased and improved shear

resistance. The conclusion was that as the width of the corrugation increased, so did the steel web's ultimate load and shear strength, resulting in a positive relationship between the critical shear buckling load of the web and the moment of inertia at the strong axis. When the dimension of the corrugation increases, the moment of inertia of the Y axis (I_y) decreases; thus, the plate girder will fail with a less critical buckling load (P_{cr}). Also, it can be concluded that as the steel plate thickness of the honeycomb web increases, the shear resistance increases as well. However, the spacing between the intermediate stiffener or the horizontal spacing of the web panel can enhance the shear resistance of honeycomb web girder if it was decreased due to increasing the action of tension field force that resists the diagonal tension developed at the web panel by the applied midspan concentrated force.