Flexural Strength of Castellated Beams with Corrugated Webs

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Abstract. Castellated beams are broadly output from standard rolled sections, especially in (I) or (H) beam sections, and they are considered as a type of steel members with good properties. From another side, the corrugated web in beam especially trapezoidal pattern was utilized to get an improved beam strength against the shear buckling rupture. Besides, there is an advantage of stability for buckling over a plain web beam. In this paper, an experimental study has been carried out on four beams with the same length (1.7m) under one point load at mid-span. This work deals with two castellated beams with corrugated webs with and without lateral stiffeners and it had the same step length for corrugation and castellation profile. The significant variable for castellated-corrugated web beams is a total height of beams. The ultimate load capacity of castellated-corrugated web beams compared with the plain and corrugated web beams. The results showed that the load capacity of castellated-corrugated web beams without and with lateral stiffeners less than that found in flat and corrugated web beams with (23.7% and 39.4%) and (13.2% and 31.03%). The mode of failure has noticed combined between web post-buckling and flange buckling.

Keywords: castellated beams, corrugated webs, web-post buckling, step length, built-up section, fold length.

1. Introduction

Castellated steel beams made in a rolling mill, their webs are cutoff their webs in a zig-zag or other styles. Then one of the parts resulted from this type of cutting is turned and welded to another segment [1]. Welded places at the contact space of the post web between openings. The term "Castellated Beam" comes from holes style in the web resulting from the process of cut, turn, and weld parts of the original beam. The castellation means “built like a castle, having battlements, or regular holes in the walls, like a castle” [2]. This kind of beam contains different types of opening, such as (hexagonal, circular, and octahedral) based on technique fabrication of split which causes weakness in web because of the increase in depth due to increase in the slenderness of web. The main reason for compressive stress tolerance plus conveying shear in a web that results from geometric composition and the flange bears the outside loading. Thus, keeping a large flange and thinner web can be achieved by a corrugated profile [3]. The corrugation of the web prevents failure in the web before reaching the yield capacity of the beam section resulting in a flat web that loss its stability and deformed transversely first. Castellated beams achieved high strength to weight proportion and the high upshot for saving material cost because the cut and rejoining web for pattern member gives a higher depth compared with the original section [4]. Web opening can serve duct functions as air cooling and heating, pipelines,
internet wires, electrical cables, gas lines [5]. Corrugated beams are reducing the probability of failure of web buckling because the geometry profile of the web as corrugated decreases the slenderness ratio that depends on three factors according to the engineering equation S= EI/L, so that achieve an economical design. Consequently, the corrugated web with a thinner plate thickness used to be without adding stiffeners comparing to ordinary flat web beams. The point of utilizing corrugated web with castellated beams is that ambition to reach for the use of thinner plates which require no or less stiffening and increase shear capacity of the web; hence it considerably reduces the cost of beam fabrication with significant weight saving. Failure of the web with presence opening depends on the opening shape, opening dimensions, the distance between opening and web post thickness [6].

Modes of failure for castellated beams shown in Figure (1) [7]:

- Mechanism of Flexural Failure.
- Welded Joint Rupture in a Web Post.
- Shear Force Mechanism (or Vierendeel Bending).
- Shear Force Buckling of a Web-Post.
- Compression Buckling of a Web-Post.
- Overall or Global Lateral – Torsional Buckling of entire span.

![Modes of failure for castellated beams](image)

Figure 1. Failure modes of castellated beams

2. Literature Review

Hosain and Spiers [10] estimated the effect of holes’ geometry and the depth expended in castellated beams to 1.5 times the original depth. The local and lateral buckling are prevented in tested beams. The results showed that the ultimate load capacity increased in three beams having panel length 15, 10 and 7.5 in with ratios 62%, 64% and 66% respectively. Galambos et al. [11] For castellated beams, a specific expansion ratio can be calculated at which the beam will carry its largest load. Tested specimens with expansion ratio (1.2, 1.35, 1.4 and 1.6) achieved increasing in ultimate load than for unexpanded specimen with (23%, 38%, 42% and 36%). Zaarour and Redwood [12] The web buckling load of castellated beams was predicted by twelve specimens which were tested; all tested beams failed in web-post buckling except two beams. The results
showed that the presence of mid-depth plate welded between the two holes of castellated section significantly increase the susceptibility to buckling. Kohnehpooshi and Showkati [13] The castellation process causes a reduction of only 4% in major bending capacity, which in turn shows satisfactory behavior of these beams subjected to non-buckling bending. The results showed that the behavior of non-buckling bending of castellated beams done by increasing in effective moment if inertia value about 2.4 times than original beam. Frans et al. [14] Hexagonal castellated beams have been studied by utilizing a numerical approach for locating hole angle and spacing between it. Various space opening (6cm, 9cm and 12cm) with various cutting angle (50%, 60% and 70%) have considered using finite-element model with ABAQUS. The maximum yield load achieved when the opening space and cutting angle are (6cm) and (60%) respectively. Khalid et al. [15] tested five specimens corrugated steel web beam under three points bending, semicircular corrugated shape with (4mm) thickness web were adopted in vertical and horizontal alignment. The study showed that the corrugated web in vertical placement could carry about (13.3-32.8%) higher moment capacity than horizontal placement. Also, higher corrugation radius indicated higher bending capacity. In addition to reduce in the weight might be achieved when using vertical corrugated web. Lho et al. [16] Full-scale four specimens trapezoidal shape corrugated web beam were tested under two-point load in order to 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. Divahar and Joanna [17] 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 increase corrugation angle led to decrease the lateral buckling capacity. Ibrahim [18] An experimental study to examine flexural behavior of flat web beam comparing with similar properties and dimensions were carried out. Trapezoidal corrugated web full scale (four beam CW and FW with the same web thickness 2.1 mm). The results of flexural capacity for the corrugated web beams where less than convention steel I-beam 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.

Based on previous studies, it can be noticed that the vast majority of researchers in castellated beams have been studied these beams with plain steel webs, or focused on built-up steel beams with corrugated webs, but it can be seen few researches that carried out merging castellated beams properties with taking advantage of corrugated steel webs to overcome the problems that accompanying the castellation such as the increment in slenderness and local buckling associated with it.

3. Scope and Boundaries

1) All specimens have simply supported condition and subjected to one-point load at mid-span of specimen.
2) The built-up I-section with plane web has approximate dimensions with (IPE 140) which was utilized as a parent section.
3) Lateral supports at midspan and both ended to avoid lateral-torsional buckling as possible that considered as a significant factor in castellated beams with corrugated webs and in some other flexural members.
4) Step length of corrugated web profile similar to that found in castellation cut pattern.
4. Specimen’s Parameters

The built-up I-section with the dimensions same as (IPE 140) but web and flange thickness were (2mm and 6mm) respectively and utilized as a parent section with features and specifications as shown in Figure (2). Other beams were two of built-up sections represented castellated beams with corrugated web with and without sideway stiffeners. Furthermore, the one trapezoidal corrugated steel web beam with details shown in table (1). The configuration of these specimens has been indicated in Figure (3).

![Fig. (2) Parent beam dimension](image)

![Fig (3) Beams Details](image)
The instructions of (ASTM-American Society of Testing and Materials) were implemented to predicted a test coupon sections. The stress and strain information were taking until the coupon specimen reaching to failure state, and record yield and ultimate stress. Modulus of elasticity and Poisson’s ratio were assumed as $200 \times 10^9$ Ps and 0.3 respectively, table (2) show the coupons summarized results.

### Table (2) Material Properties

| Specimen     | Plate thickness | Plate thickness |
|--------------|----------------|----------------|
|              | 2mm            | 6mm            |
| Yield Strength (Mpa) | 257            | 260            |
|              | 283            | 279            |
|              | 267            | 282            |
| Average      | 269            | 274            |
| Ultimate Strength (Mpa) | 412            | 405            |
|              | 432            | 417            |
|              | 441            | 419            |
| Average      | 428            | 414            |

### 5. Fabrication

The fabrication process consists of several steps: First is to make a corrugation for the steel web by utilizing angle (45º) and equal fold length to get a trapezoidal corrugated steel web. The second step is cutting specimen patterns involved weld the trapezoidal corrugated steel web with flanges to make a built-up steel section, then cut the corrugated web in a trapezoidal pattern similar to corrugated web style, as shown in Figure (4 a, and b). The third step begin after the ending of the cutting process for corrugated steel webs of a built-up section, the welding stage is beginning. The two pieces of a built-up beam resulting from the cutting process will be separated, and one of these pieces rotate and shifting over another one. Then can weld the post web between openings created in castellated beams with corrugated web, as shown in Figure (5 a, and b). The aim of making the corrugation and castellation in the same pattern was for getting a suitable web openings shape as much as possible. The geometry of the corrugated steel web for the section of the castellated beam led to use steel stiffeners (lateral stiffeners) to strengthen the weak side of
castellated beam with corrugated web. Preventing local failure can be achieved by a steel plate called “bearing stiffener” putting on the web under concentrated load and reaction positions.

Figure (4-a) Corrugation pattern style

Figure (4-b) Cutting pattern style

Figure (5-a) Corrugated web welding with flange

Figure (5-b) Web post welding

6. Results

Table (3) shows the results of tested beams “CB-01, CWB-01, CBCW-02 and CBCW-03”. The max deflection of control beam (CB-01) was (18.03mm) at ultimate load (38KN). The ultimate load capacity of (CWB-01) reach to (47.85KN) about (25.9%) more than the general control beam (CB-01), while castellated beam with corrugated web (CBCW-02) failed at ultimate load capacity (29 KN) that less than about (23.7%) and (39.4%) from control beam and corrugated web beam respectively. On the other hand, putting lateral stiffener plates in last beam (CBCW-03) to increase shear resistance of web and providing additional support to weak side of castellated beam with corrugated web. The results appeared that the ultimate load capacity reach to (33KN) less than control beam and corrugated web beam with (13.2%) and (31.03) respectively. The results also showed that the ultimate load capacity of last beam (CBCW-03) founded more than castellated beam without lateral stiffener (CBCW-02) with (13.8%).

Load-deflection diagrams that were obtained from experimental test of (CB-01), (CWB-01), (CBCW-02) and (CBCW-03) were clarified in Figure (6). From the specimens tested can be observed the failure mode of corrugated web beam represented in flange local buckling near to the mid span where large outstand unsupported flange [19,20]. While the failure mode in castellated beams with corrugated webs with or without lateral stiffener was the web-post buckling because influence of the dimensions of openings, overall depth and web thickness in these beams [21].
Table 3. Tested beam results

| Specimens | CB-01 | CWB-01 | CBCW-02 | CBCW-03 |
|-----------|-------|--------|---------|---------|
| Control   | 38    | 47.85  | 29      | 33      |
| load (KN) |       |        |         |         |
| Mode of failure | Local flange buckling | Combined between web post buckling and flange buckling | Combined between web post buckling and flange buckling |

Figure 6 Load – Deflection curves of tested Beams

From results and mode of failure shown in figure (7 a, b and c) can see the increase in depth affects adversely strength capacity. The strength capacity in castellated beams with corrugated webs is affected mainly due to the incidence of web-post buckling since it is affected by the slenderness of the web. In other words, when the critical load is reached, the slender component draws aside instead of taking up additional load. The web will be very weak against shear buckling because of introducing the openings. Thus, it can be seen that corrugation improved the capacity whereas introducing the openings resulted in severe drop in capacity.
At the onset of web buckling when the shear load is beginning to increase gradually, the web of beam resists the development of shear stress depending on the panel in corrugated web bounded between the top and bottom flange. The panel can be continuing to support a substantial increase in shear load in the post-buckling range due to the development of the tension field mechanism. The web containing a large hole as found in castellated beams does not anchorage for the diagonal tension field and can exist if founded a transverse stiffener.

![Figure 7. Tested Specimens at Failure](image)

(a) Corrugate web beam. (b) Castellated-corrugated beam without lateral stiffeners. (c) Castellated-corrugated beam with lateral stiffeners.

The transceiver stiffeners acting as struts and the top and bottom flanges acting as chords, thus forming an effective Pratt or N-truss. In the post-buckling range, the resistance offered by web plates is equivalent to that of the diagonal tie bars in a truss. The horizontal shear force acts along the weld joint have two effects represented with stress the two edges of web post in tension and compression which lead as result to buckle the web post accompanied by twisting [22].
7. Conclusion
In this test, the bending capacity of castellated beams with corrugated (with and without lateral stiffeners) webs was studied, moreover for flat and corrugated web beams. The mode of failure also investigated. Based on the results obtained can observe the following:

1) Ultimate load capacity results clarified that the castellated-corrugated web beams load capacity less than the control and corrugated web beams with ratios (23.7%) and (39.4%) respectively.

2) The castellated-corrugated web beam with lateral stiffeners gives increasing in load capacity with a ratio (13.8%) relative to the castellated-corrugated web beam without lateral stiffeners.

3) The failure mode observed on corrugated web beam is represented with local flange buckling but the failure mode for both castellated-corrugated web beams with and without lateral stiffener are combination between web-post buckling and flange buckling.

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