Shear Behaviour of Steel Girder with Web-Corrugated Core Sandwich Panels

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Abstract. Last few decades, corrugated web steel girders have the foremost widespread and used steel constructions due to their lightweight and high load carrying capacity compared with the stiffened flat web. This study aims to comprise an experimental work by testing ten specimens to improve the girders shear resistance. One reference specimen with a flat web in addition to nine models that are categorised to three groups in which each group differs in the corrugation shape. Rectangular, trapezoidal and triangular corrugation shapes of different heights (20, 40, and 60 mm) were utilised. All specimens used in the study have equal weight, which is approximately 30 kilograms per specimen. The experimental work included measuring the ultimate load capacities and load-deflection curves. Results showed that different failure modes were observed for those beams. It was also found that the beam with trapezoidal corrugation web has an increase in its strength by nearly 28% compared with the reference beam.

Keywords: Corrugated web steel beam, Shear buckling, Experimental work.

1. Introduction
Plate girders have proven their efficiency for many decades in holding different loading conditions. Plate girders are normally fabricated from welded two flanges to a web plate to an I-section shape. These girders now must meet new standards that must be lighter in weight and carry more strength [1]. In this regard, reducing the thickness of web is not an easy process as it causes many flaws, such as less resistance to buckling and low ability to carrying fatigue loading. For this purpose, plate girders webs are sometimes strengthened with stiffeners to allow using thin webs. However, welding stiffeners to the member may cause residual stresses and heat-affected zones to the beam, consequently compromising the fatigue life [2].

To allow the use of thin plates without stiffeners, corrugated webs were suggested. Such corrugated plates are considered as new structural systems that have been used for aeroplanes wings which sections were built up by riveted angle connections. Later on, it has been found that the corrugated web beam is applicable in buildings and bridges. This type of beam has the merits of higher load-carrying capacity and good economic design due to the low beam unit weight. In other words, higher web shear capacity can be produced. Corrugated steel webs can fail by yielding steel or shear buckling.
A great deal of research on beams with corrugated webs has been carried out to study and analyse the shear buckling of webs. Elgaaly et al. [3] attended a group of experiments on beams with corrugated webs tested to failure under shear (web buckling). It was concluded from the experimental as well as the analytical results that the web buckling local and global for coarse and dense corrugations. Moon et al. [4] stated that the shear modulus of a plate girder with corrugated webs was smaller than the plate girder with flat webs. Also, the authors illustrated that as the corrugation angle increases, the beam buckling strength increases to a maximum percentage of 10%. Denan et al. [5] investigated experimentally and numerically the lateral buckling behaviour of a steel section with a trapezoidal web. The results showed that section with corrugated web produces higher resistance to later torsional buckling than that with a flat web. Luo and Edlund [6] examined the effect of various parameters on the shear strength of a corrugated web beam by finite element. The results showed that an increase in the corrugation angle might change the failure mode from global to local buckling. It was summarised in Chan et al. [7] showed that corrugating the web in the vertical direction provided a higher moment capacity than that of the horizontal direction. Also, the vertical corrugation provided more considerable support for flange buckling.

The main objective of this investigation is to introduce an experimental study to investigate the shear buckling strength of a plate girder of various web-corrugated core sandwich panels (triangular, trapezoidal, and rectangular) in comparison with a standard flat web beam.

2. Experimental program

2.1 Test specimens

A total of ten I-girders with core corrugated webs were fabricated to investigate the shear performance. Each beam was 1200 mm long and supported simply on a span of 1100 mm. The models of the beams were categorised into three groups according to the corrugated profile: Group (1) consists of three rectangular corrugated profiles (RWB), Group (2) be composed of three trapezoidal corrugated profiles (PWB) and Group (3) involves of three triangular corrugated profile (TWB). The web for each group comprised of two identical skin plates and corrugated core. In comparison with the I-girders with a corrugated core web, a specimen with a flat web was used. The detailed dimensions of these specimens are shown in Figure 1 and given in Table 1. The two parallel flanges were made from a flat plate with 200 mm wide and 6 mm thick, whereas the corrugated core and skin plate thicknesses were 0.8 mm and 1 mm, respectively. Vertical stiffeners with a thickness of 6 mm were put under the loading point and above the support to prevent the lateral-torsional buckling failure.

![Figure 1. Details of tested specimens](image-url)
### Table 1. Dimensions of the tested specimens

| Group No. | Shape of corrugated | Identification | Dimensions of Parameters (mm) | α  | Weight (kg) |
|-----------|---------------------|----------------|-----------------------------|----|-------------|
|           | Standard            | Standard       | 6 200 300 2 - - - -         | 36.85 |                |
| G1        | Rectangular         | RWB1           | 6 200 300 - 1 20 0.8 90°   | 37.40 |                |
|           |                     | RWB2           | 6 200 300 - 1 40 0.8 90°   | 37.25 |                |
|           |                     | RWB3           | 6 200 300 - 1 60 0.8 90°   | 37.10 |                |
| G2        | Trapezoidal         | PWB1           | 6 200 300 - 1 20 0.8 45°   | 37.40 |                |
|           |                     | PWB2           | 6 200 300 - 1 40 0.8 45°   | 37.25 |                |
|           |                     | PWB3           | 6 200 300 - 1 60 0.8 45°   | 37.10 |                |
| G3        | Triangular          | TWB1           | 6 200 300 - 1 20 0.8 45°   | 37.40 |                |
|           |                     | TWB2           | 6 200 300 - 1 40 0.8 45°   | 37.25 |                |
|           |                     | TWB3           | 6 200 300 - 1 60 0.8 45°   | 37.10 |                |

#### 2.2 The fabrication process of specimens

The specimens were fabricated in the college of engineering laboratory of the University of Al-Qadisiyah, Iraq. The plates for flanges, web, and stiffeners for every test girder were prepared by the cutting process by using the steel cutting machine. Using such a machine can prevent adverse distortion and undesirable changes in the material. After cutting the plate, all flanges, webs, and stiffeners components were welded together with continuous fillet welds using a typical AC arc welding machine and an E60 rutile electrode. It is relatively insensitive to rust or other surface impurities. The web for each group consists of two skin plates and a corrugated this called (core corrugated sandwich panel), as shown in Figure 2. The corrugated core is attached to the face skins by welding. Given that residual stresses produced during the welding process, adequate caution was taken when welding the thin web plate by producing lateral supports at any interludes to limit initial significant web defects, including initial distortions, warping, twisting, dents and undulations.

![Figure 2. The web after welding](image)

#### 2.3 Material properties

Tensile tests were carried out in structural laboratories of the engineering college of Al-Qadisiyah University, which included calculating the yield strength, ultimate strength, and record stress-strain data on steel specimens obtained from the steel plates used to fabricate the specimens. Four gages of plates were used herein (thickness 6, 2, 1, and 0.8 mm). The testing procedure, size, and shape were implemented according to ASTM [A370]. The yield and ultimate stress for the flanges and webs were obtained from tests, which are summarised in Table 2.
### Table 2. Material properties of beams

| Type  | Young’s modulus E (GPa) | Yield stress $f_y$ (MPa) | Ultimate stress $f_u$ (MPa) |
|-------|-------------------------|--------------------------|----------------------------|
| 6mm   | 200                     | 347.20                   | 491.60                     |
| 2mm   | 200                     | 214.33                   | 282.14                     |
| 1mm   | 200                     | 210.27                   | 278.38                     |
| 0.8mm | 200                     | 198.86                   | 235.90                     |

#### 2.4 Instrumentation
The used instruments consist of one linear variable displacement transducers (LVDT), which installed below the beam at the mid-span, with a capacity of 50 mm to measure the vertical displacement. A hydraulic jack was used to supply the load with a capacity of 2000 kN, and it was applied manually using a hydraulic pump. A load cell was put between the hydraulic jack at the top of the compression flange to monitors the load. The load and displacement values were recorded in a computer program. In addition to that, the strain was measured using digital image correlation technique (DIC) following the principle of photogrammetry and digital image processing. The compression measures a series of images that are captured over a time scale from microseconds to years. A (GOM) correlation software package 2019 program was used to measure the 2D plane by Nikon camera, which is located on one side of the beam.

#### 2.5 Test Setup
Each beam has the same definite span length of 1100 mm. The specimens were tested up to failure under the action of applying one-point load at the mid-span. For the purpose of concentrating the load, a steel plate with dimensions of (200 × 200 × 10) mm was used to prevent any local failure in the flange. The supporting system was a simply supported deep beam (roller and pin). The hydraulic universal testing machine shown in Figure 3 was used to test the beams. The machine contains a hydraulic actuator, load cell, support in span, plate for applied load, and the program (lab view) on the computer. The full capacity of the machine was approximately 2000 kN.

![Figure 3. Hydraulic testing machine of specimens](image)

#### 3. Experimental results and discussion

##### 3.1 Beams failure modes
Loading was applied gradually at the mid-span of each beam. At the beginning of the loading procedure, marginal deflections were noticed at the mid-span. Observing the diagonal-shape in the web, refers to reaching the critical buckling load. Further increments of the applied loads in the post-buckling stage resulted in the web of the beam to deform in the out-of-plane. The increment of
deflection was more substantial compared to the elastic stage owing to the gradual loss in the flexural stiffness of the girder. The progress of web buckling as a result of tension field action was strictly observed until the test girder arrived the ultimate load. The applied load began to drop gradually, which exhibited that the web panel yielded, as expected earlier due to the small span-to-height ratio of the specimens. The shear force dominated the failure of all beams rather than the bending moment. Three different buckling failure modes were observed in the web, as shown in Figure 4. Mode A, Mode B and Mode C. In the first mode, the web buckled along the diagonal direction between the two stiffeners while the web buckled first in Mode B, as the load increased, other buckling line appeared at the upper left corner or bottom right corner. In Mode C, however, the web close to the top flange.

Figure 4. Experimental test specimens at failure
3.2 Ultimate load capacity
The study was conducted to choose the optimum design for the steel girders by reinforcing the web in the girder using core corrugated web and comparing it with the flat web girders. The experimental results revealed that all beams with corrugated web resist significantly more loads than the beam with a flat web by approximately 25.26%, 28.79%, and 27.63% for RWB, PWB, and TWB specimens, respectively, because the corrugation led to an increase in the stability of the web to resist the loads which as shown in Figure 5 and given in Table 3. Therefore, the beams with the corrugated web can save cost and weight with higher strength. Also, the trapezoidal corrugated showed the highest load capacity among all other configurations.

![Figure 5. Comparison of ultimate loads for specimens](image)

| symbol   | Ultimate load (Pu kN) | Mid-span deflection (mm) | Failure mode |
|----------|------------------------|--------------------------|--------------|
| standard | 120.50                 | 4.60                     | A            |
| RWB1     | 150.69                 | 3.54                     | B            |
| RWB2     | 145.58                 | 4.13                     | A            |
| RWB3     | 141.73                 | 3.14                     | C            |
| PWB1     | 154.91                 | 3.25                     | C            |
| PWB2     | 153.86                 | 3.05                     | A            |
| PWB3     | 150.45                 | 3.11                     | C            |
| TWB1     | 154.35                 | 3.65                     | B            |
| TWB2     | 151.49                 | 3.54                     | C            |
| TWB3     | 150.56                 | 3.70                     | B            |

3.3 Load-deflection relationship
The standard specimen reached the non-linear stage before the other specimens and suffered from failure in the web at a load value equal to 120.5 kN and had a mid-span deflection at the ultimate load of 4.6 mm, as shown in Figure 6.

The load-deflection curves for the first group specimens are shown in Figure 7. The deflection was 1.2 mm before buckling and become suddenly 2.3 mm after buckling. It proceeded to increase after buckling, and it became 4.1 mm at the ultimate load.
On the other hand, the load-deflection curves for the specimens of the second group are shown in Figure 8. It can be noticed that the web buckling appeared at 137.21 kN, and the vertical deflection was equal 1.67 mm. After that, the specimens failed at an ultimate load of 154.91 kN.

Figure 9 shows the load-deflection relationship for the specimens in the third group. At the initial loading stage, there was no obvious visible deformation. As the applied load increases, the deformation increases slowly. As the load reached to 134.18 kN, a visible buckling occurred on the web. The specimens had 3.7 mm mid-span deflections at the ultimate load.

A summary of the test results of all models is given with comparison in graphical form in Figure 10.

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**Figure 6.** Load-deflection curve of standard

**Figure 7.** Load-deflection curve of RWB

**Figure 8.** Load-deflection curve of PWB

**Figure 9.** Load-deflection curve of TWB
3.4 Strain of the steel web using Digital Image Correlation (DIC)

GOM is a software program that is used in DIC technology for material study and component testing and assessment. A 2D digital image correlation was presented, which approved the assessment of the digital image series. DIC technology offered a cost-effective solution for any specimens, therefore, the application of the DIC system was needed a proper preparation of tested beams. It was included covering the surfaces of the selected specimens with white paint and then utilizing as many black points as possible, in which the DIC method changed into a grid of characteristic elements. Figure 11 demonstrated the preparation of samples, painting the beams specimens with white paint and spotting with black points in the magic pen. The technique consists essentially of a digital camera and computer software (GOM correlate package 2019). A camera was used to take continuous images of the surface of investigated deep beams before and during the deformation time. The obtained digital image data was evaluation by the DIC program.
The record of longitudinal strain values that were measured at the beam by took several points along the axis of the web. From Figure 12 the strains at the region colored in blue are negative due to compression while the strains at the region colored in red are positive due to tension. At first the strain curves at all points are almost linear but, as load increased, the strain values grew rapidly, and buckling occurred at the web followed by a great increment in strains at the compression but decrement in strains at the tension region.

4. Conclusions
This paper presents a detailed investigation of the structural behaviour of cold-formed steel I-section of a web-corrugated core under a one-point load. The flexure, shear and ultimate failure, of web sections are investigated to gain a thorough understanding of their structural behaviour. The following conclusions can be drawn:

- A plate girder with a corrugated core web has a higher load-carrying capacity and less deflection, compared with the equivalent in weight plate girders with a stiffened flat web.
- The maximum load-carrying capacity of all tested beams was limited by the shear buckling of the webs. The test results also proved that three different buckling failure modes were observed in the web owing to the different depths and shapes of corrugated.
- All tested beams showed post-buckling residual strength. The residual strength has not significantly affected by the mode of shear buckling, and it can help in avoiding catastrophic failures and it might be necessary to be considered in the design.
Additionally, the experimental results showed that the corrugated core depth does not seem to have a considerable effect on the ultimate load.

5. References

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