Finite Element Analysis on Shear Strength of a Castellated Beam with Hexagonal Web Opening

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Abstract. A beam (flexural member) with several regular openings with different shapes is called a castellated beam. The castellated beams are well accepted in the industry, multi-story buildings, and power plants due to their increased depth of the section along with the web results in increased strength and stiffness. Though numerous simulation and experimental analyses have been made on the castellated beam, with intermediate transverse stiffener, bearing stiffener and torsion stiffener are used to increase a load-bearing capacity of the beam, but the study on the understanding of diagonal stiffener in the opening is very meager. The objective of the research is to investigate the linear behavior – ISMB150 and IC225 castellated beam of hexagonal openings with and without diagonal stiffeners and the effect of fillet radius at the corner of the openings is studied. Using finite element analysis software, Hyper works, with OptiStruct as a solver, under simply supported beam construction with four-point loading conditions was analyzed by developing an efficient 3D model for the analysis. Due to the openings in the section, the sharp corner of the opening is subjected to Vierendeel failure by the formation of plastic hinges at the corners, which makes critical hence by providing diagonal stiffener in the direction of diagonal tension and diagonal compression for the smooth flow of shear forces. The results show an improvement in load-bearing capacity of 1.51 times in the castellated beam than the parent section ISMB150. The stiffener provided further enhances the same to 1.45 times compared to the ISMB150 section. The linear results show lesser stress concentrations at the web opening corners, thus reducing the prominence of failure at the corners.

1. Introduction
Castellated beam finds its importance in engineering constructions in recent decades compared to the solid web beam. The significant reasons why the Castellated Steel Beam is gaining their importance are reduction in the total height of the construction; service let outs are easier, reduction in steel usage, reduction in overall cost incurred. The high strength of structural steel cannot be utilized to its best due to the limitations on maximum allowable deflections. Steel beams with perforated web openings are fabricated from hot rolled steel section is most famous owing to its improved strength, stiffness and ease of feasibility owing to its provision of opening. The fabrication of castellated beams includes bifurcating the web section in a crisscross pattern according to the cross-section as required, along its centerline, and joining the two halves by weld joint to such that the depth increases. The reduction in weight of the beam constitutes a larger section modulus and moment of inertia with better bending rigidity than the solid section counterpart, without an
increase in weight. They are largely employed for medium and long spans constructions as roof or floor beams, joists, purlins.

Their aesthetic features attracts for numerous architectural applications as the web openings of these members serve as a passage for easy directing and installation of service utilities. The most common castellated structures constitute hexagonal web openings and circular openings in the case of cellular beams. The circular web openings are commonly referred to as cells. The recent increase in usage of castellated and cellular beams highlights the need for additional research.

Kerdal and Nethercot\cite{1} have made significant studies on the typical failure flexural mechanism of the castellated beam. According to their findings, the castellated beam structures are more prone to failure due to web-postbuckling due to shear force; Vierendeel mechanism; Lateral torsional buckling; weld rupture. Samadhan G. Morkhade\cite{2} extensively studied the behavior of a rectangular I beam with varying fillet radius and stiffener arrangement experimentally. The author reported that stress concentration is critical at the corners of the opening. An empirical relation is provided by Timoshenko \cite{3} to find the lateral-torsional buckling of laterally unrestrained castellated beam given by;

\[ M_{CR} = \sqrt{\frac{\pi^2 EI_y}{(KL)^2}} \left( G I_t + \frac{\pi^2 EI_y}{(KL)^2} \right) \]  

(1)

Numerical studies on the castellated beam were carried out by a few researchers who made their significant contribution to this study field. Among the different failure mechanisms, the most important failure mechanism the beam is encountered is due to the Vierendeel mechanism. Very few notable experimental findings were carried out on the same. One of them is the experimental investigation conducted by Ferhat Erdal and Mehmet Polatsaka\cite{4} on twelve cellular beams. Different beam section was chosen in their study to identify the ultimate load-carrying capacity. Their findings reported that the beam is prone to failure by Vierendeel bending, web buckling, and lateral-torsional buckling. They also reported that all the failures are due to inadequate lateral support and normal load applied to the cellular opening. The linear torsional buckling (LTB) of the castellated beam was numerically investigated by Delphine Sonck and Jan Belis\cite{5} based on ENV3 standard – annex N. The preliminary design proposed based on the currently existing European guidelines was given, and the empirical relationship to calculate the LTB resistance of a beam \( M_{RD} \) can be calculated using

\[ M_{RD} = \frac{X_{LT} w_f y_f}{\gamma_{MI}} \]  

(2)

Where;

Reduction factor - \( X_{LT} = \frac{1}{\phi + \sqrt{(\phi^2 - \lambda_L^2)}} \leq 1 \)  

(3)

Section modulus – Wy; Nominal yield stress – fy and \( \gamma_{MI} \) the partial factor- 1.0. According to the 2T design approach proposed, the critical moment for the lateral-torsional buckling is calculated by

\[ M_{CR} = \frac{\pi}{L} \sqrt{\left( G I_t E I_y + \frac{\pi^2}{L^2} E I_z E I_w \right)} \]

K.F. Chung et al.\cite{6} proposed a new design approach on Vierendeel failure mechanisms, which is critical in castellated beams due to the plastic hinge formation at the low and high moment sides, which reduces the load bearing capacity of the beam. The shear - moment interaction curve was identified to be applicable for the medium to the large circular opening, which serves as a
conservative and effective method. As advancement in analyzing the failure mechanism, K.F.Chung et al. [7] analyzed steel beams with openings varying the shapes and sizes, the diameter of which varies between 0.5h to 0.75h. With the varying depth of opening and overall depth as parameters, shear moment interaction curves are proposed, which summarises that global shear force is a major cause for both the shear failure and Vierendeel failure. Observations also stated that the failure modes are more prominent in the castellated beam with large-sized web openings. The influence of fillet corner provision was examined by Peijun W et.al [8] numerically, focusing on the Vierendeel mechanism.

Amin Mohebkah and Hossein Showkati [9] discussed elastic bracing requirements in the castellated beam to avoid lateral-torsional buckling of the beams. The effects of central elastic lateral restraints and large lateral deflections were studied considering the provision of elastic bracings, and it was found that the provision of central elastic restraint increases the elastic buckling strength of the beam. The increased strength not only depends on the stiffness but also majorly depends on the slenderness of the beam. Ehab Ellobody [10] conducted extensive research on failure modes and lateral load-bearing capacity of normal to high strength castellated steel beams. The Parametric study was carried out by the change in geometries, strength, and buckling behavior of castellated steel beams, which summarizes a considerable decrease in the distortional buckling.

Although several reports were made on the castellated beams, very few investigations were attempted on the influence of diagonal bracing and change in the fillet radius on the load-bearing capacity of ISMB150 castellated beam. The present analysis is aimed at finite element analysis through a linear approach to identify the influence of the provision of stiffeners and change in the fillet radius of the web openings. The castellated beams were designed such that the depth is increased up to 1.5 times the actual depth of the section with an angle of cut 56°. The shear failure and stress concentration are determined with and without providing web stiffeners on either side of the web posts.

2. Methodology

2.1 The geometry of I section and tension field action
ISMB 150 is selected for fabricating the castellated beams. The castellated beams were fabricated such that the depth of the beam is 1.5 times the original depth as IC 225 with an angle of cut 56°. Generally, the angle should be within the range of about 45° (min) and 70° (max), where 45° and 60° are commonly used. The typical geometry of the castellated beam is shown in figure 1 below.

![Fig. 1 Castellated beam geometry](image)

The distribution of stress in the I section shows that flanges resist the bending moment, while web assists in resisting the shear force. During transverse loading, normal and shearing stress are developed; hence complementary shear stress is formed to satisfy the equilibrium. This shearing
stress in the beam occurs due to the internal shearing of the beam that results from shear force subjected to the beam. Consider a small element subjected to shear stress (figure 2) where, the element is subjected to principal compression in the direction AC, and the principal tension is occurring along the direction BD. As the load gradually increases and when the beam is loaded beyond the limit, first, it will deflect significantly as the stiffness is lost further tends to buckle. The web part loses its ability to resist the diagonal compression along the direction of AC, and the beam cannot take the further load. To overcome this, diagonal stiffeners are introduced on the web opening where shear is dominating, and hence forces flow through the diagonal stiffener.

![Fig. 2 Elemental representation of the shear panel](image)

The behavior is very similar to a Pratt truss (figure 3), in which the vertical members carry compression and the tension is carried by the diagonal. The web resists only the diagonal tension and this behavior of the web is called tension field action.

![Fig. 3. Pratt Truss showing the tensile field action](image)

### 2.2 Empirical equations

The following empirical relations are employed in calculating the design geometry of the castellated beam

\[
\text{Area of flange } (A_f) = B_f \times T_f
\]  \hspace{1cm} (4)
Area of web \((A_w) = B_w \times T_w\) \(\text{(5)}\)

Position of centroid of castellated T section \((\bar{Y}) = \left(\frac{\sum a y}{\sum a}\right)\) \(\text{(6)}\)

MI of T section about neutral axis \((I_T) = \left(\frac{bd^3}{12}\right) + A_f (y - \bar{y})^2\) \(\text{(7)}\)

Moment of resistance \((M_R) = A\sigma_{at}d\) \(\text{(8)}\)

Load applied over section \((W) = \frac{M_R}{L}\) \(\text{(9)}\)

The average shear stress at the ends \((\tau_{va}) = \frac{P}{2d't}\) \(\text{(10)}\)

Max. mid – span deflection \((\delta) = \delta_1 + \delta_2 < \frac{(L)}{325}\) \(\text{(11)}\)

Combined local bending and direct stress \((C_{st}) = P_s + S_s\) \(\text{(12)}\)

Max. Stiffener width \((W_{st}) = \left(b - \frac{t}{2}\right)\) \(\text{(13)}\)

2.3 Validation

The modal created in hyper works is validated against the Numerical results conducted by Wakchaure et.al\([11]\) on the finite element analysis of the castellated beam, which shows that the error is less than 1%, and it is firm to continue. And the beam deflection value obtained from Hyperworks is also validated by a Macaulay's method theoretically, and the error is found to less than 1. The corresponding analysis results are tabulated in Tables 1 and 2, respectively.

**Table 1:** Numerical validation of results obtained by Hyperworks vs. Numerical results of Wakchaure et.al

| S.NO | Section | Span L (m) | Deflection (mm) Numerically using Hyperworks | Deflection (mm) Numerically by Wakchaure et.al | Error (%) |
|------|---------|------------|---------------------------------------------|-----------------------------------------------|------------|
| 1    | IC 225  | 3          | 0.661                                       | 0.664                                         | 0.451%     |

**Table 2:** Theoretical validation of results obtained by Hyperworks vs. Macaulay’s method

| S.NO | Section  | Span L (m) | Deflection(mm) Numerical using HyperWorks | Deflection (mm) By Macaulay's method | Error (%) |
|------|----------|------------|-------------------------------------------|-------------------------------------|------------|
| 1    | ISMB 150 | 3          | 3.13                                      | 3.16                                | 0.94%      |

2.4 Material Properties

The tensile test is carried out as per the ASTM A370:2017. Coupons drawn from flanges and web of the beam were subjected to tensile axial loading, which becomes a necessary material Properties for numerical modeling of the beams. Ultimate tensile strength, breaking strength, and maximum elongation, were recorded. From these measurements, Young’s modulus, Poisson’s ratio, yield strength, and ultimate strength are used in finite element modeling of the beams was also determined. The average values of yield strength and ultimate strength are determined as 361.66 MPa and 527.94MPa, respectively. The results show that the web part undergoes more stain
hardening compared to the flange specimen. The specimens drawn from the flange part shows more ductility range compared to the web part. The variation in the properties can be attributed to the rolling directions of the individual members. Figure 4 shows the stress-strain graph obtained for the tensile samples drawn from the web and flange section.

![Tensile stress vs. strain graph of coupons drawn from (a) Web (b) flange of ISMB150](image)

Fig. 4. Tensile stress vs. strain graph of coupons drawn from (a) Web (b) flange of ISMB150

3. Finite element analysis
The aim is to simulate the linear behavior of castellated ISMB 150 beam of I shaped cross-section with the hexagonal opening using a three-dimensional finite element model developed for determining the Y-directional deformations and vonmises failure stresses. The webs, flanges, and stiffeners were modeled by a Hexa eight noded element constituting six degrees of freedom at each node, three translations, and three rotations, which enable explicit simulation of various buckling deformations. Linear elastic material with Young’s modulus $E = 2.1 \times 10^5$ MPa and Poisson’s ratio $\nu = 0.3$ is considered. The model was developed with simply supported beam configuration with one end hinged and roller support provided over the other end. A two-point load at $l/3$ and $2l/3$ of the span and central ‘y’ deflection is calculated. At one end, the translation degree of the freedom along the three-axis was restrained at the left support to simulate the pin support while at the other end, the Z-axis degree of freedom of translation was released. The rotational degree of freedom is unrestrained at both supports, and the effects of residual stresses and welding of two parts have not been considered. The study includes three major considerations - (i) parent solid ISMB 150 compared with the castellated IC225 beam, (ii) Effects on the provision of diagonal stiffener on IC225, and (iii) Effect of provision of fillet radius on the web opening corners.

The three-dimensional models developed using CATIA was numerically analyzed using hyper works in the present investigation with Hypermesh as pre-processor and Opti-struct as the solver. The hyper view post-processor was employed in analyzing the results. Careful attention in mesh sizing was laid as it is the most critical factor in FEA analysis. Regardless of the competency of the software to consider the material nonlinearity, only the linear material influence was considered in the present analysis. To determine the optimum mesh size, a mesh convergence study was conducted and the results verifies that the FEA model has converged to a solution 3mm × 3mm mesh size, which provides a balance between the accuracy and computational expense. Finer meshes are generated to model areas near the openings, to improve precision and also justifies.
The deflection results arrived through the finite element analysis are represented pictorially in figure 5, which corresponds to various loading conditions for varying beam configurations. The results show that in the ISMB 150 beam, the stiffness of the beam is degressive with a continued level of increase in the load, exhibiting an increase in deflection and a reduction in the load-bearing capacity. The stiffness gets increased in the IC225 castellated beam due to the increase in the overall web height showing a considerable decrease in the deflection. The provision of diagonal stiffener arrangement has higher stiffness, which yields lesser deflection because of the truss action it takes through the diagonal stiffener. The stiffeners are provided in the direction of the diagonal tension and compression in the web for the smooth flow of shear forces. In all the cases, the FEA results show that the stiffness of the beam is decreased with an rise in the opening area and by sharp corners. The zero fillet radius has a high-stress concentration in the sharp edge of the opening, increasing overall deflection. By providing a fillet radius of 10mm and 20mm at the corners of the web openings, the stiffness of the beam gets marginally increased with lesser deformation and a marginal reduction in stress concentrations.

Figure 6 represents the critical stresses around the sharp corners of the opening in the shear zone of IC225, where shear stress is dominant. Hence, von misses stress is high in the shear zone at both
ends and the loading points. The plastic hinge was first formed at the lower moment side following the load redistribution occurs across the web opening along the shearzone, and shear failure is more near the opening. Subsequently, other plastic hinges were formed at different places of the opening.

From the deflection results, it can be understood that the provision of diagonal stiffeners considerably increases the load-bearing capacity and decrease the overall deflection. Figure 7 indicates that the diagonal stiffeners are provided in the diagonal tension, and compression directions, a truss action in the web opening of the beam occurs to ease the flow of the forces. The analysis shows that the diagonal stiffener provides effective stability than the castellated beam with rounding the corners of the opening. Also, the shear strength of the castellated beam can be
improved by introducing shear stiffeners (Diagonal Stiffeners) on the web opening along the shear zone. Though the provision of stiffeners improves the overall load-bearing capacity, due to the openings, it is prone to fail by cracks in the corners. The formation of plastic hinges makes the hinges rotate till it reaches a plastic moment, further causing Vierendeel failure to occur. Figure 7,8 and 9 shows that the stress concentration at the web opening corners are lesser compared to stress concentration at the corners in case of IC225. The stress and strain distribution of different beam configurations are shown in contour plots in figure 10. The results show that the stress induced on the castellated beam with the stiffeners are lesser compared to the beam configurations provided with web opening corner fillet radius.

Fig. 10. Contour plots showing stress – strain distribution w.r.t load for (a) ISMB150, (b) IC225, (c) IC225 + stiffeners, (d) IC225 with fillet radius R10 and (e) IC225 with fillet radius R20

4. Conclusion
Based on the numerical simulation of the castellated beam with hexagonal web opening, the deflection and load-bearing capacity was analyzed. The results depict that the castellated beam with perforations has many local effects, influencing the load-bearing capacity. And it is found that by providing the diagonal stiffener, the stiffness of the beam is increased by a decrease in deflection. Vonmisses yield stress has been considered in the present paper, which is suitable for material like steel. The results also show that stress concentrations increase at the hole corners (Vierendeel effect) and load application point. By incorporating corrective measures like rounding the corners, providing diagonal support to increase the serviceability of the castellated beam, which paves the way for numerous structural engineering applications.

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