DE GRUYTER

Open Engineering 2022; 12: 245–253

Research Article

Hayder Wafi Al-Thabhawee* and Muslim Abdul-Ameer Al-Kannoon

# Experimental study of the behaviour and failure modes of tapered castellated steel beams

https://doi.org/10.1515/eng-2022-0028
received August 12, 2021; accepted September 10, 2021

**Abstract:** This article discusses the experimental testing of tapered castellated beams (TCBs) under mid-span concentrated load. These beams are created by cutting the webs of standard I-sections in a particular zigzag pattern and rejoining the two parts by placing variable expansion plates between web posts and welding them together. Generally, the depth of the mid-span will be increased. A standard I-section (IPE140) was selected as a parent beam to fabricate three TCB specimens and one prismatic castellated beam. The experimental results showed that the ultimate load capacity of the TCBs could be increased up to 140% of the ultimate load capacity of the parent section. Fabricating a TCB is an effective way of increasing the allowable load of a long-span member while remaining within International Building Code-defined deflection limits. The experimental results showed that the allowable load at deflection (L/360) increased up to 183% of the allowable load for the control specimen at the same deflection. Finally, the experimental results showed that web-post buckling and joint-weld rupture failure modes occurred in TCBs due to the formation of high shear forces that tried to twist the web posts.

**Keywords:** castellated beam, web post-buckling, Vierendeel mechanism

## 1 Introduction

In recent years, use of light steel components in the construction of pre-engineered buildings has become extensive due to simplicity and speed of erection, as well as other advantages such as durability and strength-to-weight ratio. However, this kind of structure has very long spans coupled with light loading, and in some cases, standard steel sections may satisfy the strength requirement but not meet serviceability requirements such as deflection criteria. To fulfil the deflection requirement for a beam, it is necessary to increase the ratio of section depth to span. As one solution, a double-tapered castellated beam (TCB) can be used to provide increased section depth at mid-span with minimal additional weight.

A castellated beam is manufactured by cutting the web of a standard I-section beam with a cutting pattern centred on its centreline. The two halves generated by the cutting are then rejoined by welding, as shown in Figure 1. The increase in beam section depth resulting from this manufacturing process gives castellated beams with increased strength and stiffness compared with their parent I-section beams. For some designs, it can be advantageous to further increase the section depth at mid-span by inserting extension plates in the middle of two T-sections, which are called "Expansion Plates" to create double-TCBs, as illustrated in Figure 2.

TCBs are usually utilised as roofing beams; roof slopes are naturally achieved because of their geometry. Additionally, as their geometry reflects the bending stress distribution for most load cases, such beams can be used more efficiently. The significant advantage of TCBs over non-TCBs is the increased stiffness and strength achieved by the insertion of plates to increase the mid-span section depth. Another advantage of this type of beam is its ease of accommodating functional requirements such as service pipes, ductwork, and electrical cables, which can be extended into the octagonal holes to reduce the floor's height. Furthermore, when used in buildings with exposed members, the hexagonal hole in the web gives an aesthetic advantage.

This article aims to study the structural behaviour of TCBs and compare their experimental results with castellated beams and with the parent I-section beam as a control specimen. In this research, five samples are tested to understand the performance of TCBs.

* **Corresponding author: Hayder Wafi Al-Thabhawee,** Department of Civil Engineering, University of Kufa, Najaf, 54001, Iraq, e-mail: hayder.althabhawi@uokufa.edu.iq
**Muslim Abdul-Ameer Al-Kannoon:** Department of Civil Engineering, University of Kufa, Najaf, 54001, Iraq, e-mail: muslim.altameemi@uokufa.edu.iq

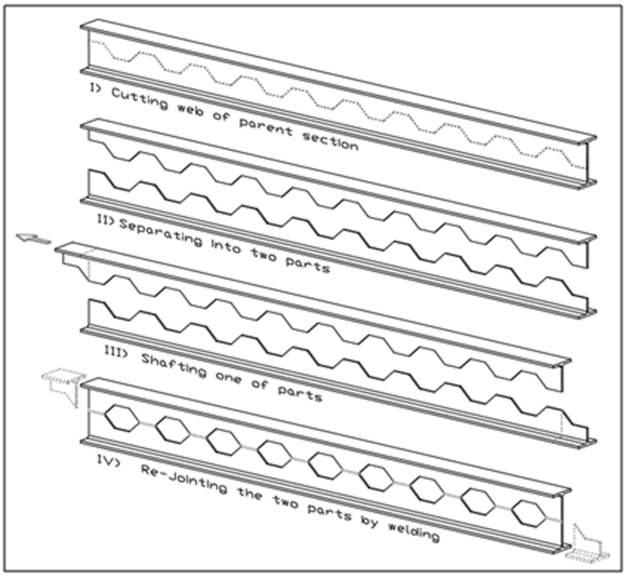


**Figure 1:** Fabrication of prismatic castellated beams [1].

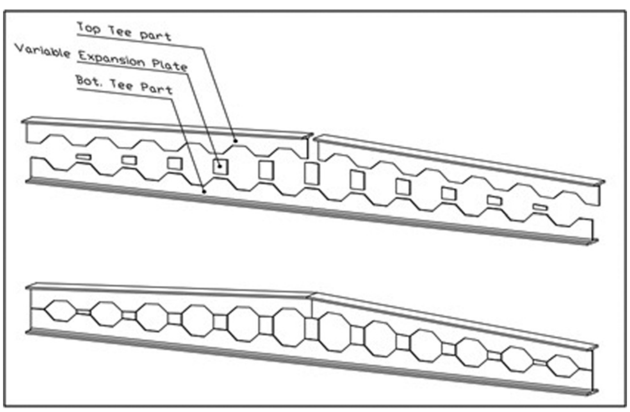


**Figure 2:** Fabrication of TCBs by placing variable expansion plates.

## 2 Research gaps in previous studies

In steel structure construction, structural researchers are working continuously to modify building materials to be lighter, stronger, and more economical. Construction with castellated beams grew in popularity in Europe in the mid-1950s because it reduced the cost of steel buildings due to the low ratio of labour costs to material costs [2]. Because of the strength and stiffness increases introduced by extended section depth, the development of this type of built-up beam was one of the essential steps in the advance of steel construction.

Tsavdaridis and D'Mello [3] investigated how a castellated beam behaves when it has web openings. Their study aimed to explore the potential effects of the shape and size of web openings on castellated beam behaviour and strength. Soltani et al. [4] developed a finite element model to investigate the structural behaviour of castellated beams fabricated using constant expansion plates. The main objective of this article was to investigate the web-post buckling failure mechanism. The results showed that castellated beams were more vulnerable to buckling because of constant expansion plates. Maulana et al. [5] carried out numerical analysis to study behaviour of a TCB with varying spaces between holes and varying angles within the hexagonal openings. Their article showed that the stress and deformation for each case were quite volatile, and it concluded that the stress distribution around the openings is more significant than in the web and flange. Tankova et al. [6] performed an experimental programme on tapered steel members to study the stability behaviour of non-uniform steel members. The experimental programme investigated different stability phenomena (flexural buckling of columns) under compressive force, lateral-torsional buckling of non-uniform members under varying bending moment, and lateral-torsional buckling of beam-column loaded with major axis bending moment and uniform compression load. All samples had tapered webs with variable tapering ratios and different shape formations. The researchers concluded that measurements of the geometrical imperfections allowed for modelling the initial geometrical imperfections in the shape of the global buckling mode with amplitude from the actual geometry. Al-Thabhawee and Al-Hassan [7] analysed the experimental results of nine castellated specimens and parent sections (control beams). In this research, steel rings were placed inside the octagonal openings of the castellated beam to reinforce the weakest parts (the web posts) and improve their strength at a relatively low cost. The results showed that the steel rings were effective in reinforcing the web posts. The strengthened castellated beam had a considerable increase in load capacity; it could be increased up to 285% compared to the load capacity of the parent beam while using only 37% more steel material (spacer plates and steel rings).

Previous studies have investigated the performance of regular castellated beams; very few studies focus on castellated beams with variable expansion plates (TCBs). The present study focuses on investigating the effectiveness of using variable expansion plates to increase more the section depth of a castellated beam at mid-span, as well as determining the maximum load of the TCB at allowable deflection according to the International Building Code (IBC) [8] and comparing the maximum load with those for the castellated beam and the parent beam (control case). To assess the economics, the weights of the TCB and the castellated beam are compared with the parent beam.

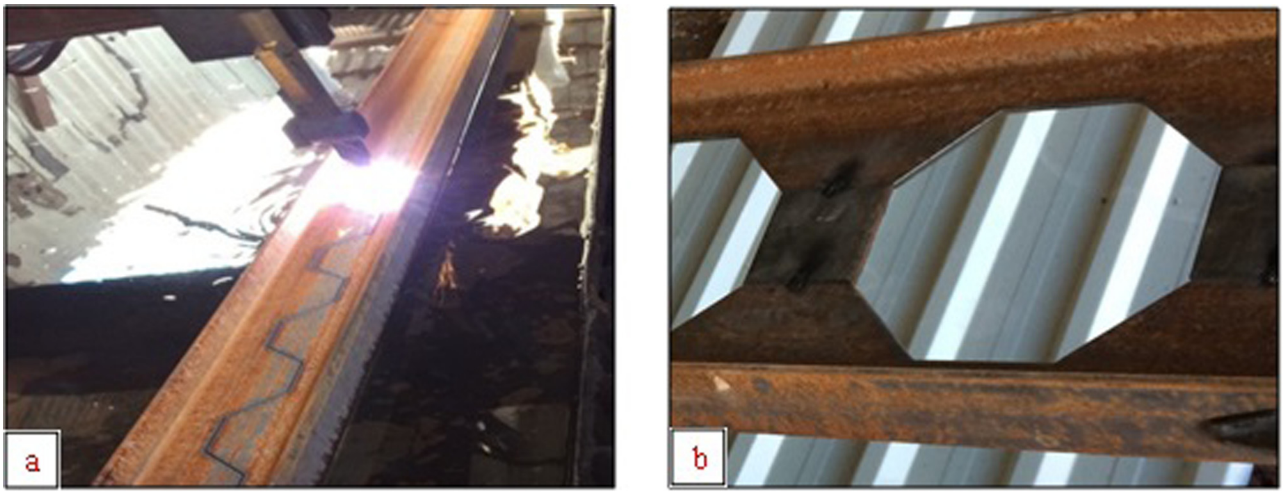


**Figure 3:** (a) Plasma CNC machine for cutting IPE140. (b) Placing the expansion plate and rejoining together.

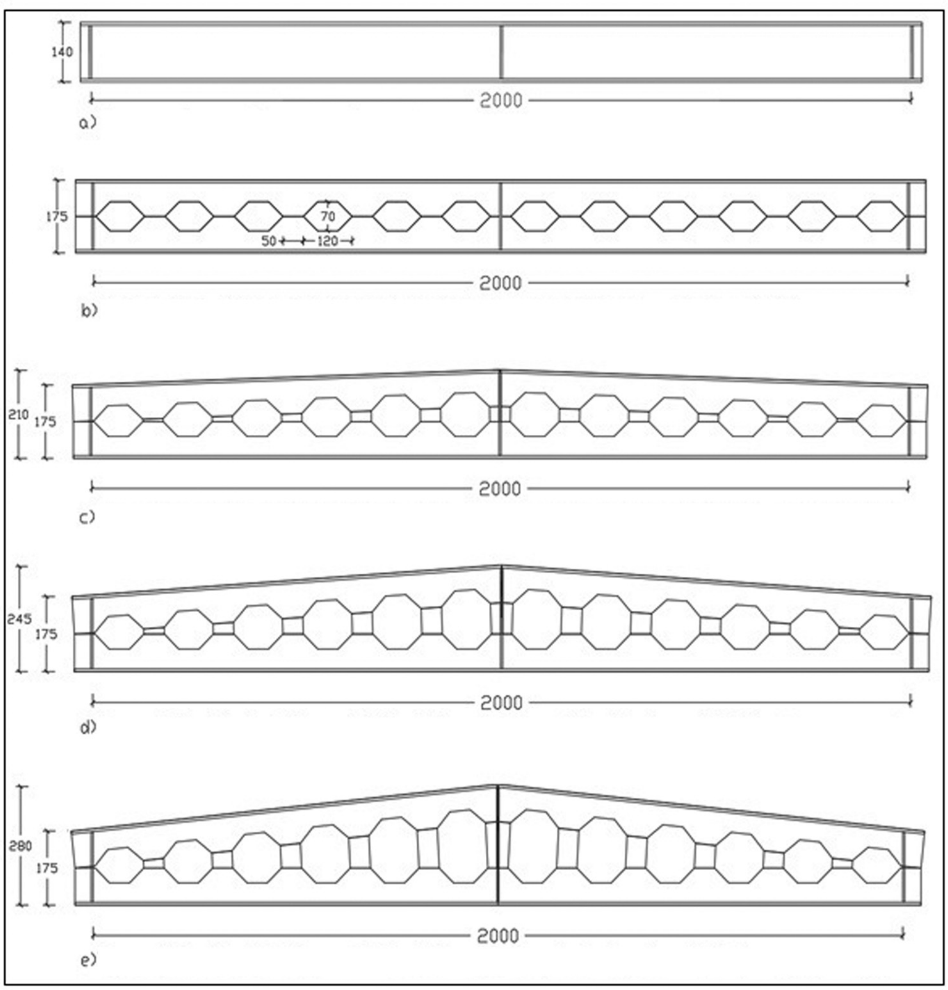


**Figure 4:** Dimensions and notations of all tested specimens. (a) Parent beam: specimen (Control), (b) castellated beam without expansion plate: specimen (CBN-0) [$H/h$ = 1.0], (c) tapered castellated beam with variable expansion plate: specimen (CBN-1) [$H/h$ = 1.2], (d) tapered castellated beam with variable expansion plate: specimen (CBN-2) [$H/h$ = 1.4], (e) tapered castellated beam with variable expansion plate: specimen (CBN-3) [$H/h$ = 1.6].

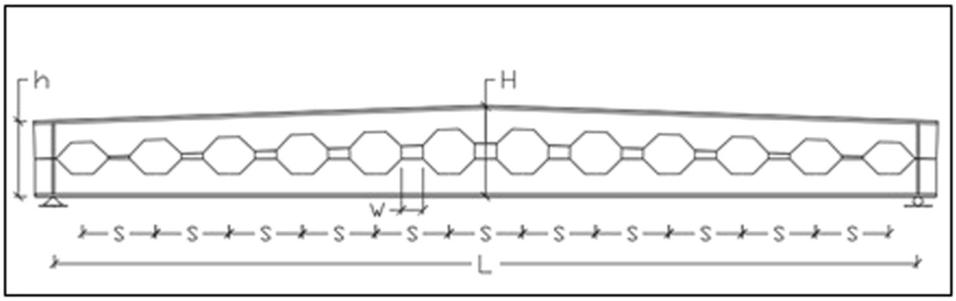


**Figure 5:** Dimensions and notations of TCB specimens.

**Table 1:** Dimensions of specimens

| Specimens | Dimensions (mm) | | | | $H/h$ |
|---|---|---|---|---|---|
| | $H$ | $h$ | $W$ | $S$ | |
| Control | 140 | 140 | — | — | — |
| CNB-0 | 175 | 175 | 170 | 50 | 1.0 |
| CNB-1 | 210 | 175 | 170 | 50 | 1.2 |
| CNB-2 | 245 | 175 | 170 | 50 | 1.4 |
| CNB-3 | 280 | 175 | 170 | 50 | 1.6 |

$H$ is the overall specimen depth at mid-span section, $h$ is the overall specimen depth at end-span section, $S$ is the spacing between two consecutive holes, and $W$ is the width of expansion plate.

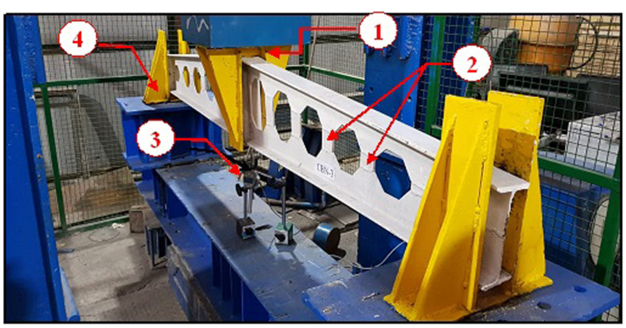


**Figure 6:** Test setup. 1. Applying load. 2. Expansion plates. 3. LVDT in mid-span for measure of deflection. 4. Restrained points for lateral torsional buckling.

## 3 Experimental study

In this research, the five specimens were constructed from a standard I-section (IPE140): three specimen TCBs were constructed using variable expansion plates; one specimen castellated beam was constructed without expansion plates; and a standard I-section beam was the control specimen. Flange thickness ($t_f$ = 6.9 mm), web thickness ($t_w$ = 4.7 mm), and span length ($L$ = 2,000 mm) were the same for all specimens. The parent I-section was cut along its web with a CNC machine to make the castellation pattern illustrated in Figure 3a, then, by using electrode welding, joining the two halves together to produce a uniform castellated beam or adding variable expansion plates between the web posts of the two halves to fabricate TCBs, as shown in Figure 3b. Tensile tests in accordance with ASTM A370 [9] were conducted on flat specimens to determine the material properties.

Three main steps were applied to create the TCB specimens. The steps are as follows:

(1) A standard hot-rolled IPE140 section was separated into two equal parts by cutting the web in a regular alternating castellation pattern.
(2) Trapezoid-shaped plates with variable dimensions were cut out to use as expansion plates (this research used waste steel plates as expansion plates).
(3) The two halves of the parent section were shifted and variable expansion plates were placed between the web posts of the two halves, then the expansion plates were joined to the bottom and top halves using electrode welding.

**Figure 7:** Failure mode of control specimen.

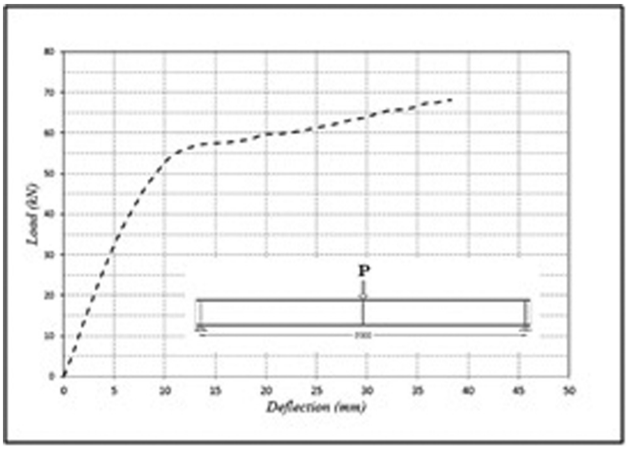


Figure 8: Load–deflection curve of control specimen.

Figure 9: Failure mode of specimen (CBN-0).

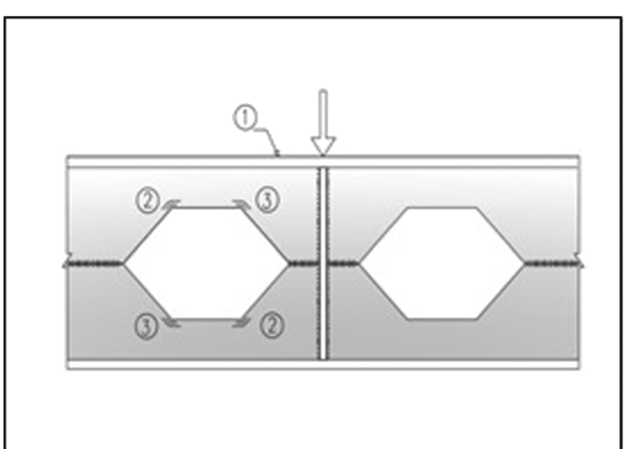

Figure 10: Sequence of Vierendeel mechanism.

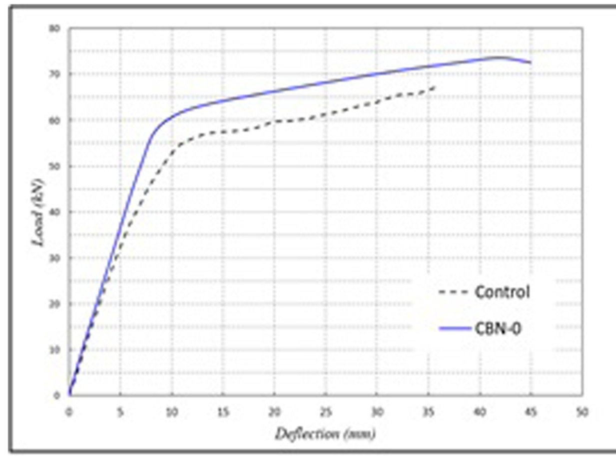


Figure 11: Load–deflection curves of CBN-0 and control specimen.

Figure 4 shows the dimensions and details of the specimens used in this study. The control specimen was an IPE140 beam (Figure 4a), which had a total depth $H = 140$ mm. This investigation utilises a control beam so that the test results for the castellated specimens can be compared with the results for the parent section. Figure 4b illustrates the details of Specimen CBN-0, which was constructed by cutting 45° angles in the web to obtain the hexagonal web openings. This sample had a uniform total depth ($H = 175$ mm) and the ratio between mid-span depth ($H$) and end-span depth ($h$) of the castellated beam (the expansion variable depth ratio) was $H/h = 1.0$. Figure 4c–e shows specimens CBN-1, CBN-2, and CBN-3, respectively, which were TCBs with variable expansion plates inserted between the upper and lower T-sections to increase their section depth at mid-span up to $H = 200$ mm, $H = 245$ mm, and $H = 280$ mm, respectively. The depth at end-span was constant ($h = 175$ mm) for all specimens. The values of expansion variable depth ratio


Figure 12: Test setup of TCBs (CBN-1, CBN-2 and CBN-3).

**Figure 13:** Failure mode of TCB (web post buckling).

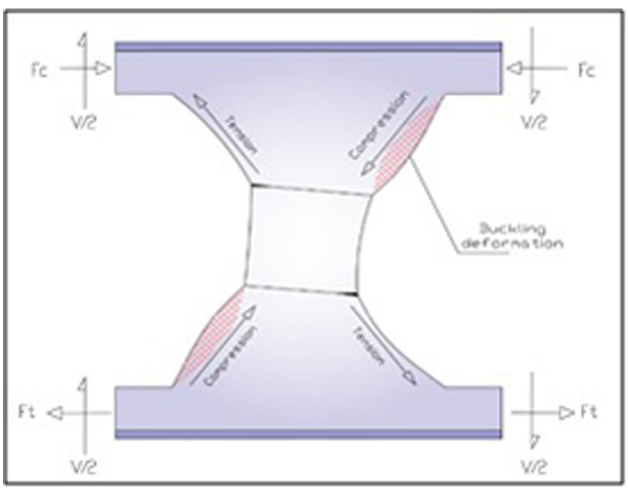


**Figure 14:** Web-post buckling due to shear force.

of the TCBs were $H/h = 1.2$, $H/h = 1.4$, and $H/h = 1.6$ for CBN-1, CBN-2, and CBN-3, respectively.

The expansion plate has the same web thickness as the parent section IPE140 (4.7 mm), and the weld thickness was 5 mm. The material properties of the specimen were $f_y = 279$ MPa, $f_u = 432$ MPa, and $Es = 2.01 \times 10^5$ MPa. All the dimensions of the specimens are illustrated in Figure 5 and Table 1.

Figure 6 shows installation of a specimen in the testing machine.

## 4 Results and discussion

Previous studies have reported five different types of failure that can occur in castellated steel beams and

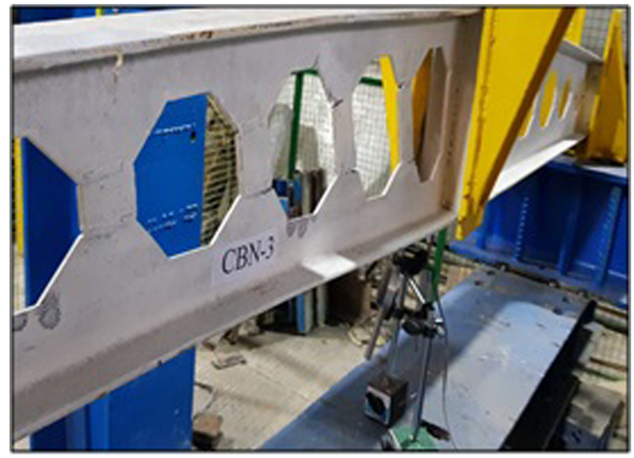


**Figure 15:** Failure model of TCB CBN-3.

were accomplished by Kerdal and Nethercott on these types of beams [10]. These failure modes are the Vierendeel mechanism, web-post buckling, joint welding rupture, lateral-torsional buckling, and the flexure mechanism [11]. These modes are mainly related to the geometry of the beam, the properties of its openings (shape, dimension, and spacing), welding quality and length, loading type, provision of lateral support, and the slenderness of the web.

**Control specimens:** The parent I-section (IPE 140) was the first beam tested in this study. It was used as a control beam to compare results with those for the prismatic castellated beam specimen and the TCB specimens. The control beam specimen failed due to the overall flexural mechanism, where the region above the neutral axis becomes under compression. At the same time, tension stress was generated in the bottom region, as shown in Figure 7. The yield load was recorded as 55 kN, at 11 mm

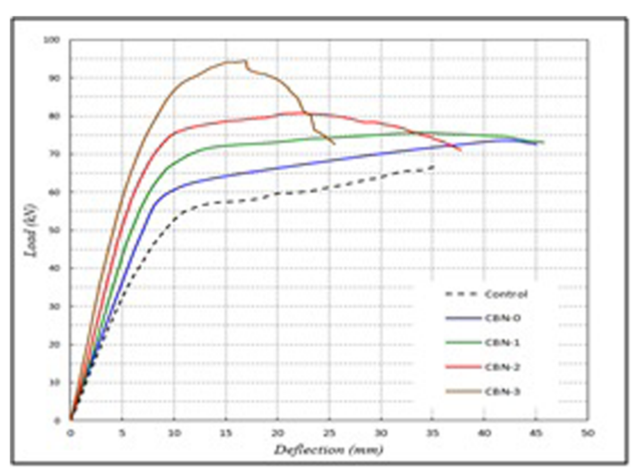


**Figure 16:** Load–deflection curve of all specimens and control specimen.

**Table 2:** Comparison of ultimate load and allowable load at maximum deflection (L/360) of TCBs with control specimen (parent beam)

| Specimens | | Expansion depth | | Ultimate load | | Allowable load at (L/360) | |
|---|---|---|---|---|---|---|---|
| | | Mid-span depth, *H* (mm) | Ratio of expansion (*H*/*h*) | Ultimate load (kN) | Ratio of ultimate load (%) | Allowable load (kN) | Ratio of allowable load (%) |
| Control beam | IPE140 | 140 | – | 67.2 | 100 | 35.0 | 100 |
| Prismatic castellated | CBN-0 | 175 | 1.0 | 73.5 | 109 | 40.2 | 114 |
| Tapered castellated | CBN-1 | 200 | 1.2 | 75.5 | 112 | 47.5 | 134 |
| | CBN-2 | 245 | 1.4 | 80.6 | 120 | 55.6 | 157 |
| | CBN-3 | 280 | 1.6 | 94.3 | 140 | 64.0 | 183 |

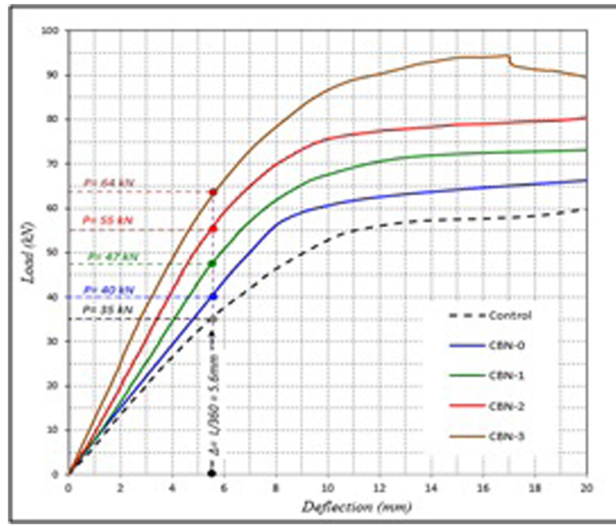


**Figure 17:** Allowable load at maximum deflection (L/360) according to IBC.

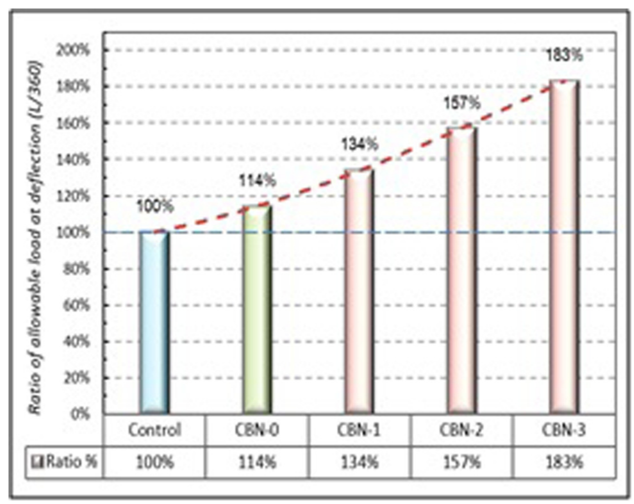


**Figure 18:** Ratio of allowable load of specimens to control at deflection (L/360).

deflection, while the ultimate load was 67 kN, at 38 mm deflection. The load–deflection curve is shown in Figure 8.

**Prismatic castellated beam:** Specimen CBN-0, which had an expansion variable depth ratio $H/h = 1.0$, failed due to the Vierendeel mechanism, with plastic hinges forming at each corner of the middle openings at mid-span of the beam, in the region of the beam where moment and shear are simultaneously present. The failure mode of CBN-0 is shown in Figures 9 and 10, which shows the yielding point sequence at the failure zone. At a load of about 62.0 kN, the first evidence of yielding appeared along line (1). When the load was raised to 65.0 kN, yielding started first at the hexagonal corners (point 2) and then at opposite corners (point 3). The yielding became notable at these points as the load gradually increased, and the Vierendeel mechanism of failure occurred when the load reached 73.5 kN.

Figure 11 shows the mid-span load–deflection diagram for Specimen CBN-0 and compares its results with the control specimen. The load capacity of CBN-0, 73.5 kN, is 10% more than that of the control beam.

**TCBs:** For specimens CBN-1, CBN-2, and CBN-3, expansion plates were inserted to increase the mid-span depth $H$ to 200, 245, and 280 mm, respectively, but the end-span depth was constant for all specimens ($h$ = 175 mm). Figure 12 shows the test setup for the TCBs.

Generally, TCBs fail due to a rupture in the joint welding, web-post buckling, or both. In this study, these two failure modes occurred in the TCBs due to the formation of high shear force that tried to twist the web post as shown in Figures 13 and 14.

For specimen CBN-3, which had the highest value of expansion variable depth ratio ($H/h$), the first indication of yielding was noted on the compression flange's inside surface close to the concentrated load, when the applied load was 86.0 kN. From there, the load gradually increased up to the failure load of 94.3 kN, after which was a period of unloading. The unloading rate was gradual at first, because of the buckling deformation in the web, but at 75.0 kN, web-post buckling failure was observed in the panel near the concentrated force, as shown in Figure 15.

In Figure 16, the load-deflection curves show the effect of increasing the mid-span depth on the behaviour of the TCBs and compares their ultimate load capacities with those of the control specimen and prismatic castellated beam. The ultimate loads of Specimens CNB-1, CBN-2, and CBN-3 increased by 12, 20, and 40%, respectively, compared with the ultimate load of the control specimen, as shown in Table 2. However, the ductility of these beams decreased compared with the behaviour of the control specimen.

Usually, the deflection of steel beams is limited to a specific maximum value. The IBC has limited service live load deflections to approximately span/360. This deflection is, supposedly, the largest deflection that ceiling joists can undergo without causing cracks in the underlying plaster. Figure 17 shows the IBC allowable loads for TCBs and prismatic castellated beams. The allowable deflection for the 2,000 mm long specimen beams used for this research was $\Delta$ = 5.6 mm.

According to the experimental results, the IBC deflection criterion indicated that the allowable load of specimen CBN-0 was 40 kN and the allowable loads for the TBCs (CBN-1, CNB-2, and CBN-3) were 47, 55, and 64 kN, respectively. As shown in Figure 18, the allowable load for specimen CBN-3 was 83% more than the allowable load for the control specimen and 60% more than the allowable load for the prismatic castellated beam (CBN-0).

# 5 Conclusion

The following conclusions can be drawn from the research:

(1) According to the testing results, TCBs can be used to modify the stiffness and strength of the parent I-section by increasing its depth at mid-span through use of expansion plates. In comparison to the parent beam, the ultimate load capacity of the TCBs can be increased by up to 40% by adding expansion plates. However, the ductility of a TCB will reduce when compared with the parent beam.

(2) TCBs satisfy serviceability criteria because their mid-span depth is greater than that of their parent beam. With respect to IBC deflection limits, the allowable load at maximum deflection L/360 increases by up to 83% more than the allowable load of the original beam.

(3) The results indicate that TCBs with expansion depth ratios $H/h$ = 1.2, 1.4, and 1.6, respectively, yield more satisfying results in terms of stiffness and strength than the prismatic castellated beam ($H/h$ = 1.0) made from the same parent beam.

(4) The experimental results demonstrate that the web-post buckling and joint welding rupture failure modes occurred in TCBs due to the formation of high shear force that tried to twist the web posts. In contrast, the prismatic castellated beam failed due to the Vierendeel mechanism.

**Conflict of interest:** Authors state no conflict of interest.

# References

[1] Al-Thabhawee HW, Mohammed A. Experimental study for strengthening octagonal castellated steel beams using circular and octagonal ring stiffeners. In: IOP Conference Series: Materials Science and Engineering. Iraq: IOP Publishing; 2019.

[2] Boyer JP. Castellated beams - new developments. ISC Eng J. 1964;1(3):104–8.

[3] Tsavdaridis K, D'Mello C. FE modelling techniques for web-post buckling response. In 6th European Conference on Steel and Composite Structures; 2019. p. 1851–6.
[4] Soltani MR, Bouchair A, Mimoune M. Nonlinear FE analysis of the ultimate behaviour of steel castellated beams. J Construct Steel Res. 2011;70:101–14.
[5] Maulana TI, Soebandono B, Susanti A. Stress and deformation study on castellated steel beam with tapered shape and hexagonal openings. Sinergi. 2019;23(1):61. doi: 10.22441/sinergi.2019.1.009.
[6] Tankova T, Martins JP, daSilva LS, Marques L. 05.10: Numerical model for the buckling behaviour of tapered steel members based on experimental tests. Ce/Papers. 2019;1(2–3):1106–15. doi: 10.1002/cepa.151.
[7] Al-Thabhawee HW, Al-Hassan A. Experimental study for improving behaviour of castellated steel beam using steel rings. Pollack Period. 2021;16(1):45–51.
[8] IBC, I. C. C. International building code, International Code Council, Inc.(formerly BOCA, ICBO and SBCCI), vol. 4051; 2018. p. 60478–5795.
[9] ASTM E8, ASTM E8/E8M standard test methods for tension testing of metallic materials 1. Annu B ASTM Stand. 2010;4(C):1–27. doi: 10.1520/E0008.
[10] Kerdal D, Nethercott DA. Failure modes for castellated beams. J Constr Steel Res. 1984;4(4):295–315.
[11] Ilanovský V. Assessment of bending moment resistance of girders with corrugated web. Pollack Period. 2015;10(2):35–44.