UDC 621
DOI: 10.15587/1729-4061.2022.262558

INVESTIGATION OF FLEXURAL AND SHEAR FAILURE MODES OF TAPERED CASTELLATED STEEL BEAMS USING EXPANSION PLATES

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Using modern technologies for fabricating steel, I-beams can be easily made by welding, and hot-rolled beams can often be produced at an economical price with slender webs and equal flanges. Experimental and theoretical studies of the behavior of tapered castellated steel beams were carried out. Due to the cost reductions associated with tapered castellated steel beams, they are a feasible alternative to prismatic components. This study assessed the influence of tapered castellation on the bending capacity and flexural stiffness of tapered castellated steel beams (TCBs) with simply supported end conditions experimentally and theoretically. Four three-point bending tests on TCBs with H/h values of 1, 1.2, 1.4 and 1.6 were conducted utilizing a standard parent I-section beam (IPE140) as the control specimen. The test findings include the ultimate load vs. mid-span deflection response curves and failure mechanisms. The testing findings indicated that the TCBs' ultimate load capacity might be up to 140 percent of that of the parent section. The Abaqus program was used to conduct a finite element (FE) analysis of TCB, which allows for material and geometric nonlinearity. The derived finite element models exhibit excellent agreement with the experimental results in terms of ultimate load capacity vs. mid-span deflection response and failure mechanisms. Based on the results of the work, TCBs can be used for increasing the strength and stiffness of the I-section parent beam with adding expansion plates. The maximum load capacity of TCBs can be enhanced when adding expansion plates up to 40 % above that of the parent beam. A TCB has lower ductility than its parent beam. Moreover, a TCB fulfills serviceability requirements since its mid-span depth exceeds that of its parent beam

Keywords: castellated beam, local buckling, steel beam, tapered, web-post buckling, Vierendeel mechanism

Received date 19.05.2022
Accepted date 26.07.2022
Published date 30.08.2022

How to Cite: *Al-Kannoon, M. A.-A., AL-Thabhawee, H. W. (2022). Investigation of flexural and shear failure modes of tapered castellated steel beams using expansion plates. Eastern-European Journal of Enterprise Technologies, 4 (7 (118)), 6–13. doi: https://doi.org/10.15587/1729-4061.2022.262558*

1. Introduction

Castellated beams (CBs) are fabricated from ordinary I-sections with cutting along the web into zig-zag patterns shifting one of the halves of the beam and then re-joining the two portions in welding. The resulting beams are deeper than their parent beams with increased bending stiffness and lighter beam weights compared to standard beams of similar depth allowing this type of beam to be used in structures with medium to long spans. At these spans, however, typical steel sections may not fulfill serviceability standards such as deflection despite their high flexural strength. To meet deflection requirements to a beam, the section depth-to-span ratio must be increased. It may be desirable to extend section depths at the mid-span by inserting "expansion plates" between upper and lower T-sections in order to generate tapered castellated beams (TCBs).

A double-tapered castellated beam is one means of providing greater section depth at mid-span for only a modest increase in self-weight. When compared to their parent beams, castellated beams have higher strength and stiffness due to the greater beam section depth created in this fabrication technique.

Therefore, studies devoted to the flexural behavior of TCBs when expansion plates with variable depth are used to produce them, the failure modes of TCBs and the bearing capacity of TCBs at allowable mid-span deflection according to IBC code are of scientific relevance. Using tapered castellated beams instead of standard steel sections is one of the practical applications of the research.

2. Literature review and problem statement

Steel structure researchers are constantly attempting to improve some types of construction materials in order to make them lighter, stronger and more cost-effective. Castellated beam structures gained popularity in Europe in the mid-1950s due to low labor-to-material cost ratio [1]. Due to the improved strength and stiffness provided with the wider sections depth, the creation of this type referring to build-up beams was the most significant advancement into the evolution of steel building. The performance of perforated beams with closely spaced web openings was investigated in [2]. In this work, an experimental investigation of distortional buckling of six full-scale castellated beams was described. Tapered castellated beams under point loads in mid-span were not discussed in the researchers' study. A FE analysis was built to investigate the flexural behavior of CBs built with constant-height expansion plates. The primary objective of the study was to look into the mechanism of web-post buckling failure [3]. Castellated beams fabricated with expansion plates were found to be more prone to buckling than those without expansion plates. The behavior of tapered castellated beams produced with expansion plates of variable depth was not examined in this study.

The behavior of a tapering castellated beam as cantilever structures with different distances between holes and various angles within the hexagonal perforations was studied numerically [4]. The study found that the stress and deformation for each sample are variable and that the stress distributions around the apertures are more critical than the stress distributions in the web and flanges.

The stability behavior of non-prismatic steel members using webs tapered with varying tapered ratio and forms was investigated [5]. The experimental program looked into a variety of stability issues. The researchers concluded that measuring geometrical defects allowed them to simulate the original geometrical faults as a global mode of buckling with varying amplitude than the real geometry. Some parametric studies of CB with circular and diamond-shaped openings were carried out. In [6], the study was performed to optimize its size by considering the ratio of the overall depth of the castellated beam to the depth of opening provided (D/Do) and the ratio of spacing of opening to the depth of opening (S/Do). From their study, they concluded that the CB gives good flexural strength results for the diamond-shaped opening with a size of 0.67 times overall depth of the beam. The study was carried out on the technology and equipment designed for manufacturing parts and components with predefined properties by 3D printing methods [7]. The purpose was to determine the optimal surfacing modes based on identifying the effect of process parameters on the quality indicators of articles. The performance of regular castellated beams has already been investigated; however, there are very few investigations of beams with castellated apexes and changeable expansion plates (TCBs).

All the above allows us to assert that it is expedient to conduct an experimental and theoretical study on the flexural behavior and bending capacity of tapered castellated steel beams.

3. The aim and objectives of the study

The aim of the study is to investigate the efficiency of using changeable expansion plates for increasing the ultimate capacity of TCBs. All this allows improving CBs performance using those plates.

To achieve the aim, the following objectives are accomplished:

– to develop experimental models for five CB specimens with and without expansion plates;

– to examine failure modes of TCBs;

– to investigate serviceability requirements of TCBs;

– to establish a numerical model using the Abaqus program.

4. Materials and methods

4. 1. Experimental study

In the experimental program, five specimens were created using the I-section of standard I (IPE140). The control specimen had a standard I-section beam without using castellated beams. Three TCB specimens were constructed with variable expansion plates. All specimens had the same effective span length (L=2,000 mm). At middlespan, all specimens were tested with a concentrated load. To create the castellation pattern, the parent Isections were sliced along its web using the machine, two pieces were joined together using electrode welding to form a standard CB or variable expansion plate inserted among the web postings of the two halves to form TCBs. Flat specimens were tensile tested according to ASTM A370 [8]. Flexural tests were carried out with concentrated load in mid-span length. Five specimens were tested to investigate the efficacy of using changeable expansion plates for increasing the ultimate capacity of the TCBs.

Fig. 1 illustrates the size and features of the specimens utilized in this investigation. A control beam was utilized to compare the findings obtained from the castellated specimens to those obtained from the parent section. Specimen CBN-0 was made with cutting 45° angle in hexagonal web apertures as illustrated in Fig. 1, *b*. The whole depth of this sample was organized (H=175 mm) and the ratio of the castellated beam H/h=1.0 was the ratio of the expansion variable's mid-span depth (H) to its depth end-span (H). In Fig. 1, *c–e*, CBN-1, CBN-2 and CBN-3 specimens are shown. These are variable expansion plates with TCBs variable expansion plates fitted among the upper and lower *T*-section for increasing the section depths at the middle-span to H=200 mm, H=245 mm and H=280 mm, accordingly. All specimens were identical in depth at the end of their spans (h=175 mm). CBN-1 CBN-2 and CBN-3 had variable expansion depth ratios (H/h) of 1.2 1.4, 1.6, correspondingly.

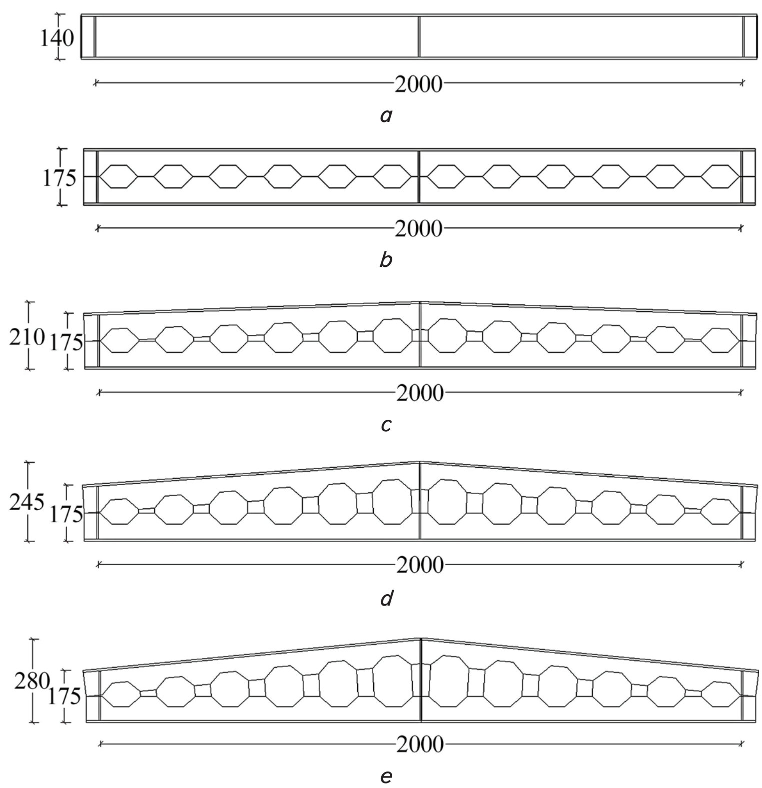


Fig. 1. Dimensions & notations of all tested specimens: *a* – parent beam, control specimen; *b* – castellated beam without expansion plate, CBN-0 specimen (H/h=1.0); *c* – tapered castellated beam with variable expansion plate, CBN-1 specimen (H/h=1.2); *d* – tapered castellated beam with variable expansion plate, CBN-2 specimen (H/h=1.4); *e* – tapered castellated beam with variable expansion plate, CBN-3 specimen (H/h=1.6)

Fig. 2 shows the test setup that was used in the experimental work, with an explanation to each part.

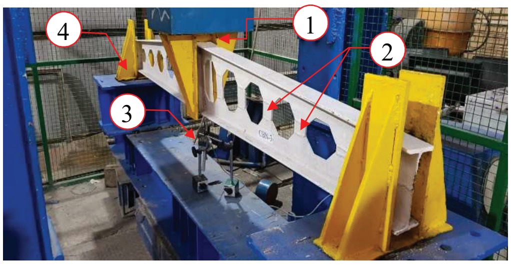


Fig. 2. Test setup: 1 – load application point; 2 – expansion plates; 3 – L V D T at middlespan to deflection measurement; 4 – buckling restraint with lateral-torsional buckling

The expansion plate's web thickness (4.7 mm) was identical to that of the parent section but the welding thickness was 5 mm. The material features of the specimens were as follows: *fy*=279 MPa, *fu*=432 MPa, *Es*=2.01×10^5 MPa. The specimens' dimensions are shown in Table 1.

Four CBN were tested, each with different dimensions to investigate the effect of the dimensions on the specimen.

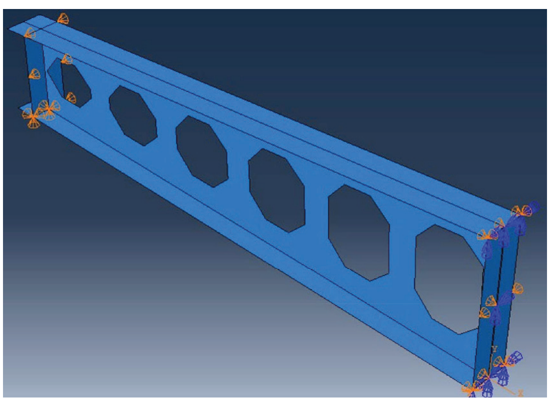
Table 1

Dimensions of specimens

Specimen	Dimension (mm)				*H/h*
	H	*h*	*S*	*W*	
Control	140	140	–	–	–
CBN-0	175	175	170	50	1.0
CBN-1	210	175	170	50	1.2
CBN-2	245	175	170	50	1.4
CBN-3	280	175	170	50	1.6

4. 2. Finite element model development

A finite element model was created to study the reactions of TCBs to a concentrated mid-span load. The FE model was created using the Abaqus CAE 2021 program [9]. Table 1 contains the designations of the created FE model that are compared to the experimental data. The FE model had identical laboratory specimens replica in size terms apertures, boundary conditions and load mechanism. This research study utilized nonlinear materials and analysis of geometry using material of an isotropic. The loads and boundary conditions for the tested half-beam are depicted in Fig. 3. Restraints were imposed in the direction of the degree of freedom used to replicate the physical supports as shown in Fig. 3, *a*. All the beams were modeled as 3D shell elements and for meshing purposes quad-dominated finite elements of type S4R were used as shown in Fig. 3, *b*.



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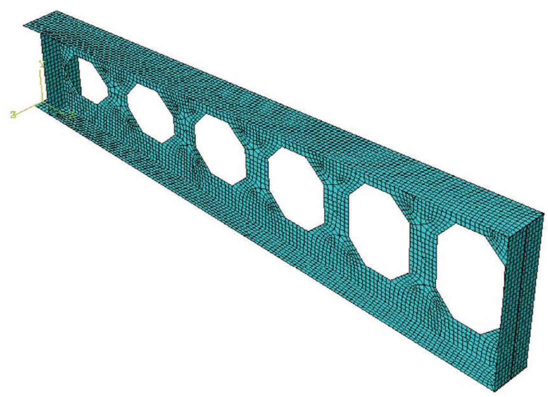

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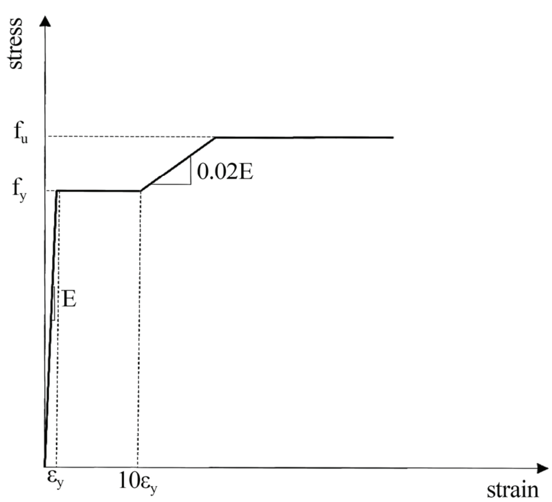


c

Fig. 3. Loading, boundary conditions and constitutive law used in the FE model: *a* – boundary conditions of CBN-3 specimen; *b* – meshing of CBN-3 specimen; *c* – constitutive law

To compare the FE model to the existing experimental beams, the specimens were idealized in a manner similar to that described in the prior section. As seen in Fig. 3, *c*, the material model incorporated linear elastic properties with strain-hardening; nonetheless, the yield and ultimate stresses, as well as corresponding strains and elasticity modulus, were obtained through a coupon test for accounting the actual material characteristics.

The results were then translated and entered into the computer software as real stresses and logarithmic strains.

5. Results of investigating tapered castellated steel beams

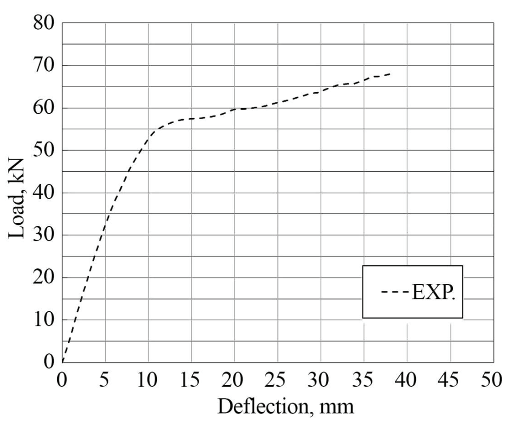
5. 1. Results of experimental models of five castellated beam specimens with and without expansion plates

5. 1. 1. Control specimen

The parent Isection (I.P.E 140) was tested initially. This specimen failed as a result of the mechanisms that allow the body to bend, which squeezes the region above the neutral axis. Control specimen testing is shown in Fig. 4.

Simultaneously, tension stress developed into the bottom portion, which is seen in Fig. 4, *a*. The yield load was 55 KN with a deflection of 11 mm and 67 KN with a deflection of 38 mm. Fig. 4, *b* depicts the control specimen's load-deflection curve.

a



b

Fig. 4. Control specimen testing: *a* — failure mode of the control specimen; *b* — load-deflection curve

5. 1. 2. Beam with prismatic castellation (without expansion plates)

The first sign giving occurred at the top flange with a load of about 62.0 kN. When the applied force exceeded 65.0 kN, yield began in the hexagonal corner and spread to the opposites corners. As the load increased, the yield became more apparent, and after reaching the load of 73.5 kN, Vierendeel's failure mechanism happened. Fig. 5 shows the load-deflection curves of CBN-0.

The mid-span load-deflection curve for CBN-0 is shown in Fig. 5, and the results are compared to those for the control specimen. CBN-0 has a load capacity 10 % more than the control beam.

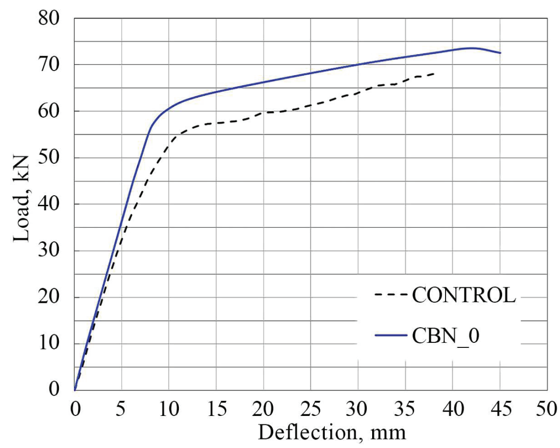


Fig. 5. Load-deflection curves of CBN-0 and control specimen

5. 1. 3. Tapered castellated beams (with expansion plates)

Expansion plates were installed in CBN-1, CBN-2 and CBN-3 specimens to raise the depth of the mid-span H to 200 mm, 245 mm and 280 mm, correspondingly. All specimens had the same depth of the end-span (h=175 mm).

When 86.0 kN were applied, the first signs of yielding were noticed from the inside surface compression flange at the concentrated test loads are based on that specimen's maximum H/h expansion variable depth ratio (CBN-3). The load was gradually increased until it reached a failure load of 94.3 kN at the point it was unloaded.

The load-deflection curves in Fig. 6 illustrate the impact of increasing the depth of the middlespan on the behavior of TCBs and compare their ultimate load capacity to that of the control specimen and prismatic castellated beam. As indicated in Table 2, the ultimate loads of CBN-1, CBN-2, CBN-3 specimens were 13 percent, 20 percent and 40 percent greater than the ultimate load of the control specimen, accordingly.

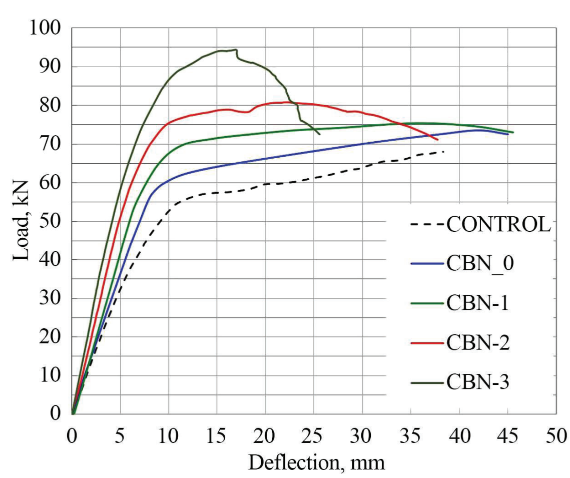


Fig. 6. Load-deflection curves of all tested specimens

Table 2

Comparison of ultimate and allowable loads of tapered castellated beams at maximum deflection (L/360) with control specimen (parent beam)

Speci-men	Expansion depth		Ultimate load		Allowable load at (L/360)	
	H, mm	*H*/*h*	Ultimate load, kN	Ratio, %	Allowable load, kN	Ratio, %
IPE140	140	–	67.2	100 %	35.0	100 %
CBN-0	175	1.0	73.5	109 %	40.2	114 %
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 %

Table 2 shows a comparison of ultimate and allowable loads for tapered castellated beams, with high values for the ultimate loads reaching 94.3 kN. Taking into account that *H*/*h* values are higher for the high values of the loads.

5. 2. Results of failure modes of tapered castellated beam

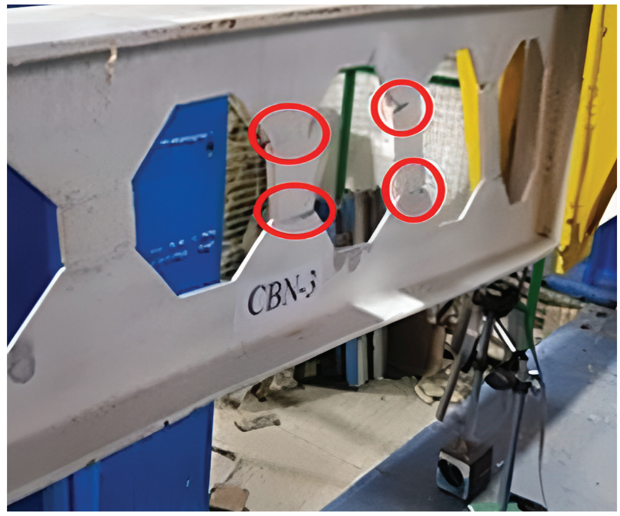
Flexure, Vierendeel mechanism, web-post buckling, welding joint rupture are five primary kinds of failure in castellated steel beams [10, 11]. The slenderness of web lateral support and web shape all affect the beam's geometry, as well as its apertures' dimensions and spacing. Other factors to consider are welding quality and length. These are all factors that influence these modes.

The experimental results of all tested specimens in the current study showed that the control specimen failed due to top flange yielding in the mid-span section under concentrated load. Whilst, in specimen CBN-0 (*H*/*h*=1.0), the Vierendeel mechanism developed, with plastic hinges emerging in every corner related to holes on either side of mid-span in the location where moment and shear occur concurrently. Fig. 7 illustrates the failure mechanism of CBN-0.

Fig. 7. Failure mode of specimen CBN-0

The TCBs often failed owing to welding joint failure, web-post buckling or a combination of the two. As indicated in Fig. 8, *a*, *b*, these two kinds of failure occurred in the TCBs as a result of the generation of a substantial shear force, which attempted to twist the web-post.

However, at 75.0 kN web-post buckling failure, the panel next to the focal forcing became slow down the unloading rate due to web buckling.



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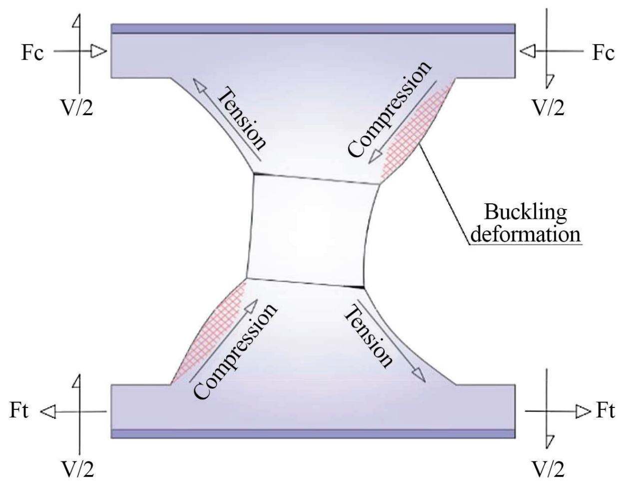


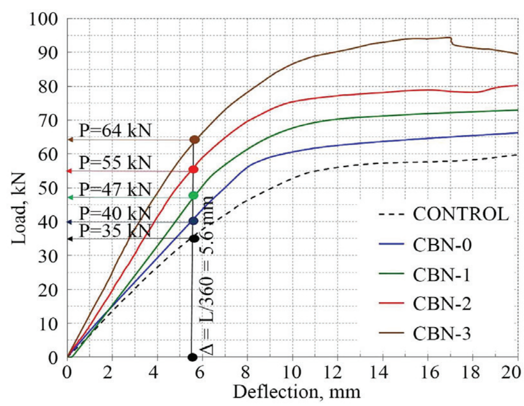
b

Fig. 8. Failure modes of CBN-3 specimen: *a* – failure mode of tapered castellated beam CBN-3 (web-post buckling); *b* – web-post buckling because of shear force

5. 3. Results of serviceability requirements of tapered castellated beam

All the TCBs with or without expansion plates showed a poorer ductility than the control specimen. Steel beam performance is mainly governed by deflection limits. For service life load deflections, the IBC has specified a limit of span/360. Ceiling joists are reported to be able to withstand this amount of deflection without damaging plaster ceilings. The IBC permissible loads for TCBs and prismatic castellated beam are shown in Fig. 9, *a*. The permissible load for specimen CBN-3 was 83 % higher than the permissible loads for the parent control specimen and 60 % greater than the permissible load for CBN-0 as illustrated in Fig. 9, *b*.

The deflection limit for the 2,000 mm specimen beams used in this study is 5.6 mm. The allowable load for specimen CBN-0 according to the IBC deflection criterion is 40 kN while the allowable loads for the TBCs (CBN-1 CNB-2 and CBN-3) are 47 kN, 55 kN and 64 kN, correspondingly according to the experimental data.



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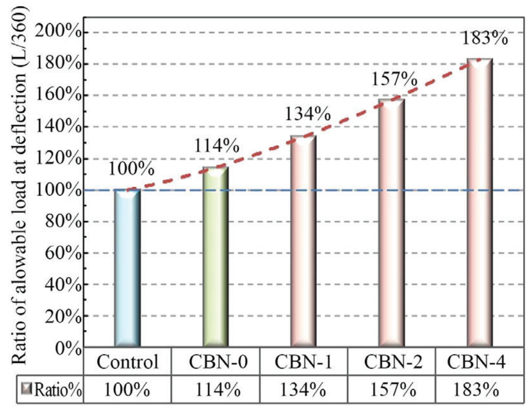


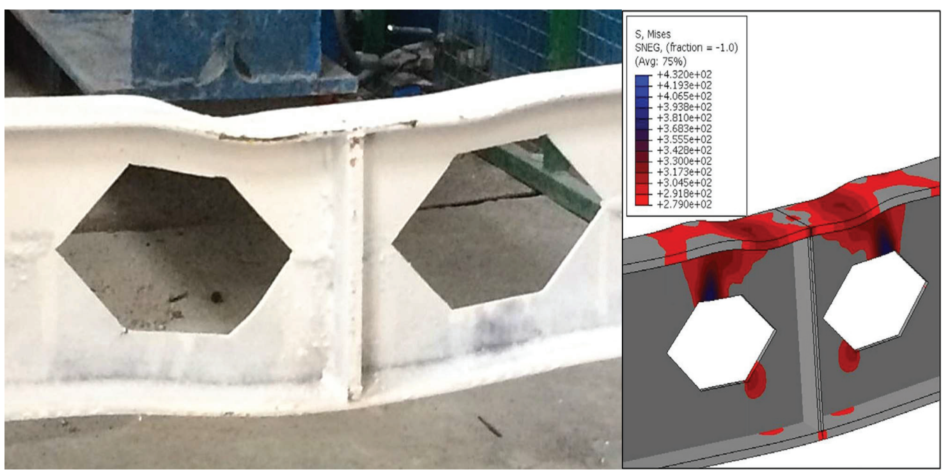
b

Fig. 9. Comparison of all specimens tested: *a* — allowable loads at maximum deflection $L/360$ based on the IBC; *b* — ratio of allowable load of specimens to control at deflection $L/360$

5. 4. Results of finite element model using the Abaqus program

In the current study, all specimens tested experimentally were numerically simulated using the Abaqus software. The results showed good agreement between experimental findings and Abaqus results. Fig. 10, *a*, *b* compares the failure modes of the experimental and theoretical tests. Fig. 10 demonstrates clear convergence between the experimental and FE analysis of CBN-0 and CBN-3, correspondingly.

Fig. 11 shows the experimentally and numerically determined load-deflection curves of all the examined specimens. The shape indicates that the load-deflection curves at the mid-span of each specimen with test and numerical method demonstrate a strong association between the initial stages of loading and after yielding has occurred. The calculated curve is stiffer than the experimental curve during the second stage of loading. Reaches failure load for each specimen.



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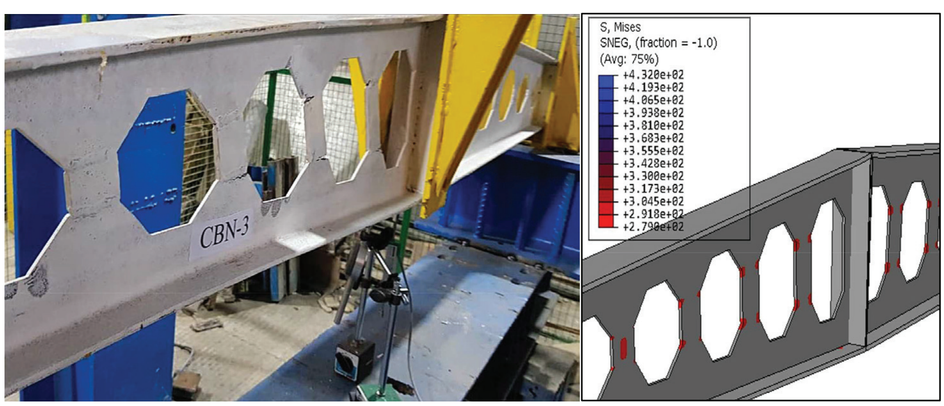

b

Fig. 10. Failure mode comparison between experimental and Abaqus results: *a* — failure mode of specimen CBN-0; *b* — failure mode of specimen CBN-3

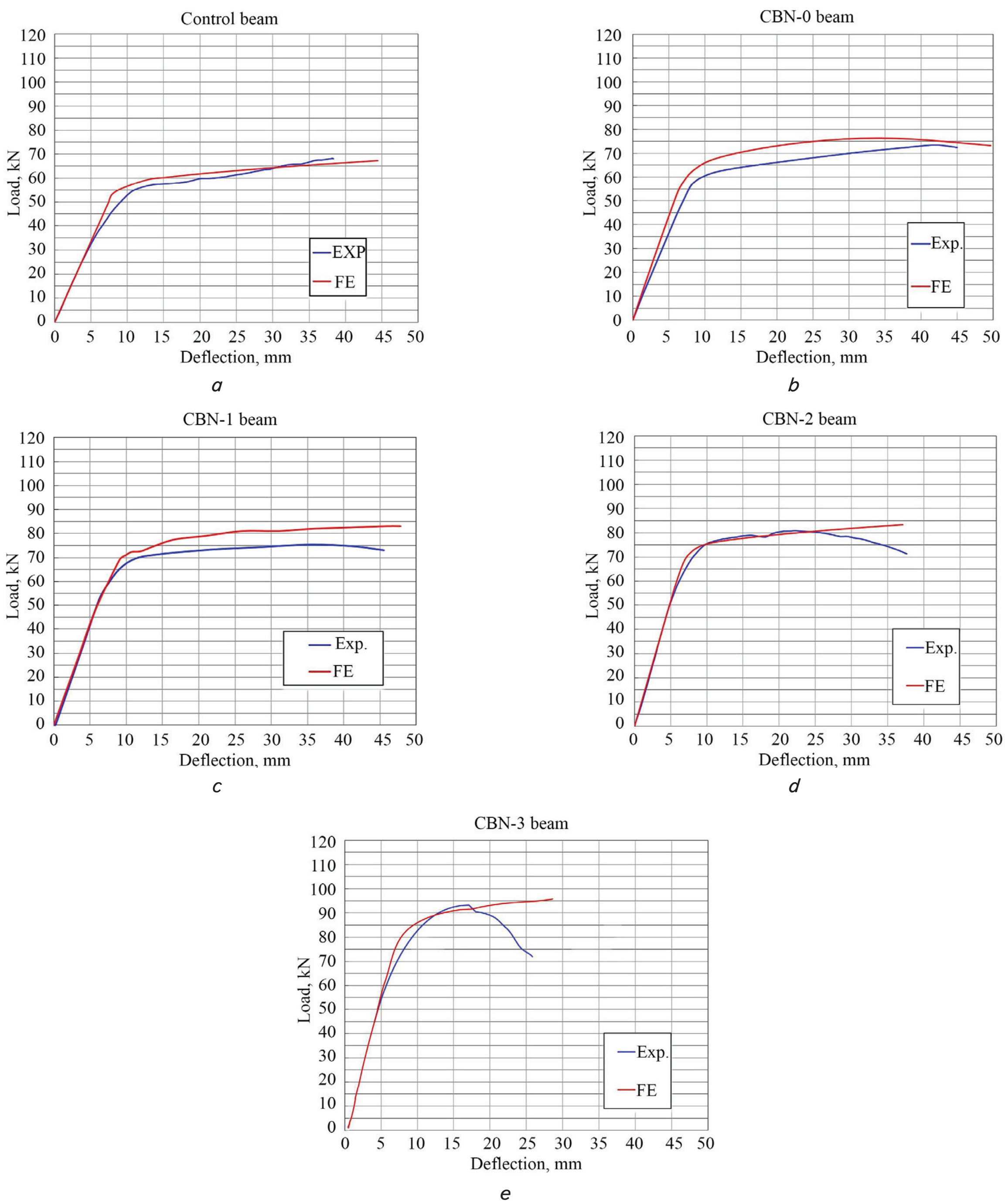

Fig. 11. Load-deflection curves for all tested specimens: *a* – control beam; *b* – CBN-0 beam; *c* – CBN-1 beam; *d* – CBN-2 beam; *e* – CBN-3 beam

The calculated curve is stiffer than the experimental curve during the second stage of loading. Reaches failure load for each specimen.

6. Discussion of experimental and finite element results

The results of the current study explained that using variable expansion plates to fabricate TCBs increases the ultimate flexural capacity of beams. Moreover, it increases the allowable load to give allowable deflection in the mid-span length of the beam according to the IBC code. Also, the results show that there are two failure modes of TCBs, web-post buckling and Vierendeel failure mechanism.

According to the results of the current experiment, using expansion plates to increase the CBs depth improves ultimate strength capacity. As illustrated in Fig. 6, the ultimate capacities of TCBs are higher than those of control specimens and prismatic castellated beams. Moreover, the TCBs often failed owing to welding joint failure, web-post buckling or a combination of both. It is suggested to add a plate to the post to strengthen it against buckling. The results of nonlinear finite element analysis using Abaqus software demonstrated a clear convergence in comparison with the experimental and FE analysis. Table 3 compares the FE results for ultimate and allowable loads at maximum deflection ($L/360$) with the experimental data. For ultimate load, the variation between predicted and experimental results ranged from 0.1 % to 3.5 % indicating that the current FE model can predict with a high level of accuracy the flexural strength and load-carrying capacity of tapered castellated beams. Referring to experimental tests and numerical simulation, Fig. 11 shows that clear convergence between them, due to the material behavior of steel was idealization as bilinear stress-strain behavior.

The results are limited to the simply supported TCBs under concentrated load at mid-span length. This study has the disadvantage that all the tested beams are not full scale. In future studies, full-scale TCBs with spans of up to 5 m can be tested. To develop this study, testing TCBs at full-scale with uniform loads along a total effective span will help in simulating using TCBs to cover a portal frame with a span of up to 20 meters.

7. Conclusions

1. Adding expansion plates increases the maximum load capacity of TCBs by up to 40 % above that of the parent beam, according to the study results. A TCB has lower ductility than its parent beam.

2. The experimental results show that TCBs failed due to web-post buckling; welding joint rupture when shear loads were applied to the web posts attempted to twist them. The prismatic castellated beam, on the other hand, failed due to the Vierendeel mechanism.

3. A TCB fulfills serviceability requirements since its mid-span depth exceeds that of its parent beam. According to IBC deflection regulations, the allowable load at maximum deflections $L/360$ is over 83 percent larger than the original beam's allowable load.

4. Regarding ultimate and allowable loads at maximum deflection ($L/360$), it was concluded that numerical models using the Abaqus program provide close agreement with the experimental results. Thus, it can be used in the analysis and prediction of failure modes of TCBs.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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