Experimental study for strengthening octagonal castellated steel beams using circular and octagonal ring stiffeners

H. W. Al-Thabhawee 1*, A. Mohammed 1

1Department of Civil Engineering, College of Engineering, Al-Kufa University
E-mail: * hayder.althabhawi@uokufa.edu.iq

Abstract: Castellated beams made by cutting web of hot rolled steel I-section in particular zigzag pattern and recollecting the two parts by welding, to form a castellated beam with hexagonal openings, or more increasing of section depth by placing expansion plates between these parts to fabricate castellated beam with octagonal openings. The main advantage of fabrication this type of beam is increasing section depth, which leads to improve its behavior compared with original beam. So as to use the castellated beams with expansion plates into its best advantages, the failure modes due to web opening need to be avoided. This paper aims to provide added strength of castellated beams with expansion plates by using two types of stiffeners (circular and octagonal ring) around octagonal web opening. This strengthening technique was suggested to reinforce web portion and avoid failure due to web-post buckling. Standard (IPE140) were chosen as a parent section for fabricating four specimens as well as original beam. The important observation through this study is that using ring stiffener leads to have significant effect on ultimate strength. In case of using circular ring stiffeners, the ultimate strength was increased up to (188%) compare with original beam. Whereas the increment in ultimate load at using octagonal ring stiffeners was reach to about (77.6%). Consequent, using circular ring stiffeners to reinforced this type of beams was more efficient than using octagonal ring stiffeners. It is worthwhile to mention that it can be used (37%) as additional steel material (Expansion plates and ring stiffeners) for increasing the load capacity of castellated beams up to (288%) relative to original beam.

1- Introduction:
In recent years, with the technology of steel structures progress, more types of steel sections were developed to improve mechanical properties of this type of structural and also to obtain sections that allow usage for more aesthetic applications by satisfying the architectural needs. The perforated section, such as, castellated and cellular members are one of the best example of newly developed section. During the second world war, castellated beams with hexagonal opening that fabricated by cutting the web portion of I-section along its centerline and shafted then re-jointed by welding as shown in Figure 1 were one such improvement occurred in built-up structural members to modify hot rolled I-section steel beams by increasing their resistance against bending due to the increased depth of section[1]. Some design cases made its advantageous to expanse the depth of section more by placing expansion plates between the two halves of the tee sections which are called "Expansion Plates" as shown in Figure 2.
Figure 1. Fabrication of Castellated Beam with Hexagonal opening (CB-H).

In addition to increase depth of castellated beams, these processes enhance area of web opening which turns into octagonal shape and can be used to pass the accommodate services. Also, the elastic stiffness and bending strength of castellated beam about its principal axis are heightened. The structural properties allow castellated steel beam with expansion plate (CB-O) to be used in long span applications with moderate loading conditions for supporting floors and roofs.

Figure 2. Fabrication of Castellated Beam with expansion plate (Octagonal opening) (CB-O). [2]

In order to use the castellated beams with expansion plates (CB-O) into its best advantages, the failure modes due to large web opening need to be avoided. The structural behavior of the castellated beams are essentially differs from solid web beam as with the existence of openings in the web portion which may cause various failure modes such as Vierendeel mechanism and web-post buckling due to shear. These
models of failure do not occur with plain webbed beams since they are a direct result of the different way
in which shear is transferred through the perforated web but failure by the formation of a flexural mechanism
or by lateral-torsional instability are entirely similar to the equivalent modes of solid web beams. All these
failure modes happen due to the instability of the web portion. A proper strengthening process will avoid
these types of failures and improves the performance of (CB-O).

The present work aims to improve structural behavior of castellated steel beams with expansion plates
(CB-O) by welding two types of stiffener around octagonal web opening (Circular and octagonal Ring) as
shown in Figure 3 which can be used to strengthening web portion and avoid failure due to Vierendeel
mechanism or web-post buckling. In order to understand performance of cases, five experimental specimens
are tested in Engineering Collage Laboratories of Kufa University.

![Figure 3. Reinforced Octagonal web opening of castellated beam with expansion plate by:
(Circular ring stiffeners. & Octagonal ring stiffeners).](image)

2- Previous Studies and Research Gap:
During second war castellated beams with hexagonal opening were one of the important modification
happened in steel members as built up section from hot rolled I-section by increasing the depth of it which
lead to increase the stiffness and the ultimate strength. In (2011), Tsavdaridis and D'Mello, studied the
structural behavior of castellated beams with webs of closely spaced openings by testing seven experimental
specimens. The purpose of their work was to examine the potential impacts of various shapes and sizes of
openings on the failure mode and ultimate strength of castellated beams. Finite element models of castellated
beams with hexagonal, circular and elongated web openings were developed and analyzed by using ANSYS
v11.0 software; The results were compared with seven experiments test specimens. They concluded that the
maximum shear stresses spread from the mid-height of the web-post nearer to the flanges in the direction
of the axial forces [3]. Soltani et al. in (2012), developed a numerical model to investigate the structural
behavior of castellated beams with hexagonal and octagonal openings up to failure. Their principal objective
was to study the web post buckling. Their work showed that the use of expansion plates could make
castellated steel beams more vulnerable to occur web-post buckling. Also, they concluded that depth of
these expansion plates must not be more than (15%) of the overall hexagonal opening depth [4]. In (2015),
Tsavdaridis and Galiatsatos investigated closely spaced cellular beams with double concentric transverse
stiffeners by using finite element analysis. From the results, they noted that Vierendeel failure occurred
more frequently for very closely spaced sections. However, as the spacing increased, the influence of the
transverse stiffener to strength of the section was decreased and web post buckling failure happened more
often. Moreover, they suggested a maximum spacing between the web openings [5].
In the previous literatures, it can be noted that there are a lack in experimental study to investigate the structure behavior of (CB-O) as shown in Figure 2. Predominantly, the castellated beams with hexagonal openings and cellular beams with circular openings are widely used in the constructions due to ease of the manufacturing. In addition, most of numerical researches indicated that the use of expansion plates could make castellated steel beams more vulnerable to occur web-post buckling in web segment. Few studies have been carried out to strength the octagonal opening of castellated beams with expansion plates in order to avoid web post buckling. Also, It can be noted that there is no regulated knowledge of how (CB-O) would behave if a stiffeners are placed around the octagonal openings. This research aims to examine the effectiveness of reinforcing (CB-O) by using stiffeners around edge of octagonal openings to improve its structural behavior and avoid web post buckling failure in web segment at high load.

3- Experimental Program:
In this study, hot rolled I-sections (IPE 140) were chosen as a parent section to fabricating four specimens of castellated beams as well as a control beam. For all specimens, flange thickness, web thickness and span length were (t_f=6.9 mm), (t_w=4.7mm) and (L=1700mm) respectively. A plasma CNC machine was used to cut the parent I-section along its web for making the zigzag pattern, then rejoining the two halves together using electrode welding to make a castellated beam with hexagonal opening or adding the square plate (as expansion plate) and welding all parts together as shown in Figure 4. The material properties were obtained from tension tests on flat tensile specimens according to ASTM A370[7].

As aforementioned, this work focused on using two types of stiffener (circular and octagonal rings) that it will placed around octagonal web opening of (CB-O) to prevent failures due to Vierendeel failure and web-post-buckling [8]. Circular and octagonal rings are used as stiffeners around edge of octagonal web opening of (CB-O). The circular ring stiffeners insulated by welding at tangent point of each sides of octagonal web opening edges as shown in Figure 3(a). But the octagonal ring stiffeners placed by welding at along length of each sides of octagonal web opening edges as shown in Figure 3(b). In order to obtain castellated beam with hexagonal opening (CB-H) that have equal side, cutting angle which used to cut the web of parent I-section was (45°) to achieve equal edge sides of hexagonal openings. The purpose of fabricating the castellated beam with equal edges hexagonal opening was to obtain octagonal castellated beam with equal edge sides opening after adding the expansion plate. The dimensions and details of experimental cases are shown in Figure 5 and Figure 6. The first specimen (CB-00) was parent beams (IPE140) which used as control beam as shown in Figure 5(a). Whilst, Figure 5(b) shows dimension and details of hexagonal castellated beam (CBC-01) which was fabricated by cutting angle of web (45°) in order to obtain equal side of hexagonal web opening.
Figure 5. Dimensions and notations of all specimens.

This specimen have total depth (H=197mm) and expansion depth ratio (H/h=1.4). The purpose of fabricating the castellated beam with equal edges hexagonal opening was to obtain castellated beam with equal sides octagonal web opening after placing square expansion plates as shown in Figure 5(c). Consequently, specimen (CBC-02) was octagonal castellated beam with square expansion plates (81mm x 81mm x 5mm) which placed between upper and lower tee section to increase its depth up to (H=278mm) and expansion depth ratio (H/h =1.985 =2.0). In order to test the effectiveness of reinforcing (CB-O) using stiffeners around edge of octagonal web openings, specimen (CBC-03) and specimen (CBC-04) that have same dimensions of specimen (CBC-02) are fabricated as shown in Figure 4(d) and Figure 5(e). In specimen (CBC-03), the shape and geometry of equal sides octagonal web openings allowed to use circular ring as stiffeners to
reinforce (CB-O). The circular ring stiffeners that have thickness (t_r=5mm) and width (B_r=50mm) are welded at tangent point with each side of octagonal web opening as shown in Fig.(3-a). So as to strengthening specimen (CBC-04), octagonal ring stiffeners that have thickness (t_r=5mm) and width (B_r=50) are placed by welded all sides of the stiffeners with octagonal web opening as shown in Fig.(3-b). Dimensional and Material Properties of Specimens are shown in Table 1.

In order to ensure load distribution from concentrated force and end supports and to avoid failure due to web buckling by compression force, transverse stiffeners were utilized at supports and mid-span. All specimens were simply supported and lateral supports are used to prevent lateral torsional buckling. The specimens were set in a test machine with adequate care taken to ensure that beams were correctly placed in the test machine and the mid-span of the beam was in line with the hydraulic jack centerline as shown in Figure 7. The applied load produced using load machine of (1000 kN) capacity at Engineering Collage Laboratories of Kufa University.

Table 1. Dimensional and Material Properties of Specimens

| Specimens  | Open Shape | H  | L  | D  | Ring Stiffeners | Material Properties (MPa) |
|------------|------------|----|----|----|-----------------|---------------------------|
| CB-00      | Plain      | 1.00 | -  | -  | -               | -                         |
| CBC-01     | Hexagonal  | 197.3| 6  | 0.82| -               | -                         |
| CBC-02     | Octagonal  | 278.3| 6  | 0.82| -               | -                         |
| CBC-03     | Octagonal  | 278.3| 6  | 0.82| Circular        | 279 432 2.01x10^5         |
| CBC-04     | Octagonal  | 278.3| 6  | 0.82| Octagonal       | -                         |

Where: 

- H: overall depth of specimen. 
- h: parent I-section height. 
- D: opening height (114.6mm). 
- w: clear distance between two successive openings (81.0mm). 
- S: spacing between two openings center to center (276.6mm). 
- t_r: thickness of ring stiffeners. 
- B_r: width ring stiffeners.
4. Results Discussion:

**Control specimen (CB-00):** Hot rolled I-sections (IPE 140) which was chosen as a parent section was tested to compare the experimental results of this beam (as control beam) with castellated beam with and without ring stiffeners. The results obtained from experimental test demonstrate that control beam failed by flexural mechanism which mean the sections above and below the neutral axis yielded in compression on upper section and tension on lower section. The testing of control beam and its failure mode presented in Figure 8. When the applied load was reach to about (62.0kN), first sign of yielding was seen at upper and lower flange with vertical deflection (9.2mm). Whilst, the maximum vertical deflection recorded was (47.0mm) at ultimate load (78.8 kN).

![Figure 7. Details of Testing Setup.](image7)

![Figure 8. Experimental setup of control beam (CB-00) and failure mode](image8)

**Specimen (CBC-01):** This specimen (Hexagonal castellated beam) failed by plastic hinges formation at four corners of the panel close to applied point load and in the region of the beam where both moment and shear are present. The failure mode of this specimen (castellated beam with hexagonal opening) is observed in Figure 9 and Figure 10 shows the sequence of yielding point at failure zone. In Figure 11 the load-deflection curve for this specimen is presented and compared with results of control specimen (CB-00). As the applied load was reach to about (77.0kN) at point (I), first sign of yielding was seen along the line marked (1) in Figure 10.

![Figure 9. Failure model of specimen (CBC-01)](image9)

![Figure 10. Sequence of yielding in specimen (CBC-01)](image10)

While the applied load was being increased to (81.0 kN) at point (II), the yielding started firstly at the corners of hexagonal opening marked (2) and then at opposite corners marked (3). Yielding at four corners of hexagonal opening of this specimen became prominent when the applied load was gradually raised and it
can be shown that a well-defined of Vierendeel mechanism had occurred when the applied load reached to maximum value at (87.6kN) at point (III). The castellated beam sustained the maximum load only briefly before web-post buckling occurred in the first panel on the lift hand side of the applied load. Consequently, the beam started to unload shortly thereafter as shown in region between point (III) to failure load (86.5kN) at point (IV) in Fig.(6). It is worth to mention that the ultimate load of specimen (CBC-01) which is equal (87.6 kN) increases by (11.1%) when comparing with the ultimate load of control beam without adding any material.

Specimen (CBC-02): In this castellated beam, its depth was increased by adding expansion plate. Figure 12 shows the load-deflection curve of castellated beam with expansion plate (octagonal web opening). It can be noted that first sign of yielding was observed, on the inside face of the compression flange near the applied load, when the load was (89.0kN). The applied load was gradually raised to ultimate load. After the applied load reach to value (120kN), it was observed that unloading started. Unloading rate was gradual at the beginning because the deformation in web but at (96.0kN) web-post buckling failure occurred at the panel close to the point load as shown in Figure 13.

Figure 11. Load-deflection curve of (CBC-01) and (CB-00).

Figure 12. Load-deflection curve of (CBC-02) , (CBC-01) and (CB-00).

Figure 13. Failure mode (Web-Post Buckling) in specimen (CBC-02)

The ultimate load of specimen (CBC-02) which was equal (120.0 kN) increased by (52.2%) and (37%) when comparing with the ultimate load of control specimen (CB-00) and hexagonal castellated beam (CBC-01) respectively. But, the ductility index of this beam which was equal (4.0) decreased to (38%) as
comparing to ductility index of (CBC-01) which was (5.5). It is worth to mention that the ductility index is the ratio of deflection at failure load of beam to the deflection at yielding point. In general, a high ductility index indicates that a beam tested are capable of undergoing large deformations prior to failure. Figure 14 is explained the web-post buckling due to shear force. It can be noted that the horizontal shear force ($V_{wp}$) which was acting along the welded joint stress between expansion plate and web-post in bending, caused tensile stress along parts (AB and GH) and compression along parts (CD and EF). In the web-post buckling, the compressed parts tend to move away from the longitudinal plane of the web while the tensioned parts tend to remain in the starting position. This mode of failure occurs usually in inelastic regime with a significant yielding of the section. In general, increasing the height of castellation beam causes the web-post buckling failure which as a results lead to rapid failure [9][10].

![Figure 14. Web-Post buckling due to shear force.](image)

**Specimen (CBC-03):** In this test, investigating the efficiency of using circular ring stiffeners for strengthening (CB-O) was searched. In previous literature, different type of stiffeners like transvers stiffeners are tested to improve structure behavior of octagonal castellated beam but ring stiffeners are not used in experimental test. Consequently, the circular ring stiffeners were placed around the octagonal web opening to avoid web-post buckling which was occurred due to web opening as shown Figure 3 (a).

![Figure 15. Load-deflection curve of (CBC-03), (CBC-02) and (CB-00)](image)

![Figure 16. Load-deflection curve of (CBC-03), (CBC-02) and (CB-00).](image)

It can therefore be observed that using circular ring stiffeners seem to have drastic effect on the elastic stiffness and the ultimate strength of octagonal castellated beams as well as considerably increases their...
ductility. It appears from Figure 15 that there is significant increase in ultimate strength of specimen (CBC-03) which was reach to (227.0 kN) increased by (188 %) and (89%) as comparing with the ultimate load of control beam and octagonal castellated beam without stiffeners (CBC-02) respectively. Moreover, the ductility index of (CBC-03) which was equal (5.9) increased to (44.6%) when comparing to ductility index of (CBC-02) which was (4.08). The important notation through this test is that the proposed strengthening technique (Circular ring stiffener) prevented the web-post buckling failure due to shear force and improved behavior of octagonal castellated beams as shown in Figure 15 and Figure 17.

![Figure 17. Modes of failure of specimen (CBC-02) and (CBC-03) at ultimate load.](image)

**Specimen (CBC-04):** In this specimen, other strengthening technique was suggested to avoid web-post buckling in castellated beam with expansion plate. In specimen (CBC-04), octagonal ring stiffeners are provided to reinforce the octagonal web opening see Figure 3(b), instead of using circular ring stiffeners, that were used in previous specimen (CBC-03). The Load-deflection curve of (CBC-04) and (CBC-02) as well as control beam is shown in Figure 16 to observe effect of using octagonal ring stiffeners. It can be noted that using octagonal stiffener leads to have significant effect on the elastic stiffness and the ultimate strength. Moreover, it increases ductility of beams and prevents unloading which occurred due to web post buckling in specimen (CBC-02). In case of using octagonal ring stiffeners, the increment in ultimate load and ductility index were about (77.6%) and (9.8%) respectively. Figure 18 shows model failure of octagonal castellated beam with octagonal ring stiffeners at ultimate load (140kN) and comparison with model failure of octagonal castellated beam without ring stiffeners.

![Figure 18. Failure Modes of specimen (CBC-02) and (CBC-04) at ultimate load.](image)
5- Economic Feasibility for Using Ring Stiffeners in Octagonal Castellated Beam

One of the most important advantages of castellated beams is their economy, the economy depends on many factors such as loading, depth, and span length requirements. The researchers continuously attempt to find new ways to decrease the cost of structures, circular ring stiffeners around octagonal web openings could provide a great cost saving. In this research, hexagonal castellated beam doesn’t consume any additional steel material but the increasing in strength compared with parent section was limited. While (CB-O) consumes amount of steel about (7.5%) with increase in strength about (11.1%) compared with parent section. In spite of octagonal castellated beam which was reinforced by adding circular and octagonal ring stiffeners consume a considerable amount of steel about (37%) and (39%) of original weight respectively but with great increasing in strength reach up to (188%) and (77.6%) compared with ultimate load capacity of original beam. Figure 19 shows relationship between ratio of weight and ultimate load of all specimens to original beam. The important observation through this study is that the proposed strengthening techniques prevents web-post buckling due to shear force occurred in octagonal castellated beam and improves its structural behavior. In this figure, the maximum ultimate load was noted in using circular ring stiffeners which reach to (227) about (288%) respectively to original beam with adding amount of steel (square expansion plates and circular ring stiffeners) about (37%) compared with total weight of original beam.

![Figure 19. Economic feasibility of using ring stiffeners with castellated beams](image)

6. CONCLUSION

From this study, it could be concluded:

1- The ultimate load of octagonal castellated beam with expansion plates (CBC-02) which was equal (120.0 kN) increased by (52.2%) and (37%) when comparing with the ultimate load of control specimen (CB-00) and hexagonal castellated beam (CBC-01) respectively. But, the ductility index of this beam which was equal (4.0) decreased to (38%) as comparing with ductility index of (CBC-01) which was (5.5).

2- It can be found that using ring stiffener leads to have significant effect on the stiffness and the ultimate strength. Moreover, it increases ductility of beams and prevents unloading which occurred due to web post buckling in (CB-O). In case of using circular ring stiffeners, the increment in ultimate load and ductility index were about (188%) and (44.6%) respectively. But, using octagonal ring stiffeners, the increment in ultimate load and ductility index were about (77.6%) and (9.8%) respectively.

3- It can be seen that using circular ring stiffeners to reinforced octagonal castellated beam with expansion plates was more efficient than using octagonal ring stiffeners. In case of using circular ring instead of
octagonal ring as stiffeners, the differential of increment for the ultimate load reach to (110.4%) relative to original beam.

4- Providing circular ring around octagonal web opening of castellated beam with expansion plate (CB-O) can be improved the stiffness response and ultimate load capacity of these beams up to (288 %) relative to ultimate load of the parent I-section with using only (37%) of origin weight as additional material (Expansion plates and circular ring stiffeners).

References:
[1] Ellobody E (2011). Interaction of buckling modes in castellated steel beams. Journal of Constructional Steel Research, 67 (5), 814–825.
[2] Al-thabhowee H W and AL-kamnoon M A (2018). Improving Behavior of Castellated Beam by Adding Spacer Plat and Steel Rings. Journal of University of Babylon, Engineering Sciences, 26 (4), 331 – 344.
[3] Tsavdaridis K D and D'Mello C (2011). Web Buckling Study of The Behavior And Strength of Perforated Steel Beam With Different Novel Web Opening Shapes. Journal of Constructional Steel Research, 67, 1605-1620.
[4] Soltani et al. (2012). Nonlinear FE analysis of the ultimate behavior of steel castellated beams. Journal of Constructional Steel Research 70, 101–114.
[5] Tsavdaridis K D and Galiatsatos G (2015). Assessment of Cellular Beams with Transverse Stiffeners and Closely Spaced Web Openings. Thin-Walled Structures, 94, 636-650.
[6] Patil S A and Kumbhar P D (2016). Comparative Study of Transverse Stiffeners and Stiffeners along the Opening Edge used for Castellated Beam. International Journal of Innovative Research in Science, Engineering and Technology, 5, 8516- 8522.
[7] ASTM E8M-99. Standard Test Methods for Tension Testing of Metallic Materials. [Metric], ASTM.
[8] Kerdal D and Nethercott D A (1984). Failure Modes for Castellated Beams. Journal of Constructional Steel Research, 4, 295–315.
[9] Liu T and Chung K (2003). Steel beams with large web openings of various shapes and sizes: finite element investigation. Journal of Constructional Steel Research, 59 (9), 1159–1176.
[10] Jamadar A M and Kumbhar P D (2015). Parametric Study of Castellated Beam with Circular and Diamond Shaped Openings. International Research Journal of Engineering and Technology, 2, 715–722.