Experimental study of encased composite corrugated steel webs under shear loading

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Abstract
This paper focuses on enhancing the shear strength of steel I-girder using different types of corrugation filled by concrete. This study used three types of corrugation shape (triangular, trapezoidal, and rectangular). Corrugation shapes had the same depth (60 mm). All specimens used in the study had equal weight, which is approximately (38) kilograms per specimen. The specimens were categorized into two groups, the first group without encasing by concrete while the second group contains self-compacted concrete to encase the corrugated steel web for two faces of I-girder. The experimental work included measuring the ultimate load capacities and load-deflection curves. The experimental results showed that the concrete filled corrugated web girders have high shear strength compared to the specimens that don’t have concrete encasing. Also, the shape of the corrugation was found to have an impact on the shear strength of the steel girders encased with concrete.

1. Introduction
Steel plate girders are efficient in various loading conditions. Plate steel girders are fabricated from welding a web with two flanges to form an I-section shape. These girders now must meet the new standard that they must carry more strength and are lighter in weight [1]. Composite I-girders are used broadly in bridges and building. According to their manufacturing method, the composite girders are classified into two types: rolled shaped beams or built-up sections [2]. Bergfelt et al. [3] studied the shear behavior of trapezoidal corrugated web beam using fifteen girder that had varying depth. The global web buckling was not apparent even in the deepest girder which had extremely thin corrugated webs. Elgaaly et al.[4] worked on a group of experiments of corrugated webs beam that were tested for the failure under shear. Failure modes were global and local buckling for dense and coarse corrugations. Buckling formulas were proposed, that have been supporting global and local buckling.

Gil et al. [5] Studied shear strength of trapezoidal corrugated steel web on nine simply-supported girder specimens that were tested at mid-span by one-point load. These girders have a corrugated web with a variable depth and a variable effective length. The results showed an increase in the theoretical global stress to local stress when the ratio of the corrugation depth to web thickness was less than 10. Ljungström and
Karlberg[6] studied the experimental results of six girders with trapezoidal corrugated webs under patch load and compared with previous studies on the same topic. The study indicated that loading sites are affect by the maximum load capacity. The load capacity reduced when a load applied at the center of the folded. When increasing the thickness ratio (tf / tw). The position of the load changed the behavior of the member and became more ductile.

Roberts and Al-Amery[7] studied experimentally shear strength of composite girders with cutters webs. The results showed that the adequate link connection between concrete and steel promote the shear strength. Shear strength and size of the cutters of the composite plate girder have an inverse relationship. The failure was due to buckling of web and plastic hinge in flange. Chen S[8] checked cracking behaviors and ultimate moment resistances. Four tested specimens of prestressed composite girders with external tendons in negative moment regions. Jun He et al.[9]studied experimentally the shear behavior of partially encased composite I-girders under anti-symmetric loading has been investigated. The experimental results show that the composite girders have super shear strength compared to steel I-girders. To restrict the shear bucking of web, by using the concrete. Vasdravellis and Uy, [10]studied shear behavior and shear-moment interaction of composite steel girders. One steel girder and fourteen composite girders have been tested under shear and bending together. Partially connected in the composite girder increased the deformation in the ultimate strength, but reduced the shear strength of the steel girder. Sihao Wang et al.[11] studied shear behavior on four steel I-girders with corrugated webs adopted different stiffener arrangements were tested under shear loading. The test results indicate that the shear buckling failed in all specimens, while stiffeners arrangement (horizontal or vertical) does not affect the equivalent shear modulus of corrugated web.

The main objective of this investigation is to introduce an experimental study to enhancing the shear strength of steel I-girder within using different types of corrugation with encasing by concrete (triangular, trapezoidal, and rectangular) in comparison with I-girders without encased concrete.

2. **Experimental Program**

2-1 **Specimen Geometry Details**

Six I-girders with steel corrugated web were fabricated to investigate the shear performance. The total length in each model were 1200 mm and supported simply on a span of 1100 mm, with 300 mm depth. Six specimens that were categorized into two series as follows: (series B) as shown in Figure 1, consisted of three girders with corrugated steel web, girders were (TWB, PWB and RWB) of corrugation shape as a (triangular, trapezoidal, and rectangular), respectively, details of corrugated web as shown in Figure 3. Girders were formed from two flanges with 6 mm thick and 200 mm wide, whereas the corrugated web thicknesses was 2mm and 300mm depth. Vertical stiffeners with a thickness of 6 mm and 300mm depth were put above at end supports and under the loading point to prevent buckling of flange or corrugated web. (series BC) as shown in Figure 2, consisted of three composite girders were (TWBC, PWBC and RWBC), the geometrical and materials properties synchronize with (series B) contains the concrete to encase the corrugated steel web for two faces of I-girder. Corrugation shapes used the same depth 60 mm. Shear bolts with 8 mm diameter and 50 mm length were used to connect concrete with steel and prevent slipping the concrete from the girder. These bolts were distributed at the corrugated web and the flange. At each face of steel plate I-girder, at the web two rows of bolts were welded, each row contains of eight bolts. While one row of bolts was welded in both flanges, the row contains of six bolts, the arrangement of shear bolts for specimens as shown in Figure 4, were connected with steel corrugated web and flange by bolts to satisfy a composite behavior between concrete and steel plate I-girder. The detailed dimensions of these specimens are given in Table 1.
**Figure 1**: Details of (series B), all Dim in mm.  
**Figure 2**: Details of (series BC), all Dim in mm.  

**Figure 3**: Geometry Details of corrugated web, (all dim in mm)  

**Figure 4**: Welding and arrangement of shear bolts


Table 1. Specimens Description

| Series   | Corrugation shape | Identification | Dimensions of Parameters (mm) | Steel weight (kg) |
|----------|-------------------|----------------|--------------------------------|------------------|
|          |                   |                | \( t_f \) | \( b_f \) | \( h_w \) | \( t_w \) | \( d_c \) |       |
| Series (B) I-girders | Triangular     | TWB           | 6   | 200   | 300   | 2   | 60   | 38.6  |
|          | Rectangular     | RWB           | 6   | 200   | 300   | 2   | 60   | 38.85 |
|          | Trapezoidal     | PWB           | 6   | 200   | 300   | 2   | 60   | 38.35 |
| Series (BC) composite girders | Triangular     | TWBC          | 6   | 200   | 300   | 2   | 60   | 38.6  |
|          | Rectangular     | RWBC          | 6   | 200   | 300   | 2   | 60   | 38.85 |
|          | Trapezoidal     | PWBC          | 6   | 200   | 300   | 2   | 60   | 38.35 |

2-2 The fabrication process of specimens
The specimens were fabricated in the college of engineering laboratory of the University of Al-Qadisiyah, Iraq. All steel plates of the test specimen for (flanges, web, and stiffeners) were taken from one source with a different thickness using a steel cutting machine, to cut steel plates according to the required dimensions. The web was welded to the flanges linearly, after which the stiffeners were welded on them using a typical AC arc welding machine and an E60 rutile electrode. It is relatively insensitive to rust or other surface impurities. For composite girders with corrugated web after welded the shear bolts, one face of I-girder was cast with concrete, and after seven days, the other face was cast. 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 significant initial web defects, including initial distortions, warping, twisting, dents and undulations. Fabrication process is shown in Figure 5.

![Fabrication process](image)

2-3 Material Properties
For Self-compacted concrete, the material properties including compressive and tensile strength of cubes and cylinder were computed at 28 days after casting of the concrete. For steel plate, tensile tests were carried out, the yield and ultimate stress, and record stress-strain data of the samples cut off corrugated webs, flanges and stiffeners were obtained from I-girders. Two thicknesses of plates were used here (6 and
2 mm). The testing procedure was performed according to ASTM [A370]. Material properties are given in Table 2.

| Material          | Compressive strength (MPa) | Tensile strength (MPa) | Components (Steel) | Thickness (mm) | Yielding stress (fy MPa) | Ultimate stress (fu MPa) | Young's modulus (E GPa) |
|-------------------|-----------------------------|------------------------|--------------------|----------------|--------------------------|--------------------------|--------------------------|
| Concrete          | 34                          | 3.47                   | Corrugated web     | 2              | 450                      | 520                      | 202                      |
| flange/ stiffener |                             |                         |                    | 6              | 358                      | 467                      | 204                      |

2-4 **Instrumentation**

The instruments used consist of electronic device (dial gage), which installed at the mid-span below the girder, with 40 mm capacity, to measure the vertical displacement during the testing process very carefully. A hydraulic jack was used to supply the load with a capacity of 200-ton, 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 monitor the load. The load values were recorded in a computer program (The Lab VIEW). 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 (Canon Camera), which is located on one side of the beam.

2-5 **Test Setup**

The hydraulic universal testing machine shown in figure 6 was used to test the two series of specimens. Simply supported I-girders with a clear span of 1100 mm were subjected to one concentrated load at mid-span using a hydraulic jack. A load cell approximately of 200-ton capacity, was mounted under the hydraulic jack to record loads during the loading process. A steel plate (distribution plate) installed between the load cell and the flange of girder, was used to ensure the applied load is stable in the vertical direction and to prevent any slip and failure in the flange. At both ends of the girder, side supports were mounted. Supporting beam under the girder, to ensure the stability of the level during the test. The (Lab VIEW) program was used as a control system; the data were saved automatically in (Microsoft Excel).

![Figure 6. The hydraulic universal testing machine](image-url)
3. Experimental Results and Discussion

3-1 Modes Failure of Girders

At the mid-span of each girder, loading was applied progressively. At the beginning of the loading procedure, the deflection at midspan of the girder was registered at each load pulse. The progress of web buckling 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. For three steel I-girders the failure was local shear buckling in corrugated web. At triangular and trapezoidal corrugated web (TWB and PWB) the local buckling appears in two adjacent folds but, in rectangular corrugated web (RWB) the local buckling appears in one-fold. The failure for all three composite girders was shear failure (TWBC, RWBC and PWBC). Deflection increases linearly with increasing shear strength before cracking appears in concrete. Figure 7, shows the modes failure of test specimens.

![Figure 7. Modes failure of specimens](image-url)
3-2 Ultimate load and deflection

For all test specimens, one shear load was applied at the mid-span of the girder. The experimental results showed that the composite girders covered with two-face concrete bear much greater loads than steel girders not covered with concrete. Regarding the composite girders (TWBC, RWBC and PWBC) they gave much ultimate load than the steel girders (TWB, PWB and RWB), by approximately (63.9%, 62.63%, and 64.37%) respectively. To the increase can be attributed to an increase in the stability of the web to resist the loads as given in Table 3. Therefore, the composite girders with the corrugated web can save higher strength. According to corrugation shapes the triangular corrugated web showed the highest load capacity for two series. The deflection of all tested specimens showed significant convergence between each series separately. The relationship between the load and deflection at the center of the girder shows in figure 8.

Table3. Experimental results and failure modes of tested specimens

| Series          | Identification | First crack (KN) | Ultimate Load (KN) | Ultimate Deflection(mm) | Failure mode       |
|-----------------|----------------|------------------|--------------------|-------------------------|--------------------|
| Series (B)      | TWB            | -------          | 218                | 9.4                     | local shear buckling |
| I-girders       | RWB            | -------          | 213                | 10.5                    | local shear buckling |
|                 | PWB            | -------          | 207                | 11.5                    | local shear buckling |
| Series (BC)     | TWBC           | 252              | 604                | 28.5                    | shear failure       |
| composite       | RWBC           | 270              | 570                | 31.8                    | shear failure       |
| girders         | PWBC           | 185              | 581                | 33.55                   | shear failure       |
Figure 8. Load-Deflection curves
3.3 Strain of the specimens using Digital Image Correlation (DIC)

GOM is a software application for the analysis of materials and the testing and evaluation of components of DIC technology. The estimation of the digital image sequence was assisted by a digital 2D image correlation. For any specimens, DIC technology provided an inexpensive approach, so careful preparation of checked specimens was required to implement the DIC method. The surfaces of the individual specimens were coated with white paint and then as many black points as possible were employed, in which the DIC process was converted into a grid of forms. Figure 9 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.

![Figure 9. Random speckle pattern of specimens](image_url)

3.3 Strain results of the specimens

The longitudinal strain values measured at the girders were recorded at several points along the web face. From Figure 10, the strains at the blue colored region is negative due to compression, while the red colored region is positive due to tension. At the beginning of the loading process strain was appeared almost stable and linear. After the progress in the loading process, the regions of compression and tension began to appear more clearly. Upon reaching the final load, that is, when the model failed, the fold in which the buckling failure occurred became a compression zone, approximating the angle of failure, and around it was a tension zone, this is in relation to the series(B). As for the series (BC), at the beginning of the appearance of the cracks, the regions of cracks and the areas under the load became tension areas and their surroundings closer to the compression regions.
Conclusion

Three steel I-girders and three composite girders with different corrugated shapes of steel web were tested under one shear loading, to investigate shear capacity and failure modes of test specimens. From the experimental results of this study the following conclusions can be made:

1. According to the corrugated shape, triangular corrugated web gave the highest shear strength of the two series.
2. The series (BC) showed an increase in ultimate load capacity compared with series (B). Concrete encapsulation on two faces of I-girders led to enhancing load capacity, because the concrete support the corrugated steel web and make it stiffer.
(3) The composite girders (TWBC, RWBC and PWBC) they gave much ultimate load than the steel girders (TWB, PWB and RWB), by approximately (63.9%, 62.63%, and 64.37%), respectively.

(4) The test results also proved that two different failure modes were observed, local shear buckling was appearing in corrugated web for series(B), while series (BC) appear shear failure.

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