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EFFECT OF EXPANSION RATIO ON DEFLECTION OF THE CASTELLATED BEAM FOR DIFFERENT SUPPORT CONDITIONS

Vhora Nilamben Anavarbhai[1], Jyoti Yadav[2]
M. Tech Scholar, Civil Department, SRK University, M.P.India[1]
Asst. Professor, Civil Department, SRK University, M.P.India[2]

Abstract: *Experimental investigation has been performed on twelve short and long castellated beam-column elements. The castellation process effectively increases the section resistance because of increasing the depth of the section without any additional weight. By increasing the depth of the beam, major axis bending resistance and stiffness are improved as the major axis moment of inertia (Ix) and the section modulus (Sx) are increased. It has been noticed that, researches that considered castellated elements subjected to axial and bending moment are limited compared to those considered elements subjected to bending moment only. In this research castellated beam-columns are studied under different load eccentricity to investigate the effect of castellation on beam-column strength. Behavior and strength of castellated beam-column are also investigated using the finite element analysis utilizing ANSYS software. The finite element results are found to be in a good agreement with their experimental counterparts.*

Keywords: *Castellated steel beam-columns, Castellated steel beams, castellated steel columns,*

1. Introduction

Castellated beams, columns and beam-columns have been used as structural members in steel structures. Castellated beams and columns are fabricated from a hot-rolled steel I-section, by cutting the section web on a half hexagonal line down its center. The two halves are moved across by a single spacing and then rejoined together by welding. This process increases the depth of the steel element and accordingly, the major axis bending resistance and stiffness, without any additional steel weight. This results in the possibility of utilizing castellated member in long spans with moderate loading conditions in roofs and floors. The fabrication process results in openings on the member web, which can be utilized to accommodate services. Accordingly, the overall height of the building can be significantly reduced, regardless of increasing the element depths, compared to using elements with solid webs, where services are only possible beneath the beams. Regardless of the increased cost due to the fabrication process, the advantages of using castellated steel elements outweigh the disadvantages. Mohebkhah and Showkati [1] Studied the effect of lateral bracing on castellated steel element capacities and concluded that the effect of bracing became reduced in the elastic buckling range, whereas this effect is enhanced with the increase of the laterally unbraced length. They developed a general equation to predict the castellated flexural members' stiffness and capacity. The developed formula accounted for the member slenderness. Nethercot and Kerdal [2] investigated the behavior of castellated steel beams without the provision of lateral supports. He developed empirical equations that could be used to estimate the co-efficiency of bending (Cb) for castellated-beams under various conditions. Ellobody [3] [4] studied the effect of combined lateral-torsional and distortional buckling modes on the behavior of castellated and cellular elements. In his study, he considered normal and high strength steel castellated elements and concluded that failure load of castellated steel elements was likely reduced due to the steel beams. He Also, found out that, utilizing high strength steel has contributed to an increase in the failure load of less slender castellated beams. He furthermore concluded that the Australian Standards equations predicting the behavior of steel beams under lateral-torsional buckling were conservative, however, when castellated elements were failing in web distortional buckling the equation was otherwise. Finally, when high strength beams by lateral-torsional buckling, the AS expressions were quite conservative. Abu-Sena et al. [5] Conducted a parametric study to predict the buckling behavior and the element capacity of beam-column elements. They considered the initial imperfection in the F.E.A and developed an analytical model to predict the interactive strength compared to the finite element non-linear analysis of EC3 design approach. Yuan et al. [6] Studied the critical buckling load of simply supported castellated columns. They considered the buckling about the major axis and concluded that the presence of the web openings resulted in shear deformations along the castellated steel column and contributed to reduction in the buckling capacity of the castellated steel column. They moreover concluded that web shear deformations couldn't be neglected, even if the second moment at the opening location's area was taken into consideration in predicting the buckling strength of the castellated steel column. Kumbhar and Jamdar [7] investigated the behavior of castellated elements with sinusoidal openings. They used these types of openings to study the possibility of optimization. They considered different sizes of web openings and found that when sinusoidal web opening sizes were equal to 0.55 times the total depth of the beam element, along with the strength of the element might reach the maximum. They also concluded that utilizing these types of openings resulted in further shear transfer area. Cheng [8] studied the critical buckling load (CBL) of cellular columns. They focused on the major buckling axis and considered the web shear deformations that have a clear influence on the buckling capacity of the cellular elements. They concluded that the effect of shear deformations on the cellular element increased along with the increase in the cross-section area of the tee section above the openings and the diameter of the web opening, however it decreased with the web thickness and the length of the cellular element. Shaikh and Autade [9] Studied the effect of web shear deformation on the critical buckling load of castellated beams.

They found out that, the depth of the web openings had a significant effect on the shear deformations that might occur in the castellated steel element. They also presented an analytical solution to predict the critical buckling load of the castellated steel element and found out that the utilization of rounded holes avoided Vierendeel effect (to avoid stress concentration), and local failure of the beam. The provision of a plate below the concentrated load and reinforcement at the beam's weak sections could be used to enhance the beam's capacity. Sonck and Belis [10] studied the effect of residual stresses on the weak-axis flexural capacity of both castellated and cellular columns. They concluded that the weak axis flexural capacity was affected by the residual stress simulation. Wang et al. [11] used the finite element method to investigate the post-buckling behavior of the web of castellated beams when subjected to vertical shear. They concluded that the web thickness and the inclination angle of the web opening had a significant effect on the shear buckling factor. They moreover presented a simplified method to predict the shear buckling factor of castellated steel beam. Yuan et al. [12] investigated the transverse deflection of perforated beams. They considered two different boundary conditions and concluded that web shear effect could significantly increase the transverse deflection of castellated and cellular beams particularly when the beam has a short length and deep section. Elaiwi et al. [13] presented theoretical and numerical solutions for calculating the deflection of hexagonal castellated beams with simply supported boundary condition, considering the influence of shear deformations that might occur in the web. Elaiwi et al. [14] investigated the effect of the web opening on the lateral-torsional buckling resistance of castellated beams. They developed an analytical solution that could be used for the design and practicality. They concluded that plastic failure was the failure of short castellated beams' mode whereas lateral-torsional buckling was the mode of long beams' failure, accordingly, the longer the beam, the less important was the nonlinearity. Hadeed and Alshimmeri [15] studied the effect of castellation with and without strengthening on the structural behavior of castellated-beams and compared the results with the origin solid steel beam. They found out that, the load carrying capacity of the castellated steel beams was increased compared with the original solid beam, while mid-span deflection values at service load were decreased comparing with the origin solid steel beam. Liu et al. [16] studied octagonal web openings elements. They used high strength bolt to connect the two halves of the elements in site instead of utilizing the factory welding. They draw a comparison between bolted and welded web opening elements and found out that, the structural behavior of bolted elements was further improved than the welded elements. Considerable amount of research has investigated the behavior of castellated steel beams and/or columns. However, most of these studies were confined on the lateral-torsional buckling of castellated steel beams, types of openings (either circular or hexagonal web openings), the buckling behavior of castellated steel columns and the deflection of castellated beams. Nevertheless, no research seemed to have investigated the behavior of castellated steel beam-column elements. Therefore, this study will have the precedency in contributing towards the implementation of castellated beam- column elements into numerous structures such as office buildings, car parks, shopping centers, hospitals almost any structure with a suspended floor. This paper reports on short and long castellated steel beam, column and beam-column elements. Experimental study was developed to examine the behavior of castellated steel beam-column elements. Linear interaction diagrams were plotted to illustrate the effect of castellation on linear buckling behavior of castellated elements. Also, non-linear interaction diagrams were plotted to investigate the effect of castellation on the element capacity. This paper presents different castellation ratios (R), where R equals the ratio between castellated element and the original solid web element. Therefore, enhancement diagrams were plotted to investigate the best castellation ratio, enhancement diagrams plotted. The current study aims at investigating the effect of castellation on the beam-column elements strength. This study presents short and long beam-column elements with three different (e/d) ratios, where (e) is the load eccentricity and (d) is the section depth. The first (e/d) ratio is equal to zero so these elements represent the pure axial elements, the second (e/d) ratio is equal to 0.5 and the third (e/d) ratio is equal to 0.75. Also, two castellation ratios (R) were considered 1.3 and 1.5. The castellation ratio (R) is the ratio between castellated section depth to the original section depth. The results of experimental work performed in this research will be compared to the finite element non-linear analysis to validate the applicability of finite element as a numerical tool.

2. Experimental Program

Twelve specimens are tested to study the effect of castellation on the beam column elements behavior and strength. One of the commercially available IPE sections was chosen carefully with the standard section dimensions as shown in Fig 1. The experimental program consisted of 3 groups. Group I, was focused on the axial compression behavior of 4 short and slender I- section columns. The parameters considered were the effect of castellation ratio (R) and the slenderness ratio of the steel columns. The columns were instrumented to examine their behavior in terms of the load-axial displacement and load-lateral displacement responses. Groups II-III, were focused on the axial-flexural behavior of 8 short and slender I- section beam columns. The parameters considered were the effect of castellation ratio (R), the slenderness ratio of the steel sections and the eccentricity to section depth ratio (e/d ratio). Group II was focused on the structural behavior of 4 short and long I-beam column sections that had ratio of e/d = 0.5, while group III was focused on the structural behavior of 4 short and long I-section members that had ratio of e/d = 0.75. The I- sections were instrumented to examine their behavior in terms of the load-axial displacement and load-lateral displacement response. The identification of each specimen in further sections of this research will indicate specimen length followed by castellation ratio followed by eccentricity to section depth. For example, L17-R1.3-e0.0 refers to specimen that has length of about 1700mm, castellation ratio equals to 1.3 and pure axial specimen, so e/d ratio equals to 0.0.

2.1 Material Properties

Three tensile coupon tests are performed to specify the mechanical characteristics of tested steel specimens. The representative stress-strain curves of all tested specimens. Mechanical properties of the tested steel specimens.

2.2 Castellated Beam Specimen Preparation

Section opening arrangement and dimensions, for R = 1.3 and R = 1.5. The steps of specimen fabrication from IPE200 to castellated element. After fabrication, a loading plate was welded at one end of the specimen. The boundary conditions for all test specimens were pin ended at both ends, the other end connections are shown in
a) Section dimensions R=1.5.
b) Section dimensions R=1.3.
Castellated element dimensions.

2.3 Test Setup

The end boundary conditions were pinned-pinned, so the specimen from one end was supported on the bearing plates by a simple connection to permit rotation, while, the upper end of the specimen was supported by using steel elements that also permitted rotation as shown in Fig 6. The specimen was permitted to move down, in the same time the specimen was restrained horizontally. Also, out of plan movement was restrained by using lateral support to ensure specimen out of plan stability.

a) Original IPE200 solid section.
b) Cutting path on the original section.
c) Cutting the specimen into two parts.
d) Alignment of the two parts.

All specimens were tested under vertical load using one test setup. Testing machine capacity was 1000 kn. Load cell position was based on e/d ratio. For column elements load cell was on the top center of the specimen while for beam column elements load cell was eccentric to satisfy the required e/d ratio. For group I, three LVDTs were used; one of them was mounted at the top loading plate to measure the vertical displacement, where the other two

LVDTs were mounted at the mid-height to measure the lateral displacements as shown in Fig 8. For groups II and III four LVDTs were used; one of them was mounted at the top loading plate to measure the vertical displacement, where three LVDTs were mounted at the mid-height to measure the lateral displacements and the rotations.

3. Test Results

3.1 Failure Modes

Group I: pure axial loading
Four castellated columns were tested two of them were short and the others were long, by applying axial load at the top center of the specimens. The experimental tests showed that the failure mode of the short columns was the local buckling and web shear deformations, while the failure mode of long columns was overall flexural buckling as shown in Fig 10. Groups II-III: beam columns members of (e/d=0.5 & e/d=0.75) Eight castellated beam columns were tested four of them short and the others are long, by applying load at the top loading plate. The experimental tests showed that the failure mode of the short and long beam column elements was lateral torsional buckling mode.
e/d = 0.75, so the increase in eccentricity of castellated beam- column elements decreases the axial load capacity. Fig 16 shows that beam column elements that have e/d = 0.75 can sustain bending moments greater than that have e /d =0.5, therefore, the increase in the eccentricity of castellated beam- column elements increases the moment capacity.

4. Conclusions

An experimental investigation and finite element non-linear analyses have been conducted on twelve short and long castellated steel column and beam column elements. The F.E.A results of ultimate capacities and deformed shapes were verified with experimental counterparts and were found to be in a good agreement. For short columns, castellation decreases ultimate capacity due to the effect of local buckling that occur in the web, also the increase in castellation ratio (R) decreases the ultimate capacity due to the increase in section depth that led to increase in the effect of local buckling. To improve ultimate capacity of castellated short column elements, the upper and lower openings are required to be closed. For long columns, castellation decreases the ultimate capacity due to the effect of shear deformation that occur in the flanges in the location of the openings, also the increase in castellation ratio (R) increases the shear deformation that led to less ultimate capacity of the element. So, castellation decreases the ultimate capacities of short and long columns. For beam and beam-column castellated elements, a parametric study was carried out to investigate the effect of castellation on the bending capacity. Four castellation ratios (R) were considered, in addition to solid web elements (R=1).
Solid web elements were considered to investigate the improvement that occurs due to castellation rather than solid web elements. Four (e/d) ratios were considered to study the effect of load eccentricity on the element capacity, also, pure bending castellated elements were considered.

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