Behavior of corrugated steel compact I-section beams

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Abstract: The present study deals with the experimental behavior of steel beams with a corrugated section, which is approximately equivalent to a compact I-shape plate girder section. Each part of the compact section (flanges and web) was transformed to its equivalent corrugated shape, depending on the available steel plate in the local market, by two plates separated by internal steel stiffeners of a zek zak shape. Six specimens were fabricated and tested in which one of them was considered as a control beam with no corrugation while the other five ones were with various schemes of corrugation for the flanges and the web. The experimental results showed that an increment of nearly 22% in the ultimate load was obtained when the section's height increased by 25% due to the corrugation process. Furthermore, the mid-span deflection reduced by 57% as the section's height increased by 29%. Besides, the modes of failure changed from flexural to shear in all the tested corrugated specimens.

Keywords: Steel beam, Corrugated web, Shear failure, Corrugated flang, Plate girder

1. Introduction

In many civil structures, particularly bridges and industrial buildings, steel beams and girders with corrugated webs and flat plate flanges are increasingly being used [1–4]. Their first used was in France, the concept history of replacing flat webs with corrugated webs backs to the 1970s. The use of corrugated webs was successfully implemented in a bridge structure in Japan in 1993 [5,6]. Corrugated sections are manufactured by fastening a corrugated plate between two flat flanges or webs, (usually by welding). The common corrugation shape is typically trapezoidal on the web, but there are other types, such as rectangular, triangular, and sinusoidal. Plate girders have proved their usefulness in holding multiple loading conditions for several decades. They are usually made from welding two flanges to an I-section to form a web plate [7]. Reducing plate thickness is not a simple choice for this purpose, as it creates much weakness, such as reduced ability to carry fatigue loading and poor buckling strength. To avoid this weakness, the plate webs of girders are often strengthened with stiffeners at both faces to permit using thin plates. Nonetheless, welding of stiffeners to the member compels the beam to experience residual stresses and heat-affected areas resulting in a subsequent compromise for the fatigue life [8]. Corrugated webs have been suggested to enable the use of thin plates without stiffeners. Such corrugated techniques provide new structures that are used in
airplane wings. It was discovered that the corrugated web beams could be found in houses and bridges. This type of beam benefits from higher load carrying capacity and good economic design owing to the low beam unit weight. A great deal of testing has been conducted on corrugated web beams to study and evaluate shear buckling webbing [9,10,11]. A group of studies on beams with corrugated webs was tested for shear failure (web buckling) by Elgaaly et al. [12]. The web local and global buckling for coarse and dense corrugations was inferred from the experiment as well as the analytical findings. Moon et al.[13] stated that the shear modulus of a corrugated plate girder had a smaller value than that of a flat web. The authors have illustrated that the beam buckling angle increases buckling strength to approximately 10%. Denan et al. [5] showed that corrugating of the web in the vertical direction can provide a greater moment capability than the horizontal direction. Also, more meaningful support was provided for flange buckling by vertical corrugation.

No studies were found about using corrugation in flanges of steel beams, therefore the primary aim of this work is to incorporate an experimental investigation of steel beams of I-sections that have corrugated cross-sections at both flanges and/or web which are approximately equivalent to a steel beam of compact section and having flat web and flanges.

2. Experimental program

A bunch of six specimens were made to investigate the behavior of beams with corrugated sections at the flange and/or web. The length of all beams was 1200 mm with a centre-to-centre clear span between supports of 1100 mm. The geometry and details of the corrugation for the flanges and web as well as the dimensions of the control and examined sections are shown in Figure 1 and tabulated in Table 1. The 6 mm flange thickness of the control beam was replaced by two 2.5 mm steel skins thickness and connected by 1 mm corrugated steel plate, which is approximately equivalent to the flange thickness. Similarly, the 5 mm web thickness of the control beam was also replaced by two 2 mm steel skins thickness and connected by 1 mm corrugated steel plate, which is approximately equivalent to the web thickness. The overall width of the section and net web height in all models were kept constant at 120 mm and 228 mm, respectively. The distances between the skins of the flanges \(d_f\) were varied (i.e. 20, 30 and 35 mm) while the distance between the skins of the web \(d_{cw}\) was kept at 38 mm. Also, four steel stiffeners of 5 mm thickness were used under the applied loads and the support to prevent local buckling.
a) Cross-section details

Figure 1. Beam geometry and section details

b) Overall geometry

Table 1. Dimensions of the tested specimens

| Identification | \( b_f \) | Top flange | Bottom flange | Web |
|----------------|---------|------------|---------------|-----|
|                | \( t_f \) | \( t_s \)  | \( t_c \)  | \( d_c \) | \( b_c \) | \( h_w \) | \( t_w \) | \( t_{cw} \) | \( t_{cw} \) | \( d_{cw} \) | \( b_{cw} \) |
| FW             | 6       | --        | --          | --      | --        | 6       | --        | --          | --      | --        | --        |
| C20WB3         | 6       | --        | --          | --      | --        | 2.5     | 1         | 20          | 40      | --        | --        |
| C20WBT4        | 120     | --        | --          | --      | --        | 20      | 30        | 2.5          | 1       | 20        | 40        |
| C30WBT3        |         | --        | --          | --      | --        | 30      | 40        | 2.5          | 1       | 40        | 30        |
| C35WBT3        | 2.5     | 1         | --          | --      | --        | --      | --        | --          | --      | --        | --        |
| C35WT3         |         | 35        | 40          | 6       | --        | --      | --        | --          | --      | --        | --        |

3. Specimens fabrication process

Plate samples were prepared for flanges, web and stiffeners for each plate girder beam. The cutting process was executed by using a steel cutting machine to prevent distortions and unwanted changes. Furthermore, a particular ripple machine was used to make the required corrugation. After these two processes, each flange and web was assembled alone by welding to form its final shape. The welding process in all specimens was made using E60 wire electrode. The welding of all element was started from the mid-span of the beam and directed toward its ends. Each welding length for each part was divided into two stages in which the first one provides continuous welding for a distance of 100mm, while the next 100mm was left to be welded in the second stage. It should be mentioned that the bottom skin of the top flange and top skin of the bottom
flange was divided into two parts to ensure full welding length of the corrugated plate. Figure 2 shows some of the welding process used in this study.

4. Material properties
Steel plates used to fabricate the specimens were tested in the laboratory of the engineering college of Al-Qadisiyah University. The yield and the ultimate strengths of steel plate specimens obtained from the plates with thicknesses of (6, 5, 2.5, 2 and 1 mm) were recorded [Table 2]. The ASTM A370 specifications were considered for preparing and testing procedure in this test.

| Plate thickness (mm) | Yield stress $f_y$ (MPa) | Ultimate stress $f_u$ (MPa) |
|----------------------|--------------------------|-----------------------------|
| 6                    | 335                      | 487                         |
| 5                    | 342                      | 460                         |
| 2.5                  | 272                      | 310                         |
| 2                    | 253                      | 297                         |
| 1                    | 238                      | 285                         |

4. Test Setup
A hydraulic universal testing machine with a capacity of 2000 kN was used to test all beams, as shown in Figure 3. A stiffened steel beams were used to apply two-point loads on the top flange of the beams to avoid local failure under load concentration. A pin-roller supports were fixed to provide a clear span of 100mm. Each specimen was tested up to failure under the action of applying two-point load. The machine contains a hydraulic actuator, load cell and LVDTs connected to a computer program (lab view) that record the load and deflection during the loading process.
6. Experimental results and discussion
Load on each beam was applied gradually up to failure. At each load stage, the fellow deflection at the mid-span of the beam was recorded. During initial loading stages, the deflection at the mid-span was checked for all specimens. By increasing the load, a local buckling for the control beam's top flange occurs at a load of 340 kN due to axial flexural stresses. For the other corrugated specimens, a shear buckling at the web occurs at a load ranged from 420 kN to 520 kN, as shown in Figure 4. It is evident from the load-deflection curves given in Figure 4 that the corrugated beams' nonlinear behaviour started at a more remarkable load value than that of the control beam by about 23.2% for beam C35WT3 to 35.3% for beam C30WBT3. Increasing the applied load led to the starting of the post-buckling phase, which causes the beam web deforming in the out-of-plane mode for the corrugated specimens and boosting the local deformation of the top flange for the control specimen until failure occurs.
The ultimate load, deflection, failure mode and ductility index were recorded and calculated for all specimens (see Table 3). It can be noticed that the ultimate load capacity of the corrugated beams increased by a ratio ranged from 28.1% for beam C20WB3 to 35.3% for beam C30WBT3 if compared with the control beam. On the other hand, a noticeable decrease in the ultimate deflection for all specimens occurred to reach 54.1% for beam C35WBT3 if compared with the control beam. These decrements in the deflection referred that the corrugated specimens became more brittle than the control beam, this might also occurs because the increase in stiffness of the beam due to increasing in section height However, the observed deflections are still acceptable since the ductility index is greater than 2.

Moreover, results showed that the failure modes had been changed from flexural failure at the top compression flange of the control beam to shear buckling failure at the corrugated specimens’ web, as shown in Figure 5. This change in the mode of failure may be due to the reduction in web thickness, making the critical buckling stress less than that of the control beam.
### Table 3. Experimental results of tested specimens

| Specimen | Ultimate load (kN) | Load ratio w.r.t. control beam (%) | Yield deflection (mm) | Ultimate deflection (mm) | Deflection ratio w.r.t. control beam (%) | Failure mode | Ductility index |
|----------|--------------------|-----------------------------------|----------------------|--------------------------|------------------------------------------|--------------|----------------|
| FW       | 441                | --                                | 2.6                  | 18.1                     | --                                       | Flexural Failure | 6.9           |
| C20WB3   | 500                | 13.3                              | 4.2                  | 13                       | -28.1                                    | Shear buckling and yielding | 3.1           |
| C20WBT4  | 515                | 16.7                              | 3.7                  | 8.9                      | -50.8                                    | Shear buckling and yielding | 2.4           |
| C30WBT3  | 558                | 26.5                              | 3.8                  | 11.7                     | -35.3                                    | Shear buckling and yielding | 3.1           |
| C35WBT3  | 545                | 23.5                              | 3.2                  | 8.3                      | -54.1                                    | Shear buckling and yielding | 2.6           |
| C35WT3   | 495                | 12.2                              | 3.5                  | 13.9                     | -23.2                                    | Shear buckling and yielding | 4             |

**Figure 5.** Experimental test specimens at failure
7. **Conclusions**

From the experimental results of the ultimate load, deflection and failure mode from the tested specimens, the following conclusions could be drawn:

1. Changing the web and flanges of compact I-section from a flat plate to corrugated plates will change the failure mode from flexural to web shear failure.
2. An increment in the ultimate load capacity of 22% could be obtained for beams with corrugated flange and web as the total height of the section increases by about 25%.
3. Flat web and flange compact I-section have a better ductility index than specimens with corrugated plates.
4. Using corrugation in flanges will redistribute the stresses over the section to be more concentrated in the web rather than flanges.

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