Experimentally Flexural Behaviour Study of Steel Beams with Corrugated Webs

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Abstract. The corrugated web girders had a wide applications because of its many favourable properties. Such as there is no need for intermediate stiffeners to avoid local buckling of the web and the reduction in web to produce by this technique. This study is an experimental investigation of flexural behaviour of I-section steel beams with corrugated webs and flat flange. The study involved testing six groups of steel beams. Each group consisted of two identical specimens and the average result was taken for compression. The first two groups consisted of standard and built-up I-section beams which served as a control beams. The other four groups content a corrugated web beams with different corrugation profiles (trapezoidal, rectangular, sinusoidal and zigzag). The experimental results showed that flexural contribution of the web does not exceed 7-11% from the total beam bending capacity for all configurations types. The rectangular corrugated web had the higher bending capacity and mid-span deflection among all the corrugation types.

1. Introduction
Steel beam with the corrugated web is widely used in construction applications, commonly a shear and compressive stress transfers the web while the flange carries the outer load [1] by using the thinner web and a larger part of the material for the flanges. However, the compressive strength might pass the critical point before reaching the yield that leads to the web’s loss of stability. It is this developing use of I-beam resistance that transfers the stiffeners by the system (corrugated web). This system could be carried out without weakening the load-carrying capacity of the beam. This also results in improved higher stability which avoids failure of the web exhibit and promotes accuracy of yielding which causes a loss of stability and deforms transversely when using the flat web [2]. Research on steel girder with corrugated web was started by [3].The wide applications of the corrugated web in bridges, as in bridge Cognac in France, and the constriction of the shear wall. Also, its use increased in heavy industrial buildings. Mohammad and Seshadri (1997) [4] showed no contribution of the web in bending capacity along the whole beam and could be neglected. Johnson and Cafolla (1997) [5] presented an experimental study on the trapezoidal corrugated web effect in flange local buckling and plate girder flexural behavior. Five specimens were tested, the result showed that is small web contribution on the flexural capacity [5]. B. Jáger et al., (2017) [6] Full-scale four specimens trapezoidal shape corrugated web beam were tested under two point-load in examine the flexural behavior and slenderness effect on the web. The result showed an increase of flexural strength than the capacity of DAST-Ri 015 1990 by (6-17 %). Also, subjected modification for slenderness ratio by 1.5 times than conventional slenderness value [7]. B. Jáger et al., (2017) [6] conducted a series of numerical study on corrugated web beams under bending, they found that the failure mode at moment capacity of the corrugated web was affected by flange web thickness ratio. Chan et al., (2002) [8] Showed that the corrugated web in vertical placement could carry about (13.3 to 32.8%) higher moment capacity than horizontal placement. Also, higher corrugation radius indicated higher bending capacity. In addition, reduction in the weight might
be achieved when using a vertical corrugated web. Abraham et al., (2013) [9] an experimental investigation of lateral buckling behavior for steel section that cold-formed with trapezoidal web were presented. Flat web in addition to two angles of trapezoidal corrugated with 30° and 45° were prepared and tested under two point-loading. The results showed the trapezoidal corrugated with (30°) have a higher carrying capacity than plain and (45°) trapezoidal corrugated web. Also, it was concluded that increasing corrugation angle leads to a decrease in the lateral buckling capacity. Ahmed et al., (2017) [10] this study showed that the flexural capacity for the corrugated web beams was less than convention steel I-beams by about (10-20 %). And the flat web beams showed a combined local buckling of web and flanges. Whereas, web local buckling was prevented in corrugated specimens. Luo and Edlund (1996) [11] A numerical study using finite element method was carried out to investigate the effect of multiple parameters on the shear strength of the trapezoidal corrugated web. The results showed that the increase of corrugation angle might change failure mode from global to local buckling. Kazemi (2010) [12] introduced a three-dimensional finite element analysis to study the behaviour of lateral-torsional buckling behavior for I-section trapezoidal with corrugated web and to study the effect of bracing with lateral elasticity on the critical moment. In this study, simply supported I-beam was tested, and the result shows for plastic and inelastic behavior specimens with corrugated web, the bracing effect initially increased to a certain point as the unbracing lateral length increases then it decreases until the beam behaves elasticity. De’nan et al., (2017) [13] In this research, a three-dimensional analysis using (LUSUS) finite element program was used to model triangular corrugated web beams with different corrugation angle (15°, 30°, 45°, 60° and 75°). Thin shell element was used to model corrugated steel webs. It has been noted that, the stiffness of the beam increased when the angle of corrugation was (45°, 75°). From the literature mentioned, there was no flexural study for steel beam with different configurations webs. Therefore, this research focused on tested flexural study of different corrugations types: trapezoidal, sinusoidal, triangular and rectangular, in addition to flat web girder steel I-section under two-points loading to verify properties and failure mode, study the ratio of flexural contribution strength of the corrugated web, and founded the value of bending capacity of a steel beam with different corrugation profiles.

2. Experimental Program
Standard beam with flat web rolled (IPEA300) and built-up flat web (FWB) corrugated web with beams have similar properties and dimensions with many corrugations, including trapezoidal, rectangular, triangular and sinusoidal were used in this test.

3. Specimen’s fabrication
Six groups including two beams for each group to identify the flexural behavior. All specimens fabricated and welded to one layer by fillet 4mm argon metal. The dimensions of the specimens as follows: The clear span was 2.7m. For all the beams the dimensions (flange width bf = 150 mm, web height hw = 300 mm, web thickness tw = 3 mm, flange thickness tf = 8 mm, Θ= angle with horizontal axis, depth of beam H = 316mm, h=The corrugation depth, s= Projected length of the inclined panel and d=Dimeter of sinusoidal wave). Specimen’s details are shown the table (1) and Fig. (1a-1e).

4. Material Properties
To conduct the mechanical properties of the steel used in this current work, two coupons were cut from each specimen: the first from the flange, and the other from the web. Table (2) shows physical properties of steel web and flange which are used in current study.
The specimens were fabricated by cutting steel plates with different thicknesses and shapes. Then, they were welded by Argon gas. The models were made to ensure that the middle span of the beam was a corrugated web, where it was made by pressing machine for all shapes. Except for the rectangular shape, the plate was cut at (L) shape and welded to each other, as well as the sinusoidal web. Which were made from steel pipe that was opened in the middle by the Computer numerical control (CNC), then welded each half with the reverse of the other half to give the sinusoidal shape. (Metal argon gas) welding method was used. Welding with carbon dioxide made of soft steel covered with a layer of red copper to protect it. The most important advantages of welding carbon dioxide are: full arc control, does not give a crust or powder on the welding line, and give about 95% penetration and long-lasting non-stop

5. Beam Setup and Bracing system

Lateral torsional buckling is a controlling factor in corrugated web beams and some flexural members, in which the deformation varies from in-plane deflection to lateral and torsional modes of deformation [14]. When corrugated web beams are not laterally restrained, it is important to consider lateral-torsional instability as a potential mode of failure, as shown in Fig. (2). Based on this factor, the beams could be categorized into two categories [15]:

- With suitable lateral displacement support in which the beam’s material yields at the maximum part, and the plastic moment capacity for beam is attained.
- With unsuitable lateral displacement lateral support, which leads to failing the beam before it can reach its entire moment capacity.

Table 1. Designation of Tested Beam

| No. Of group | Type of beam | $b_f$ (mm) | $t_f$ (mm) | Hw (mm) | tw mid span (mm) | tw external span (mm) | $\theta$ with horizontal axis | d (mm) | b (mm) | B (mm) | ds (mm) | S (mm) |
|--------------|-------------|------------|-----------|---------|-----------------|------------------------|-----------------------------|-------|-------|-------|-------|-------|
| G1           | FWB1 (IPEA 300) | 150        | 9.2       | 278.6   | 6.1             | 6.1                    | -                           | -     | -     | -     | -     | -     |
| G2           | FWB         | 150        | 8         | 300     | 3               | 8                      | -                           | -     | -     | -     | -     | -     |
| G3           | TWB         | 150        | 8         | 300     | 3               | 8                      | 40.48                       | 70    | 234   | 70    | 100   | -     |
| G4           | RWB         | 150        | 8         | 300     | 3               | 8                      | 90                          | 100   | -     | 70    | -     | -     |
| G5           | SWB         | 150        | 8         | 300     | 3               | 8                      | -                           | 144   | -     | 149   | -     | -     |
| G6           | ZWB         | 150        | 8         | 300     | 3               | 8                      | 37.87                       | -     | 180   | 70    | 120   | -     |
Table 2. Physical properties of steels

| Specimen     | Yield stress (MPa) | Ultimate strength (MPa) |
|--------------|--------------------|-------------------------|
| Flange (8) mm| 275                | 410                     |
| Web (3) mm   | 300                | 425                     |
Strain gauges location are shown in fig. (3). Two strain gauges were connected at the top flange, two were attached on the bottom flange and two strain gauges were put on the web and pasted by adhesive material for all beams. The scheme of the division of normal strain was discerned in a linear direction of the specimen and perpendicular to the section. The reading from the strain gauge was registered using a data logger system connected by a computer.

One linear variable displacement transformer (LVDT) was used in this test and fixed under the bottom flange at mid-span to determine the deflection for specimens.

6. Experimental Test Result
The beams were examined under the same pattern of loading and had the same cross section. The experimental program focused on investigating the gross structural behaviour of different types of corrugated web beams with variable corrugations.
6.1. Load-Deflection Curve
Elastic-plastic curves with similar initial stiffness for all beams were examined. The main domination for the flexural behaviour of all flat and corrugated web beams ended by a slight drop causing local buckling failure either in web or in the flange. While the rectangular corrugated web beam profile provided higher plastic stiffness behaviour than other corrugated web beams. As shown in Fig. (4).

![Figure 4](image.png)

6.2. Strain and normal stress
Normal strains were measured for each beam. The results of the normal strains for every four stages of loading increased are registered. The records along the depth of every beam are given in Fig. (5). Generally, the strain deformation due to local buckling in flat web beams was insignificant because the local web failure occurred in the middle panel near the point loads relatively onward from the beam centre (where the strain gauges were installed). Otherwise appropriate to the outcome of the tensile coupon test, the strain of (0.00137) versus the flange yielding stress (275 MPa) is the start of the plastic stage, while the web stayed in the elastic region with small tension and compression stresses. Also, it can be observed that the corrugated web reduced strain from that of the flat web but led to increased strain in the tension and compression flange.

6.3. Mode of failure
The modes of failure that appear during the test were generally divided into buckling failure of top flange and buckling of the web. A combined failure which merged between the two modes above appeared in flat web control beams because of they have not vertical stiffeners. Generally, the standard FWB1 showed a local buckling in the web and local flange buckling. The local buckling depended mainly on the amount of the unsupported out of plane for the flange and unsupported along the web. While, FWB Combined Global web and flange buckling due to slender the web and unsupported it. This caused the concentration of compressive load on the flange, which led to the global buckling. The failure region reduced with minimize the horizontal distance between sequential corrugation folds, the flat web beams FWB1, FWB induced a huge failure region that (400,420mm) respectively, and that was because there is no any intermediate stiffener to support the flange. While in corrugated web beams, the RWB indicated the minimum local flange failure region (220mm). While, SWB yielded into maximum failure region (370mm). as shown in fig. (6a-6f). The maximum load-deflection results are on table (3).
Figure 5. Normal strain distribution along the depth at mid-span section of beam (a,b,c,d,e and f).
Table 3. Experimental results of the tested beams

| No. of group | No. of beam | Beam designation | Total applied (load kN) Pu | Max. Mid-span deflection (mm) Δu | Mode of failure |
|--------------|-------------|------------------|---------------------------|----------------------------------|----------------|
| 1            | 2           | FWB1             | 267                       | 36.8                             | Combined local web and flange buckling |
| 2            | 2           | FWB              | 200                       | 35                               | Combined Global web and flange buckling |
| 3            | 2           | TWB              | 220                       | 17.3                             | Local flange buckling |
| 4            | 2           | RWB              | 242                       | 30                               | Local flange buckling |
| 5            | 2           | SWB              | 230                       | 24                               | Local flange buckling |
| 6            | 2           | ZWB              | 235                       | 25                               | Local flange buckling |

6.4. Bending Contribution of Web

The experimental bending moment of the flange (Mf) and web moment (Mw) portion were calculated from the strain distribution along beam mid-span. The total experimental moment at the elastic stage (My) which is the sum of flange and web moments then compared with moment from the free body diagram (My Exp.) which equal (0.45 Pu). The web contribution in bending were about (7-11%) and that value cannot be neglected as listed in table (4).
Figure 6. Mode of failure for all beams (a, b, c, d, e and f).
Table 4. Bending Contribution ratio of Web

| Specimen | Py(Exp.) (KN) | My Exp. (KN.m) | Mf (kN.m) | Mw (KN.m) | My(Mw+Mf) (KN.m) | Mw/Mf | Mw/My |
|----------|---------------|----------------|------------|------------|------------------|--------|--------|
| TWB      | 200           | 91.5           | 72.7       | 8.64       | 81.34            | 0.12   | 0.11   |
| RWB      | 225           | 102            | 73.7       | 8.77       | 82.4             | 0.12   | 0.11   |
| SWB      | 210           | 96             | 74.8       | 6          | 80.8             | 0.08   | 0.07   |
| ZWB      | 220           | 100            | 77.06      | 6.4        | 83.46            | 0.08   | 0.07   |

7. Conclusions

In this test, the bending capacity of structural beams with (flat, trapezoidal, rectangular, sinusoidal and zigzag or triangular) web beams had been studied experimentally. Based on the results acquired:

1. The flexural capacity of the beam with corrugated web greater than flat web built-up beam. However, the increase was about (10-21%).
2. The web contribution in bending capacity were found to be (7-11%) comparing with the total bending moment and this portion cannot be neglected in the calculation of corrugated web flexural capacity.
3. Web local and global buckling failure were appeared in flat web beams (standard IPEA300 and built-up), a combined with compression flange local buckling. While, all the corrugation shapes prevent local web buckling.
4. The rectangular corrugated web showed the higher that carrying capacity and stiffness among all corrugation profiles in addition to the rectangular shape had better stiffens and yielded into minimum compression flange failure region.

8. References

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