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Finite Element Analysis of Castellated Steel Beam

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Abstract— ***Use of castellated beam for various structures rapidly gaining appeal. This is due to increased depth of section without any additional weight, high strength to weight ratio, their lower maintenance and painting cost. The principle advantage of castellated beam is increase in vertical bending stiffness, ease of service provision and attractive appearance. However one consequence of presence of web opening is the development of various local effects. In this paper steel I section was selected, castellated beams were fabricated with increase in depth of web openings. To analyze the behavior of castellated steel beams having an I-shaped cross-section, modeling is conducted using finite element software package ANSYS14. Analysis is carried out on beam with two point load and simply supported support condition. The deflection at centre of beam and study of various failure patterns are studied. The beams with increase in depth are then compared with each other and with parent section for various parameters and for serviceability criteria. From the finite element analysis results, it is concluded that, the Castellated steel beam behaves satisfactorily with regards to serviceability requirements up to a maximum web opening depth of 0.6h. Castellated beams have proved to be efficient for moderately loaded longer spans where the design is controlled by deflection***.

Index Terms- **Castellated Beam, Web Opening, Cellular Beam, Virendeel Mechanism, Plastic Hinges.**

I. INTRODUCTION

Engineers are constantly trying to improve the materials and practices of design and construction. One such improvement occurred in built-up structural members in the mid-1930, an engineer working in Argentina, Geoffrey Murray Boyd, is castellated beam. Castellated beams are such structural members, which are made by flame cutting a rolled beam along its centerline and then rejoining the two halves by welding so that the overall beam depth is increased by 50% for improved structural performance against bending. Since 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 minimum allowable deflection, the high strength properties of structural steel cannot always be utilized to best advantage. As a result several new methods aimed at increasing stiffness of steel member, without any increase in weight of steel required. Castellated beam is one of the best solutions.

The responsibility of a Structural Engineer lies in not merely designing the structure based on safety and serviceability considerations but he also has to consider the functional requirements based on the use to which the structure is intended. While designing a power plant structure or a multi-storied building, the traditional structural steel framing consists of beams and girders with solid webs. These hinder the provision of pipelines and air conditioning ducts, electrical wiring required for satisfactory functioning for which the structure is put up.

The re-routing of services (or increasing the floor height at the design stage for accommodating them) leads to additional cost and is generally unacceptable. The provision of beams with web openings has become an acceptable engineering practice, and eliminates the probability of a service engineer cutting holes subsequently in inappropriate locations. Beams with web openings can be competitive in such cases, even though other alternatives to solid web beams such as stub girders, trusses etc are available. This form of construction maintains a smaller construction depth with placement of services within the girder depth, at the most appropriate locations. The introduction of an opening in the web of the beam alters the stress distribution within the member and also influences its collapse behavior.

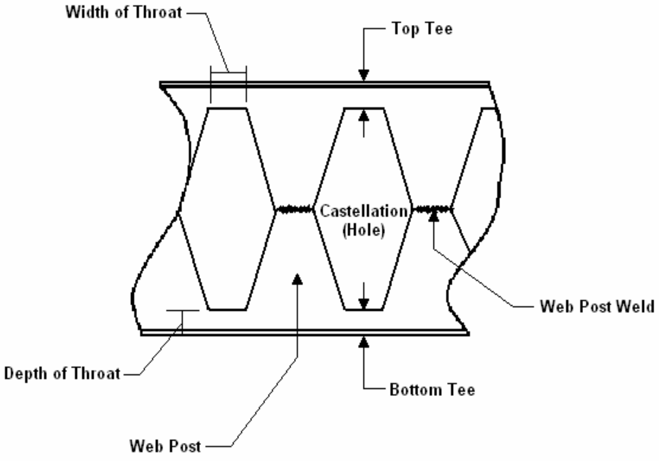


Fig.1 Terminology

Web Post: The cross-section of the castellated beam where the section is assumed to be a solid cross-section.

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.

II. FORMULATION OF RESEARCH OBJECTIVES

To achieve economy, castellated beam fabricated from its parent solid webbed 'I' section should have maximum possible depth. An available literature does not deal with the behavior of castellated beam with increase in depth of openings. This paper investigates the effect of web openings on various structural aspects of castellated beam, various modes of failures, and effect on deflection with increase in the depth of web openings are analyzed with the help of finite element analysis software ANSYS 14. Depth of beam increased in processes of castellation by 40, 50 and 60%, with hexagonal shaped openings of angle 60^0. Since the castellated beams are relatively slender and have web openings, which have an influence on their resistance. The major failure modes of castellated beams are web post buckling [1]-[2] and lateral-torsional buckling. The failure modes mainly depend on area of openings, location of opening, length of the tee-section above and below the opening, opening depth, type of opening and type of loading. The experimental testing on steel beams with web opening of various shapes and sizes was also carried out. Six potential failure modes [2] associated with castellated beams are-

A. Formation of Flexure Mechanism

This mode of failure can occur when a section is subject to pure bending. The span subjected to pure bending moment, the tee-sections above and below the holes yielded in a manner similar to that of a plain webbed beam, although the spread of yield towards the central axis was stopped by the presence of the holes by which time the two throat sections had become completely plastic in compression and in tension.

B. Lateral-Torsional Buckling

Non-composite castellated beams are more susceptible to lateral-torsional buckling than composite beams due to lack of lateral support to the compression flange [5]. The lateral torsional buckling behavior of castellated beams is similar to that of plain webbed beams. The holes had a significant influence on lateral-torsional buckling behavior.

C. Formation of Vierendeel Mechanism

Vierendeel bending is caused by the need to transfer the shear force across the opening to be consistent with the rate of change of bending moment, in the absence of local or overall instability, hexagonal castellated beams have two basic modes of plastic collapse, depending on the opening geometry. The failure is dependent on the presence of a shear force of high magnitude in the holes through span. It is found that all steel beams with large web openings of various shapes subjected to important parameter in assessing the structural behavior of perforated sections is the length of tee sections above and below the web opening which controls the magnitude of local Vierendeel moments acting on the tee section. [3].

D. Rupture of the Welded Joint in a Web Post

Rupture of a welded joint in a web-post can result when the width of the web-post or length of welded joint is small. This mode of failure is caused by the action of the horizontal shearing force in the web-post, which is needed to balance the shear forces applied at the points of contra flexure at the ends of the upper I-section.

E. Shear Bucking of a Web Post

The horizontal shear force in the web-post is associated with double curvature bending over the height of the post. In castellated beam one inclined edge of the opening will be stressed in tension, and the opposite edge in compression and buckling will cause a twisting effect of the web post along its height.

F. Compression Buckling of a Web Post

This mode of failure is similar to the crippling of the web in a plain webbed beam. It can occur in regions near concentrated loads or reaction forces. The web post may exhibit this mode of failure when it is subjected to same load condition introduced by secondary beam. [5]

III. ANALYSIS BY ANSYS

A. Model Geometry: Guidelines-

ISMB 150 was selected as a parent section for fabricating castellated beam. Following guidelines are followed for constructing model of castellated beam from parent section.

- The hole should be centrally placed in the web and eccentricity of the opening is avoided as far as possible.
- Stiffened openings are not always appropriate, unless they are located in low shear and low bending moment regions.
- Web opening should be away from the support by at least twice the beam depth, D or 10% of the span, whichever is greater.
- The best location for the opening is within the middle third of the span.
- Clear Spacing between the openings should not be less than beam depth D.
- The best location for opening is where the shear force is the lowest.
- The diameter of circular openings was generally restricted to 0.5D.
- Depth of rectangular openings should not be greater than 0.5D and the length not greater than 1.5D for un-stiffened openings.
- The clear spacing between such openings should be at least equal the longer dimension of the opening.
- The depth of the rectangular openings should not be greater than 0.6D and the length not greater than 2D for stiffened openings. The above rule regarding spacing applies.
- Corners of rectangular openings should be rounded.
- Point loads should not be applied at less than D from side of the adjacent opening.
- If stiffeners are provided at the openings, the length of the welds should be sufficient to develop the full strength of the stiffener.
- If above rules are followed ,the additional deflection due to each opening taken as 3% of the mid-span deflection of the beam without the opening.

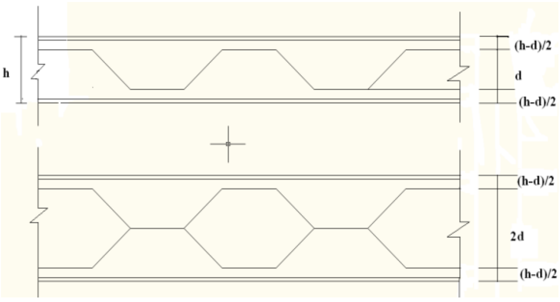


Fig.2 Mathematical Formation of Castellated Beam

B. ANSYS Analysis Procedure

With finite element modeling a three-dimensional (3D) finite element model is developed to simulate the behavior of castellated steel beams having an I-shaped cross-section. Modeling was done using finite element software package ANSYS 14. Zirakian and Showkati [2] and provided useful information in the form of failure loads, failure modes, load–lateral deflection curves and load–strain curves that could be used in developing finite element models. Geometrical details of analyzed beams are simulated using the four-node shell element. This element has five degrees of freedom at each node, two 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 $\nu = 0.3$, In this study, the effects of residual stresses and welding of two parts have not been considered [5]. Each I-shaped beam is characterized by its span L, flange width bf, flange thickness tf, depth of parent h, depth of castellated beam hc and web thickness tw. Web perforations were hexagonal in shape, with side (sh) and are uniformly spaced at distance S along the span of the beam. The size of the elements along the span of the beam is restricted not to exceed twice the size of the element across the flange. Several mesh configurations are attempted until the above-provided limitations are set after providing convergence of the predicted buckling load within reasonable execution time. Detailing of various beams as below:

For Ic 210 –

Span L =2000mm, hc=210mm, bf = 80 mm, tf = 7.6 mm, HW = 194.8 mm, tw = 8 mm

For Ic 225-

L =2000mm, hc=225mm, bf = 80 mm, tf = 7.6 mm, HW = 209.8 mm, tw = 8 mm

For Ic 240-

L =2000mm hc=240mm, bf = 80 mm, tf = 7.6 mm, hw = 224.8 mm, tw = 8 mm,

It should be noted that, although the thickness of the elements does not appear in the figure, it is used by ANSYS to generate the stiffness matrix of the modeled beam.

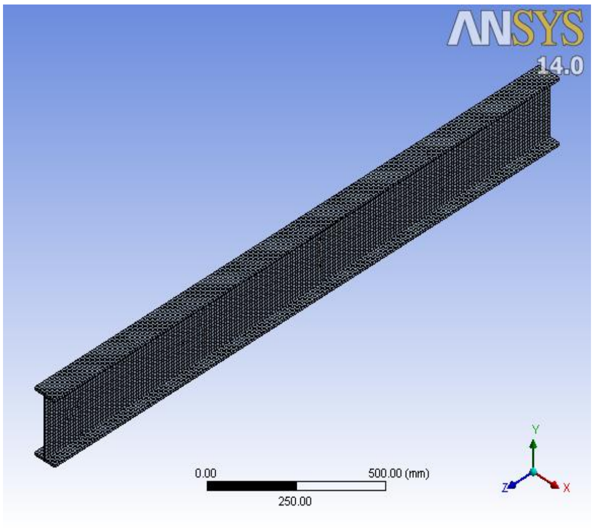


Fig.3 Typical Finite Element Mesh for a Castellated Beam

The beam geometry is defined using a Global Cartesian coordinate system with its origin located at the mid-height of the cross-section at the right end of the beam. As indicated in Fig.3, the depth of the beam is directed along the Y-axis while its longitudinal axis coincides with the Z-axis.

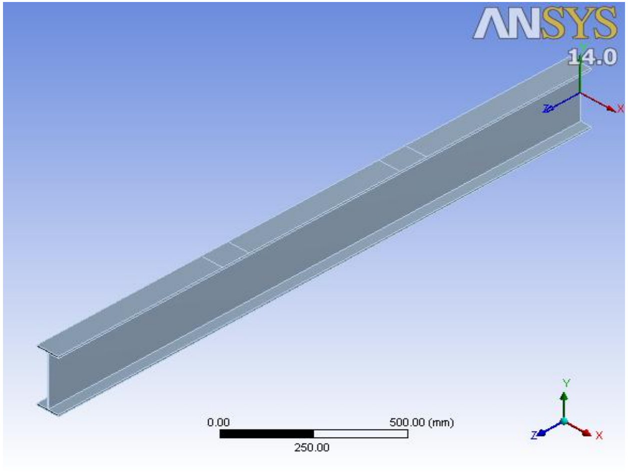


Fig.4 Position and Orientation

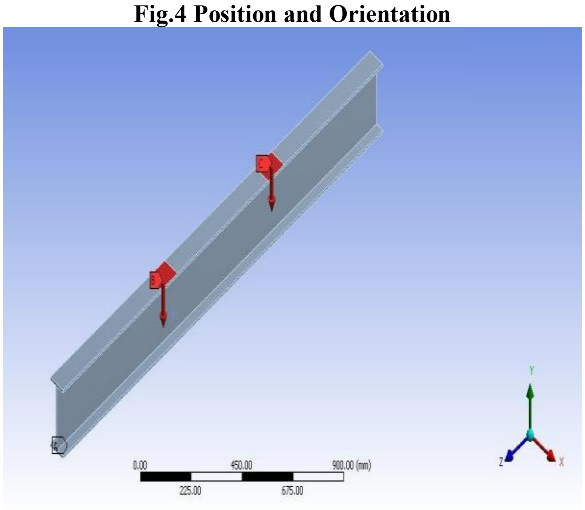


Fig.5 Position of force application for Ic 210

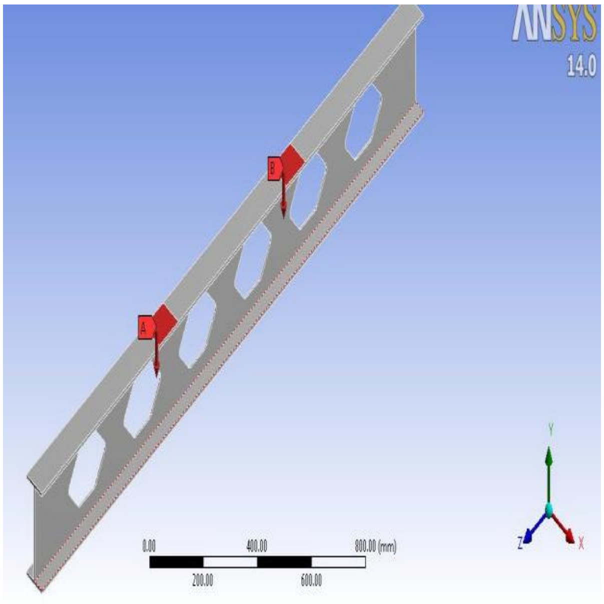


Fig.6 Position Of force application for Ic 210

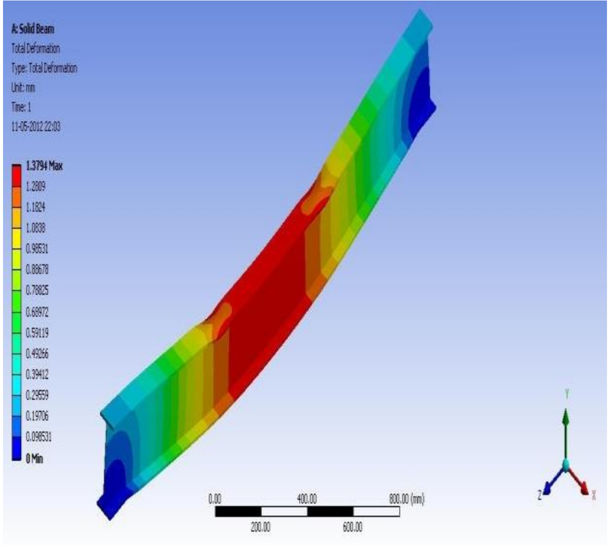


Fig.7 Total Deflection of ISMB 150

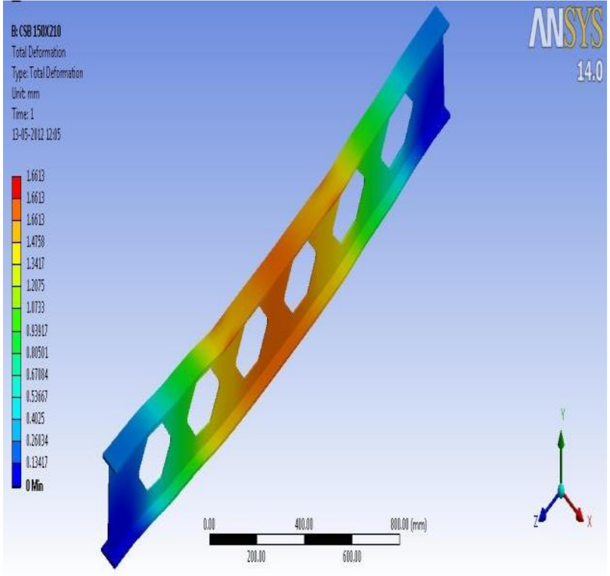


Fig.8 Total Deflection of Ic 210 mm

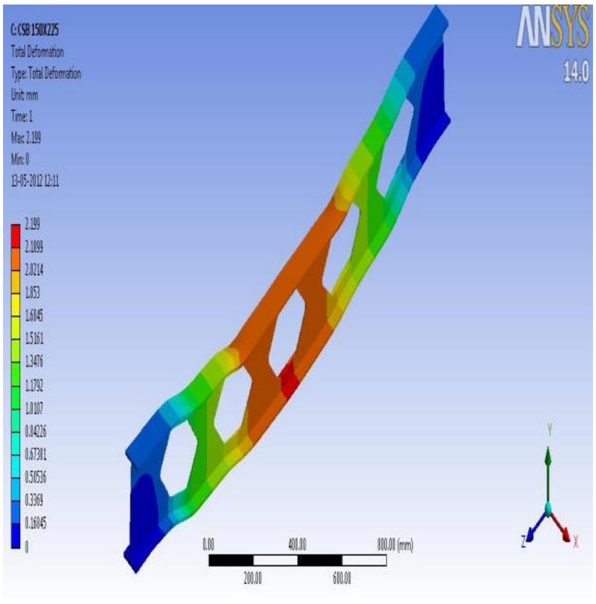


Fig.9 Total Deflection of Ic 225 mm

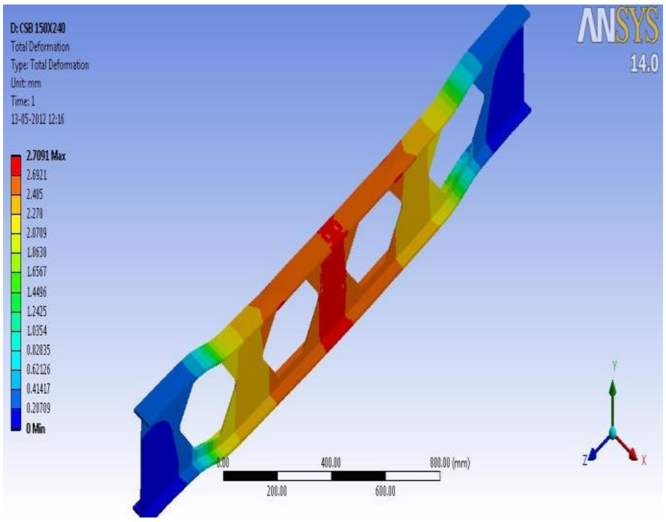


Fig. 10 Total deflection for Ic 240

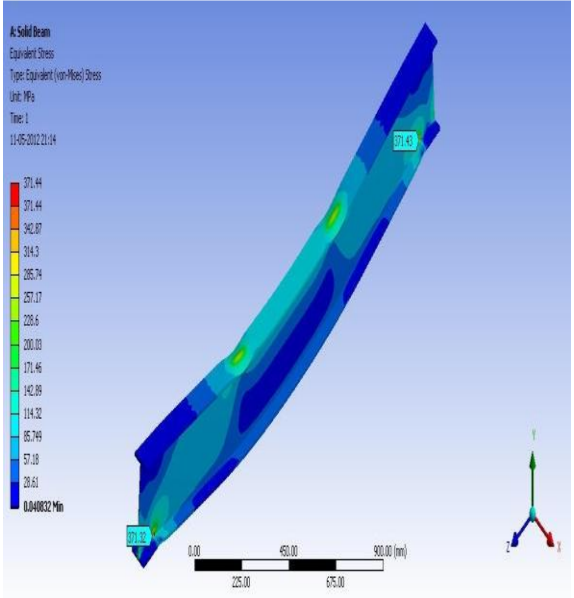


Fig.11 Maximum Stress of ISMB 150mm

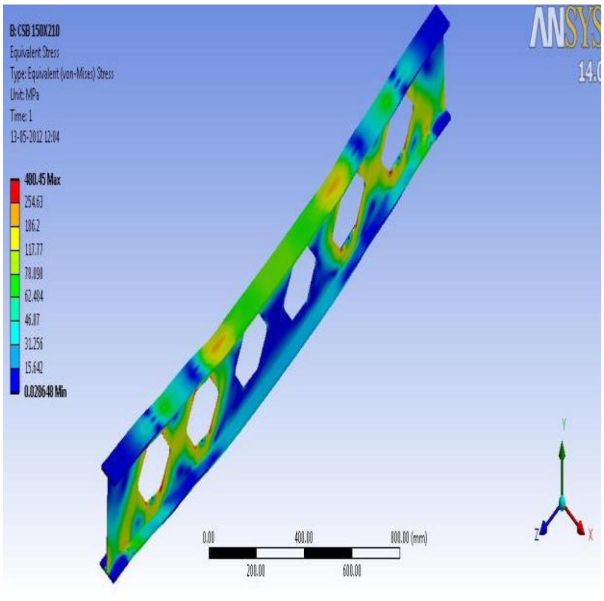


Fig.12 Maximum Stress of Ic 210mm

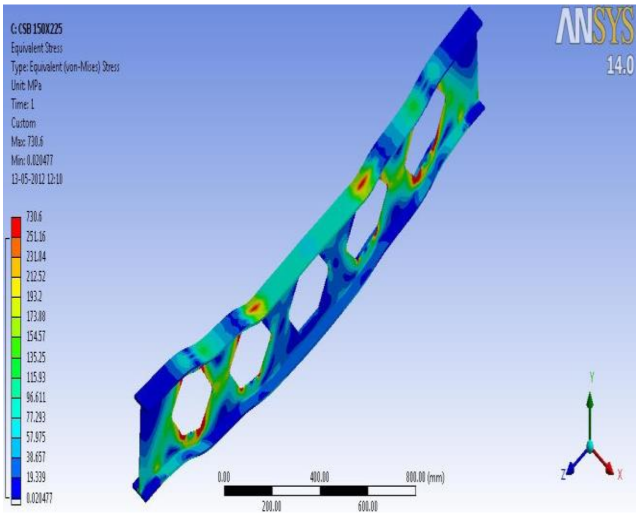


Fig.13 Maximum Stress of Ic 225mm

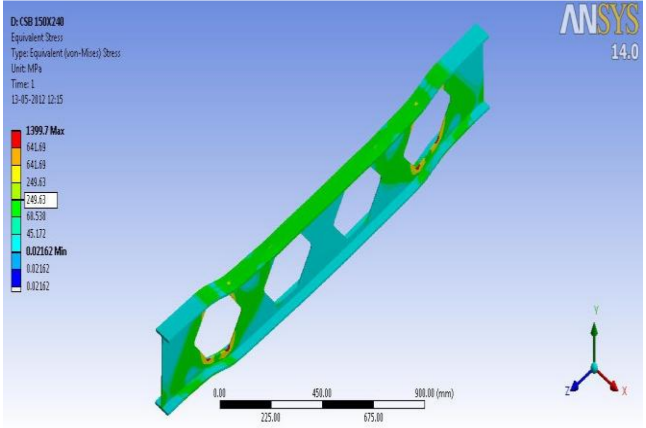
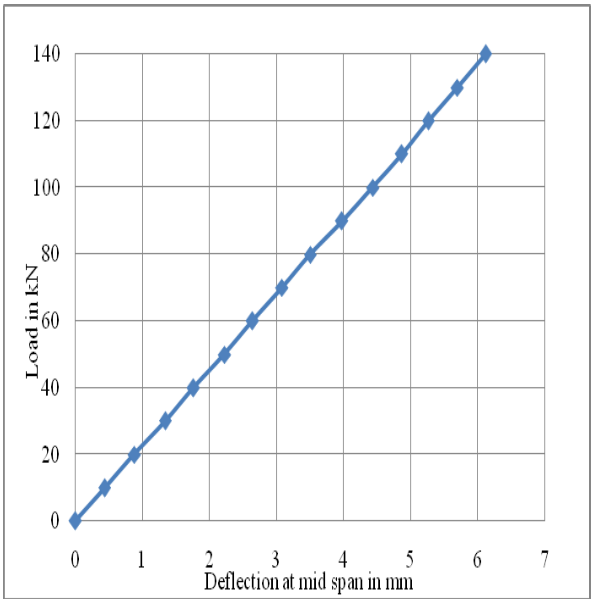


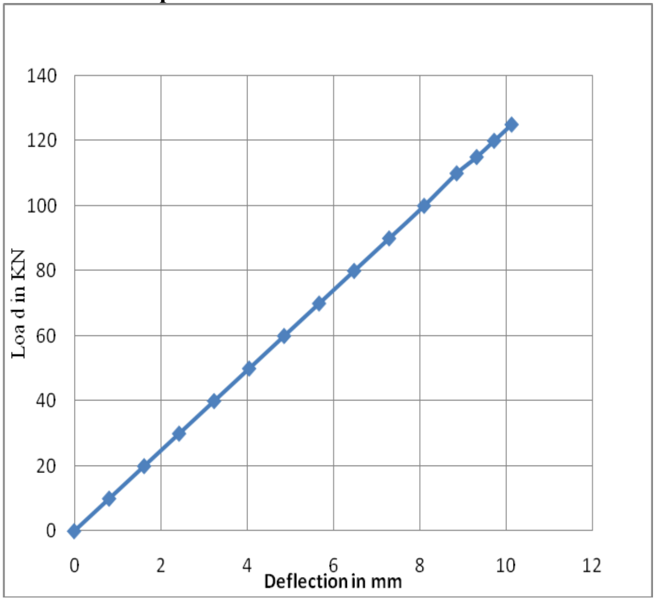
Fig.14 Maximum Stress of Ic 240mm

IV. RESULTS OF ANSYS ANALYSIS

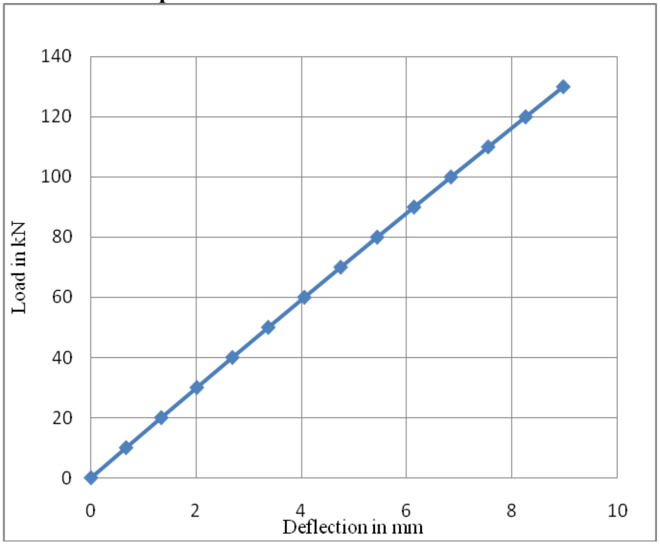
All Tables are shown in Appendix.



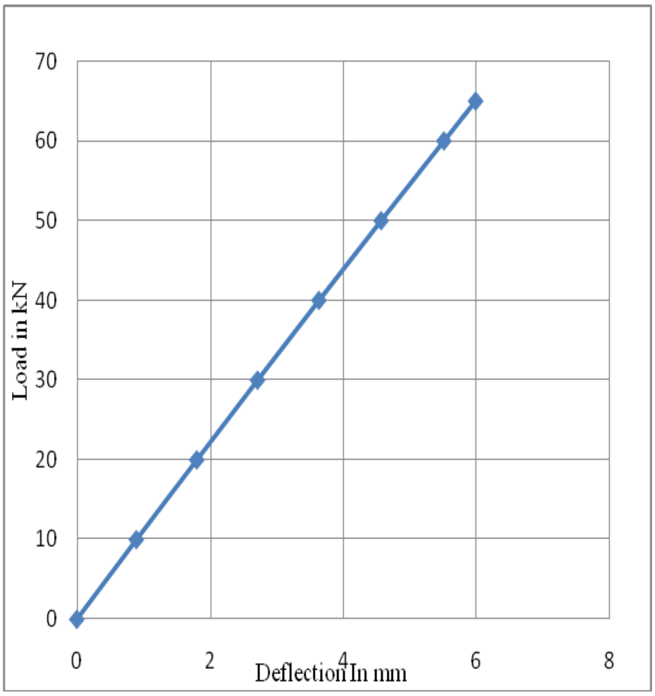
Graph.1Load v/s Deflection ISMB150



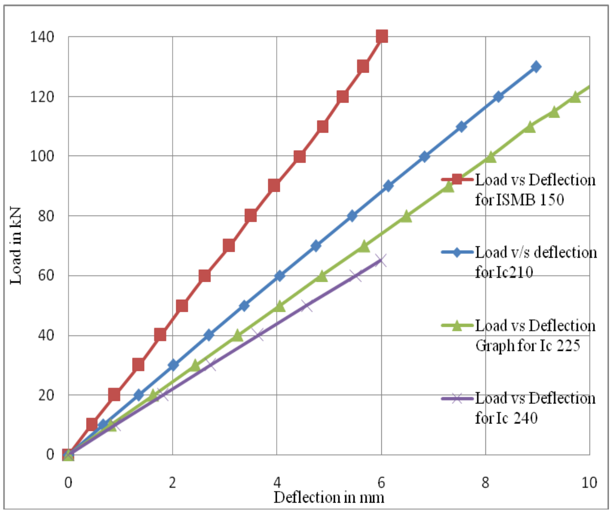
Graph.2 Load v/s Deflection for Ic210



Graph.3 Load v/s Deflection for Ic225



Graph.4 Load v/s Deflection for Ic240



Graph.5 Comparision of Ansys Results

The beams tested above cannot be compared directly among themselves because of different failure modes of beams.

Serviceability limit for beam= L/325

=1900/325

= 5.846 mm

V. CONCLUSION

From the finite element analysis results, it is concluded that, the Castellated steel beam behaves satisfactorily with regards to serviceability requirements up to a maximum web opening depth of 0.6h. Castellated beams have holes in its web, which lead to local effects in the beams. This causes the beams to fail in different local failure modes, which reduces their virgin load carrying capacity. Hence, it is irrational to compare the structural behavior of beams having different modes of failure, based only on strength criteria.

The finite element analysis effectively captured the different failure modes of all the beams. From this analysis, it was observed that as the depth of opening increases, stress concentrations increases at the hole corners (Vierendeel effect) and at load application point. The results also confirm that the flexural stiffness of castellated beams decrease as the depth of opening increases. So 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. It is conclude that the castellated beams are well accepted for industrial buildings, power plant and multistoried structures, where generally loads are less and spans are more with its economy and satisfactory serviceability performance.

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Appendix

Sr. No.	Load (kN)	Deflection (mm)
1	0	0
2	10	0.6648
3	20	1.3338
4	30	2.0085
5	40	2.6839
6	50	3.3652
7	60	4.0506
8	70	4.7402
9	80	5.4341
10	90	6.1325
11	100	6.8345
12	110	7.5412
13	120	8.2522

Sr.No.	Load (kN)	Deflection (mm)
1	0	0
2	10	0.8099
3	20	1.6199
4	30	2.4298
5	40	3.2397
6	50	4.0497
7	60	4.8596
8	70	5.6695
9	80	6.4795
10	90	7.2894
11	100	8.0993
12	110	8.8534
13	115	9.3143

Table I. Load and Deflections of ISMB 150
&
Table II.Load and Deflections of Ic=210

Sr. No.	Load (kN)	Deflection (mm)
1	0	0
2	10	0.43572
3	20	0.87945
4	30	1.3412
5	40	1.7549
6	50	2.1888
7	60	2.5782
8	70	3.0065
9	80	3.4618
10	90	3.8235
11	100	4.2372
12	110	4.651
13	120	5.0647

Table.III Load Vs Deflection for Ic 225
&
Table.IV Load v/s Deflection for Ic 240

Sr. No.	Load (kN)	Deflection (mm)
1	0	0
2	10	0.8934
3	20	1.8018
4	30	2.7130
5	40	3.6347
6	50	4.5686
7	60	5.5123
8	65	5.9880

Sr. No.	Beam	Deflection (mm)	Load by ANSYS (kN)	Local Mode Of Failure	Global Mode of failure
1	ISMB 150	5.84	135	Failure of compression flange	Lateral Torsional buckling
2	Ic 210		85	Failure of compression flange	Flexural buckling of Web
3	Ic 225		70	Failure of compression flange and Vierendeel effect	Web buckling
4	Ic 240		65	Vierendeel effect and Failure of compression flange	Flexural buckling of Web

Table V. Comparison of ANSYS Results for Serviceability Limit