Experimental Investigation on the Flexural behaviour and Stiffener Requirements of Castellated Steel Beam

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Abstract—This paper presents an experimental and analytical study on the flexural behavior of castellated steel beam with and without stiffeners. Castellated beams are steel beams with web openings and they gain its advantage due to increased depth of section without any additional weight. In this paper steel I section ISMB 150 is selected and castellated beams are fabricated such that depth of the beam is 1.5 times greater than the original depth. The beam is analyzed using Finite Element Analysis (ABAQUS) to compare the deflection of steel beam with and without web openings of ISMB 150 section. Two point load is applied and stress distribution and deflection of the beam with and without stiffeners is studied experimentally. From the test results obtained from ABAQUS it is observed that the stress concentration increases at the hole corners along the shear zone and at load application point. Stiffeners are introduced diagonally on the web opening along the shear zone, in order to increase the efficiency of the section. From the test results it is concluded that the castellated beam has a lesser deflection that the solid beam and the shear strength of the castellated beam can be improved by providing diagonal stiffeners along the web openings.

Key words: Castellated Beams, Castellated Steel Beam

I. INTRODUCTION

Methods of achieving economy in steel, with consequent reduction in the deadweight of a structure, while at the same time maintaining or increasing the strength of a given span, have been the objectives of the Consulting Engineer and Architect ever since steel framing as we now know it was accepted as an independent load carrying unit in building construction. Since the Second World War many attempts have been made by structural engineers to find new ways to decrease the cost of steel structures.

Due to limitations on maximum allowable deflections, the high strength properties of structural steel cannot always be utilized to best advantage. As a result several new methods have been aimed at increasing the stiffness of steel members without any increase in weight of the steel required. Castellated beams were one of these solutions.

A. Castellated Beams

Castellated Beam is a name commonly used for a type of expanded beam. It is made by expanding a standard rolled shape in a manner which creates a regular pattern of holes in the web. Castellated beams have had occasional usage in this country for many years, during which time they were produced by simple hand procedures. Though these fabrication methods were not conducive to broad development, castellated beams have long been recognized as advantageous structural members. The pattern of holes in the web presents an attractive appearance for beams exposed to view. The web holes are becoming even more functional with the increase of piping, conduits and ductwork in modern construction.

The greatest advantage, however, is the economy effected by the increased load carrying capacity and stiffness. Castellated (or expanded) beams are fabricated from wide flange 1-beams. The web of the section is cut by flame along the horizontal x-x axis along a "zigzag" pattern as shown in Fig. 1. The two halves are then welded together to produce a beam of greater depth with hexagonal openings in the web (Fig. 2), or rectangular plates may be inserted between the two parts producing octagonal holes. The resulting beam has a larger section modulus and greater bending rigidity than the original section without an increase in weight.

However, the presence of the holes in the web will change the structural behaviour of the beam from that of plain webbed beams. Experimental tests on castellated beams have shown that beam slenderness, castellation parameters and the loading type are the main parameters, which dictate the strength and modes of failure of these beams.

Castellated beams have been used in construction for many years. Today, with the development of automated cutting and welding equipment these beams are produced in an almost unlimited number of depths and spans suitable for both light and heavy loading conditions. In the past, the cutting angle of castellated beams ranged from 45\(^o\) to 70\(^o\) but currently 60\(^o\) has become a fairly standard cutting angle, although 45\(^o\) sections are also available. It should be noted that these are approximate values, actual angles will vary slightly from these to accommodate other geometrical requirements.

As roof or floor beams, joists or purlins, these sections may replace solid sections or truss members. Their aesthetic attributes produce an attractive architectural design feature for stores, schools and service buildings. In structures with ceilings, the web openings of these members provide a passage for easy routing and installation of utilities and air conditioning ducts.
II. OBJECTIVE OF THE STUDY
- To analyze the flexural behavior of castellated beam with hexagonal shaped opening by analytical and experimental investigations.
- To compare the test results of the castellated beam specimen (IC225) with that of the parent beam (ISMB150).
- To enhance the strength of the castellated beam by providing diagonal stiffeners.

III. REVIEW OF LITERATURE
These are some of the conclusions drawn from various literature reviews about castellated beam,
- As the depth of opening increases, stress concentrations increases at the hole corners (Vierendeel effect) and at load application point. By taking corrective measures, i.e. by rounding hole corners, providing reinforcement at critical section, providing plate below point load, etc. the serviceability performance of castellated beams can be improved in practice [1].
- As size of beam is increasing, deflection of beam is decreasing. As the web opening move towards the centre of beam, stress goes on decreasing and hence deflection is reduced [2]. Hence from this [2] paper if stiffeners are provided along the shear zone, stress can be controlled and shear deformation can be minimized.
- Increase in web post width (e), result in increase of predicted buckling load to yielding mechanism load. As the web thickness (tw) increases, the corresponding predicted buckling load and yielding mechanism load increases [4].
- As the web thickness increases, the corresponding predicted buckling load and yielding mechanism load increases. As web post width decreases, the corresponding predicted buckling load and yielding mechanism load increases due to the decrease in area of web openings [5].
- Hence from the various literature reviews it is observed that failure occurs as the depth of the opening increases and also due to the stress concentration across the holes. It can be reduced by taking corrective measures like providing stiffeners.
- And stiffeners may be provided along the shear zone so that stresses can be reduced and deflection can be controlled and shear failure can be minimized.

IV. DESIGN PARAMETERS
A. Basic Terminologies and Design Considerations
Throughout this paper various terms will be used to discuss castellated beam components and testing results. This section introduces the reader to the definition of these terms and Figure 3 illustrates the terms.
- Web Post: The cross-section of the castellated beam where the section is assumed to be a solid cross-section.
- Castellation: The area of the castellated beam where the web has been expanded (hole).
- Throat Width: The length of the horizontal cut on the root beam. The length of the portion of the web that is included with the flanges.
- Throat Depth: The height of the portion of the web that connects to the flanges to form the tee section.
- Expansion Percentage: The percentage change in depth of the section from the root (original) beam to the fabricated castellated section.

B. Section Properties
Based on certain specifications from the euro code and knowledge gained from the literature of previous research works the design parameters and the section properties are considered and defined as follows.
- ISMB 150 Hot rolled section of length 1200 mm is chosen for the casting, testing and analysis of castellated steel beam of length 1000 mm

Fig. 3: Basic terminologies of a castellated steel beam
The perforations made in the web are greatly affecting the structural performance of the beam. Therefore, some logical and practical considerations need to be observed while providing perforations in the beam. Following are the general guidelines which are given by Eurocode and some of them are based on the field or practical considerations. These standards in web perforations can be changed or modified without affecting the structural performance of the beam. The standard dimensions of a castellated steel beam is given in the fig 4.

Fig. 4: Standard dimensions of a castellated steel beam

Fig. 5: Standard dimensions of a solid web beam ISMB150
- Cutting angle is chosen as 450°
- Spacing of the Holes = 75 mm
- Length of the specimen = 1000 mm
- Stiffener Dimensions = 190*15*5 mm
V. SOFTWARE ANALYSIS

A three dimensional finite element model is developed to study the behavior of castellated beam. Modeling and analysis is done using ABAQUS/CAE SOFTWARE. Three different models are created and their stress concentration and load deflection behavior is studied.

In order to study the flexural behaviour of castellated steel beam three different cases are considered:
- Model 1: Solid web beam ISMB150
- Model 2: Castellated Steel Beam
- Model 3: Castellated Steel Beam with Diagonal Stiffeners

The various steps involved are the rendering of the model for its given dimensions, fixing its boundary conditions and application of two point loads at equal intervals and meshing is done and then analysis is carried out.

The following assumptions are adopted for analysis.
- Yield strength \( f_y = 2.5 \times 10^8 \text{ N/m}^2 \)
- Young’s modulus \( = 2 \times 10^{11} \text{ N/m}^2 \)
- Poisson’s ratio \( = 0.3 \)
- Density of Steel \( = 7830 \text{ kg/m}^3 \)

Fig. 6: (a) & (b) Dimensions of a Castellated Steel Beam

Fig. 7: Model of Solid web beam ISMB150

Fig. 8: Model of Castellated Steel Beam without stiffeners

Fig. 9: Model of Castellated Steel Beam with Diagonal Stiffeners

Fig. 10: Stress distribution of beam with solid web

Fig. 11: Stress distribution of castellated beam without stiffeners

Fig. 12: Stress distribution of castellated beam with Diagonal stiffeners
VI. EXPERIMENTAL INVESTIGATION

The specimen of length 1000 mm is placed on the test setup with simply supported end conditions and two point loads are applied at a distance of 330 mm from the edges and an LVDT is placed at the midpoint to calculate the maximum deflection. Load is applied at an increment of 4 KN and the corresponding midpoint/maximum deflection is recorded, the same procedure is repeated for all the three specimens. The ultimate load and the corresponding ultimate deflection is obtained for all the four cases.

Table 1: Analytical Results

<table>
<thead>
<tr>
<th>S. No</th>
<th>Specimen</th>
<th>Ultimate Load (KN)</th>
<th>Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solid Web Beam</td>
<td>94</td>
<td>9.73</td>
</tr>
<tr>
<td>2</td>
<td>Castellated Beam Without Stiffener</td>
<td>118</td>
<td>7.86</td>
</tr>
<tr>
<td>3</td>
<td>Castellated Beam with Diagonal Stiffeners</td>
<td>147</td>
<td>4.12</td>
</tr>
</tbody>
</table>

Table 2: Results Obtained from Experimental Investigations

<table>
<thead>
<tr>
<th>Load (KN)</th>
<th>ISMB 150</th>
<th>IC 225 (WOS)</th>
<th>IC 225 (WDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.35</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>20</td>
<td>0.90</td>
<td>0.21</td>
<td>0.25</td>
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VII. RESULTS AND DISCUSSIONS

Stress concentration is more near the opening leading to shear failure. Hence the webs are stiffened by providing diagonal stiffeners across the openings of the beam along the shear zone to reduce the stress concentration and to reduce the shear deformation.

When the castellated beam is subjected to vertical shear, complementary shear stresses are developed to satisfy equilibrium of the beam. As a consequence, the beam develops diagonal tension and diagonal compression. Consider a small element in equilibrium inside the solid portion of the web subjected to a shear stress $\tau$ (Fig.16).

Fig. 16: Load vs Deflection curves.

Fig. 17: Shear Panel

Fig. 18: Shear Force through Diagonal members (Truss Action)
The element is subjected to principal compression along the direction AC and principal tension along the direction BD. As the applied loading is gradually increased, $\tau$ in turn will increase and the beam will buckle along the direction of the compressive diagonal AC. The beam cannot take further increase in compressive stress. To overcome this, diagonal stiffeners are introduced on the web opening where shear is dominating and hence forces flow through diagonal stiffener (Fig 6.3). The shear force causes diagonal tension and compression in the web and hence the diagonal stiffeners are provided in the direction of diagonal tension and diagonal compression for the smooth flow of shear forces. The behaviour is very similar to a Pratt truss, in which the vertical members carry compression and the tension is carried by the diagonal.

Serviceability limit for beam = $L / 325 = 1000 / 325 = 3.07\text{mm}$

<table>
<thead>
<tr>
<th>Specimen Details</th>
<th>Max. Allowable Deflection (mm)</th>
<th>Serviceability Load (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISMB 150</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>IC 225 (WOS)</td>
<td>3.07</td>
<td>90</td>
</tr>
<tr>
<td>IC 225 (WDS)</td>
<td>115</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Maximum Allowable Deflection and their Corresponding Loads

VIII. CONCLUSION

- From the experimental and software analysis it was clear that steel beam with hexagonal openings show more load carrying capacity and lesser deflection as compared to solid beam and steel beam.
- If diagonal stiffeners are provided along the shear zone of web openings, deflection can further be reduced.
- The Serviceability load of IC 225 is observed to be 38.46% more than that of the ISMB150.
- The load bearing capacity of the castellated beam is further increased by 27.8% by providing diagonal stiffeners.

Hence it is concluded that, shear strength of castellated beam can be improved by introducing shear stiffeners along the shear zone.

REFERENCES

[9] Indian Standard code of practices for General construction in steel, IS 800-2007, third revision, bureau of Indian standards