Experimental and Analytical Investigations of Cellular Steel Beams

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Abstract – *Castellated beams became popular day by day as an efficient structural form in steel construction since their introduction. Their design and making process provides greater flexibility in beam proportioning for strength, depth, size and location of holes. The advantages of manufacturing these beams is to increase overall beam depth, the moment of inertia and section modulus, which results in greater strength and rigidity. Cellular beams are the castellated beams with circular openings. Cellular beams are used as primary or secondary floor beams in order to achieve long spans and service integration. They are also used as roof beams, and are the best solution for curved roof applications, combining weight savings with a low-cost manufacturing process. The purpose of the current research is to study optimum shape and size, stiffness and load carrying capacity under applied load and finite element analysis of non-composite castellated beams. The first part of the research program focuses on the comparison of experimental and analytical study to optimise the shape of openings and verify the accuracy of finite element analysis on ANSYS software. In the second part of the research, parametric study conducted to optimise the parameters effecting the structural performance of cellular beams by finite element analysis. The parameters adopted in this work are consistent with BS-5950.*

Key Words: **Castellated beams; Cellular beams; Spacing ratio; Opening ratio; Aspect ratio**

1. INTRODUCTION

Construction industry has been one of the leading fields among many others in the world. Structural engineering has a major role in the construction field which every day becoming more widespread and sophisticated. One of the main materials used by structural engineers is structural steel. The history of structural steel industry is over one hundred years old. As the technology of steel structures progress, more types of steel sections were produced to improve the structural steel's mechanical properties and also to obtain sections that allow usage for more aesthetic applications by satisfying the architectural needs. Perforated sections, such as, castellated, cellular and sinusoidal beams are good example to such newly developed sections. Castellated beam section with hexagonal opening was the first that developed in the past. The main aim in producing such sections was to increase their resistance against bending due to the increased height. This approach would also cause an increase in the moment of inertia leading to sections that better meet the serviceability and aesthetic requirement. Researchers and designers keep trying to develop these kinds of members with the aim of achieving steel sections with better mechanical properties, more economical and lower risks for failure. The smooth rounded edges of the openings in cellular beams resolved one of the main problems in castellated beams which is the sharp edges of the hexagonal opening. In most cases, these sharp edges caused some failure modes in the beam web due to accumulation of high shear stresses around the perforations.

2. EXPERIMENTAL PROGRAM

In the experimental part of the research, the ultimate load carrying capacities of steel castellated beams are tested in universal testing machine (UTM) of 1000kN capacity. IS MB 100 section is selected as the parent section for fabricating castellated beams. The tests have been carried out on three non-composite castellated steel beams. Circular, hexagon and rectangular shape openings used for the experimental program.

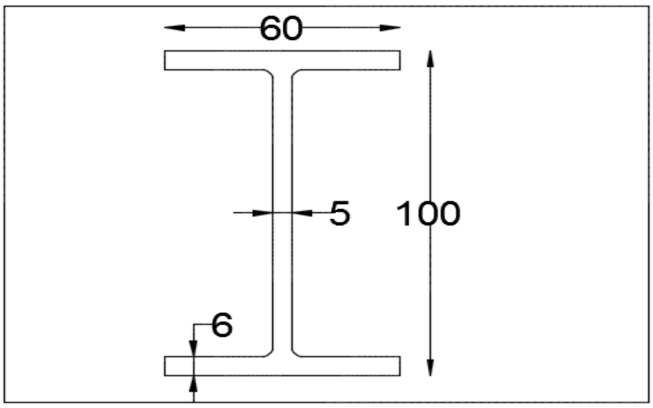
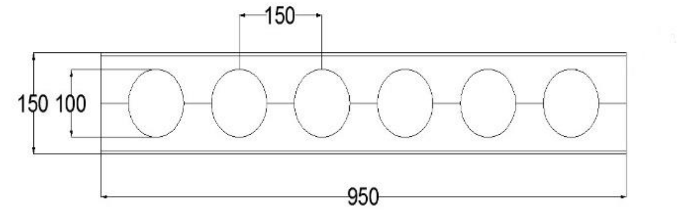


Fig -1: ISMB 100 dimensions in mm

2.1. Test setup

The tests were carried out on simply supported castellated beams with central concentrated load. The specimen was clamped at two ends. After fixing the specimens, a dial gauge is fixed at the middle of the beam to measure the mid span deflection for each load increment. For each beam, the adjustment of loading rod positions has been applied carefully. The purpose of this action is to prevent the eccentric loading.



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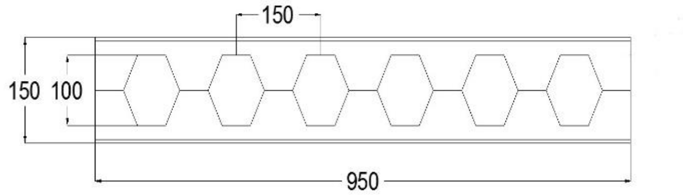

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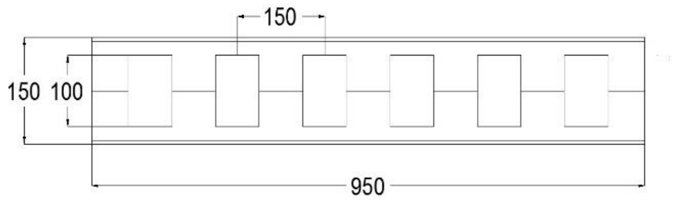

(c)

Fig -2: Dimensions of beams (a) Cellular (b) Hexagonal (c) Rectangular

2.2. Test procedure

During the tests, the load was applied in a step-by-step manner and, the applied load and the readings of dial gauge were monitored and consequently recorded at regular intervals. All specimens were loaded at its midpoint slowly until failure. As the load was increased the dial gauge needle started moving, and at the onset of failure there was a sudden large movement of the needle. The load corresponding to this point will be the failure load of the specimen.

(a)

(b)

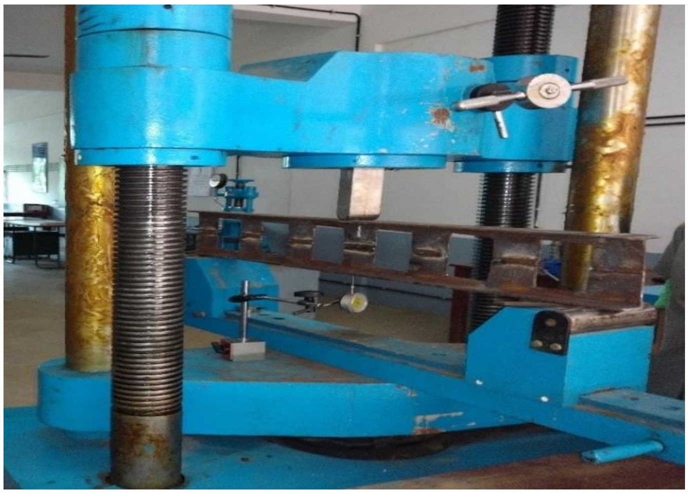

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Fig -3: Testing of steel beams (a) cellular (b) Hexagonal (c) Rectangular

3. FINITE ELEMENT METHOD

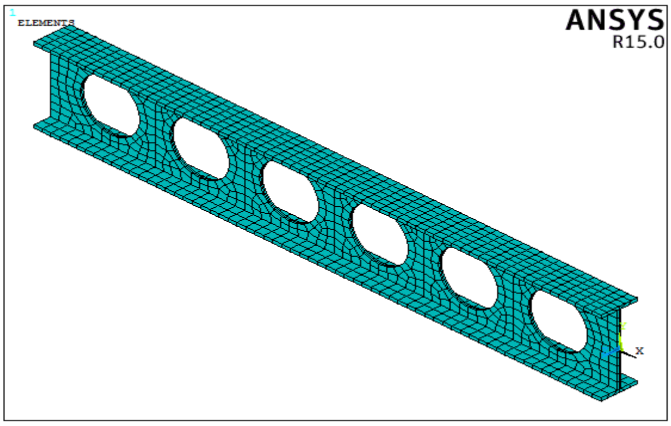
The finite element method (FEM) is a numerical technique for finding approximate solutions of partial differential equations as well as integral equations. The basic concept behind FEM is that a body or structure is divided into smaller elements of finite dimensions called finite elements. The original structure is then considered as an assemblage of these elements at a finite number of joints called nodes. ANSYS is a general purpose Finite Element Analysis program that solves a vast area of solid and structural mechanics problems in geometrically complicated regions.

3.1. Modelling

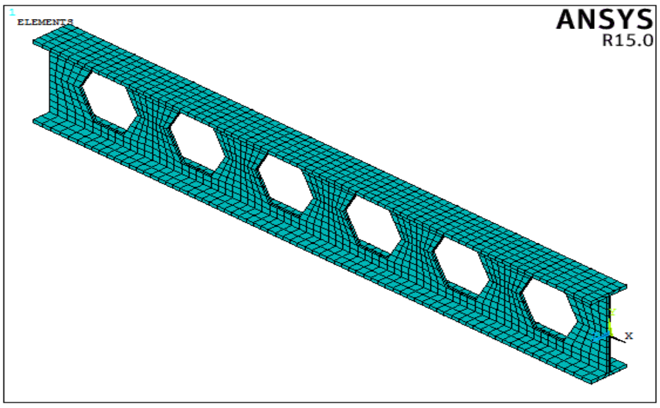
The castellated steel beams are modelled and analyzed in ANSYS software by finite element analysis. For steel structures SOLID 185 is the most appropriate element which specify the properties of steel. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. SOLID185 is used for 3-D modeling of solid structures. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. The material properties given are modulus of elasticity, Poisson's ratio and yield strength for the nonlinear analysis.

Table -1: Material properties of steel

Modulus of elasticity (Es)	200000 MPa
Poison's ratio(υ)	.3
Yield strength (fy)	250 Mpa



(a)



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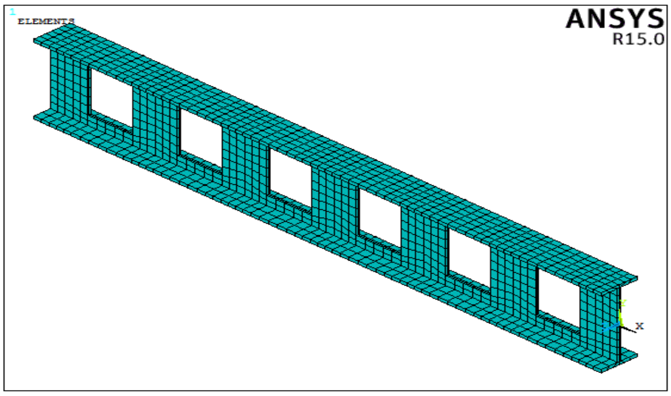

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Fig -4: Models of steel beam (a) cellular (b) Hexagonal (c) Rectangular

3.2. Analysis

Displacement boundary conditions are needed to constrain the model to get a unique solution. To achieve this, the translations at the nodes (UX, UY and UZ) are restrained in left end side in order to obtain a hinged joint and the translations at the nodes (UY, UZ) are restrained in the right side in order to obtain the roller joint. The force F, a gradually increasing load in the downward direction is applied at the center of the beam until failure.

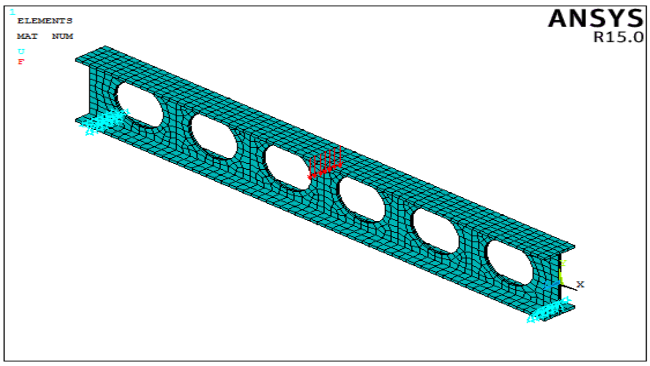


Fig -5: Load and boundary conditions on beam

4. PARAMETRIC STUDY

The optimisation of the parameters is important to make the use of cellular beams in to its best advantages. The parametric study is conducted for the parameters like spacing ratio (S/Do), opening ratio (D/Do) and aspect ratio (L/D) on the stiffness of cellular beam. The study is conducted as per Euro code specifications. ISMB 300 is also analysed with different aspect ratios. A standard rolled steel I beam is chosen from IS code which is ISMB 300. Two end fixed condition and uniformly distributed load is considered for the parametric study. Dimensions of the steel beam model are given below

Depth of the section = 300 mm
Width of flange, B = 140 mm
Thickness of flange, t_f = 13.1 mm
Thickness of web, t_w = 7.7 mm
Load intensity on each beam =100 kN/m^2

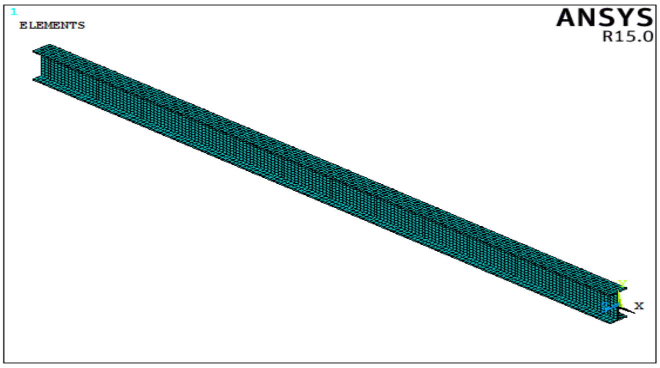


Fig -6: Standard I section

4.1 Specifications as per Euro code

The perforations made in the web affect the structural performance of the beam. Therefore, it is essential to study the effect of opening parameters to avoid failures of beam. The Euro code (BS-5950) gives the detail design guidelines for cellular beams. The limits of applicability web perforations are

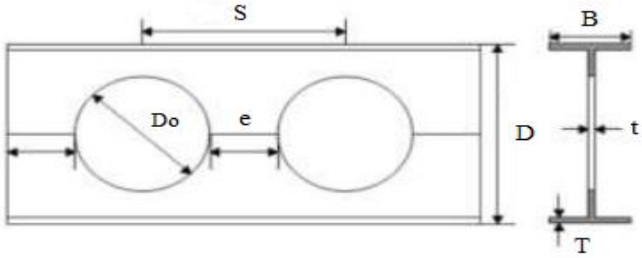


Fig -7: Geometric parameters of cellular beam

a) 1.08 < S/ Do < 1.5

b) 1.25 < D/ Do< 1.75

For this study the spacing ratio is varied from 1.2 to 1.5 and opening ratio varied from 1.25 to 1.75 with aspect ratio 5, 10 and 15. The below table shown the variation of parameters in each aspect ratio. Total 60 cellular beams are modelled and analysed and ISMB 300 is also analysed for 5, 10 and 15 aspect ratio.

Table-2: Parameters considered within each aspect ratio

Sl. No	D	S	Do	D/Do	S/Do
1	420	288	240	1.75	1.2
2	430	312	260	1.65	1.2
3	450	360	300	1.5	1.2
4	475	420	350	1.35	1.2
5	500	480	400	1.25	1.2
6	420	312	240	1.75	1.3
7	430	338	260	1.65	1.3
8	450	390	300	1.5	1.3
9	475	455	350	1.35	1.3
10	500	520	400	1.25	1.3
11	420	336	240	1.75	1.4
12	430	364	260	1.65	1.4
13	450	420	300	1.5	1.4
14	475	490	350	1.35	1.4
15	500	560	400	1.25	1.4
16	420	360	240	1.75	1.5
17	430	390	260	1.65	1.5
18	450	450	300	1.5	1.5
19	475	525	350	1.35	1.5
20	500	600	400	1.25	1.5

5. RESULTS AND DISCUSSIONS

The results of this study can be mainly included under 3 part such as the result of experiment study on castellated beams, the result of comparison of experiment and finite element analysis study and finally the result of parametric study of cellular beams under different spacing ratio, opening ratio and aspect ratio.

5.1. Experimental results

The graphs show the results of experimental analysis on the effect of shape of opening on the stiffness and ultimate load capacity of beam. The x axis of the graph represents load and y axis represents the deflection. From the experimental tests, it is observed that the cellular beam has more load carrying capacity and stiffness comparing the other shape of opening beams. The curved portion of the cellular beam reduced the stress concentration and prevent the failures than other two beams.

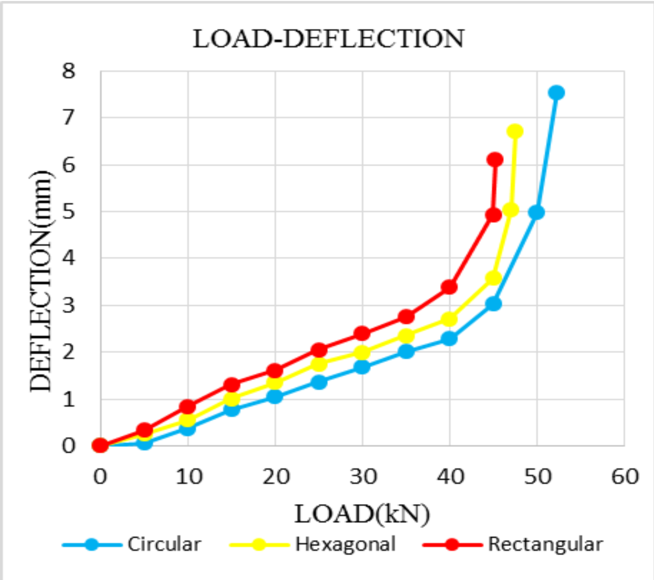


Chart-1: Load-deflection curve from experiment

5.2. Comparison of experimental and analytical results

To validate the obtained FEA results, comparison with experimental results are necessary. Here the results obtained from the experiment is compared with the results from finite element analysis in ANSYS. The deflected diagrams for each beams from the finite element analysis are also shown in figures. The maximum mid span deflection from finite element analysis is compared with the experiment.

Table-3: Comparison of cellular beam results

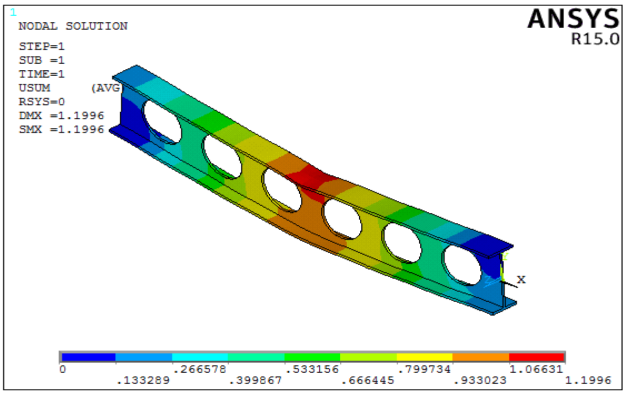
Load(kN)	Deflection(mm)	
	Analytical	Experiment
10	0.3962	0.37
20	0.7924	1.05
30	1.199	1.68
40	1.706	2.29
50	3.854	4.98
52.3	6.7339	7.55
53	7.896	---
54	10.1	---

Table -4: Comparison of hexagonal beam results

Load(kN)	Deflection(mm)	
	Analytical	Experiment
10	0.4136	0.56
20	0.8272	1.35
30	1.259	1.99
40	1.8501	2.71
47	3.202	5.05
47.5	4.219	6.71
49	5.561	---
50	9.266	---

Table -5: Comparison of rectangular beam results

Load(kN)	Deflection(mm)	
	Analytical	Experiment
10	0.5255	0.84
20	1.051	1.61
30	1.6309	2.39
40	2.583	3.38
45	4.382	4.93
45.2	4.603	6.11
46	5.6407	---
47	8.201	---



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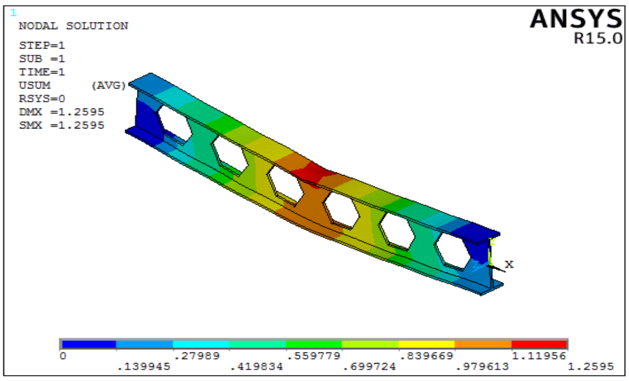

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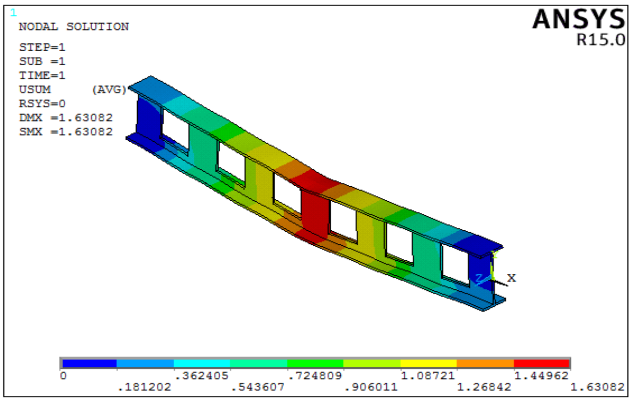

(c)

Fig -8: Deflected diagrams (a) Cellular (b) Hexagonal (c) Rectangular

From the comparison of results it is observed that the finite element analysis is good agreement with the experimental results. From both of the analysis, cellular beam have more load carrying capacity and stiffness.

5.3. Parametric Study results

The parametric study results are expressed as graphs. The x axis of the graph represents the opening ratio change as 1.25, 1.35, 1.5, 1.65 and 1.75 and y axis represents the deflection. In each graph the spacing ratio vary as 1.2, 1.3, 1.4 and 1.5 plots differently. The graphs are plotted separately for aspect ratio 5, 10 and 15. The graphs are starts from the deflection value of ISMB 300 in all the aspect ratio plots.

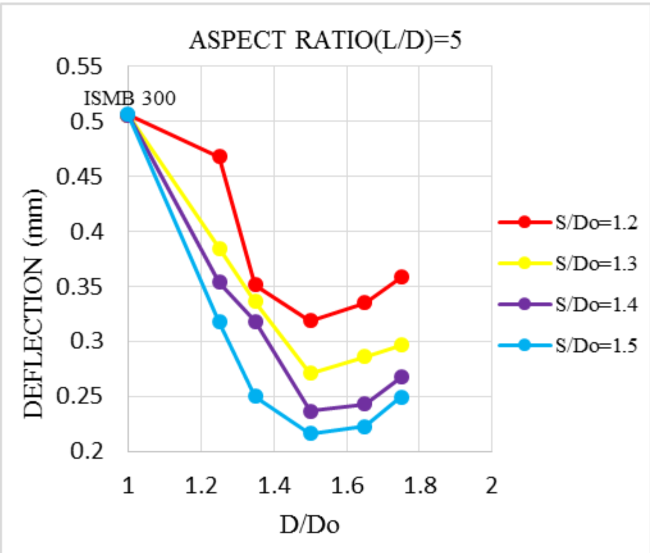

Chart-2: Opening ratio-deflection curve with aspect ratio 5

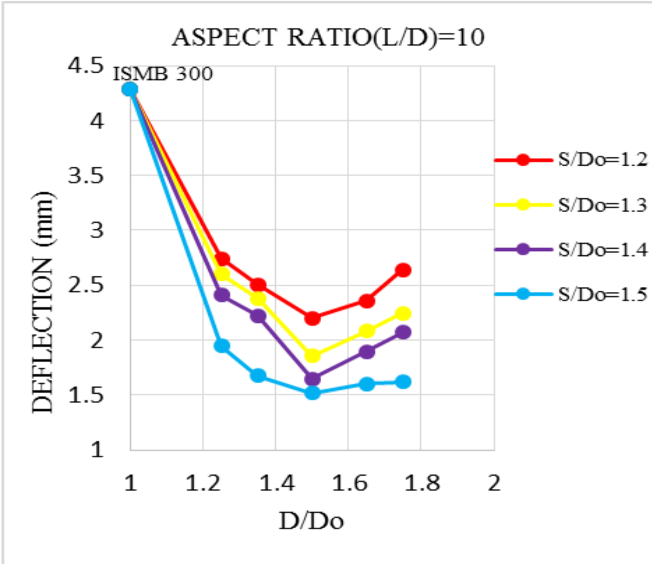

Chart-3: Opening ratio-deflection curve with aspect ratio 10

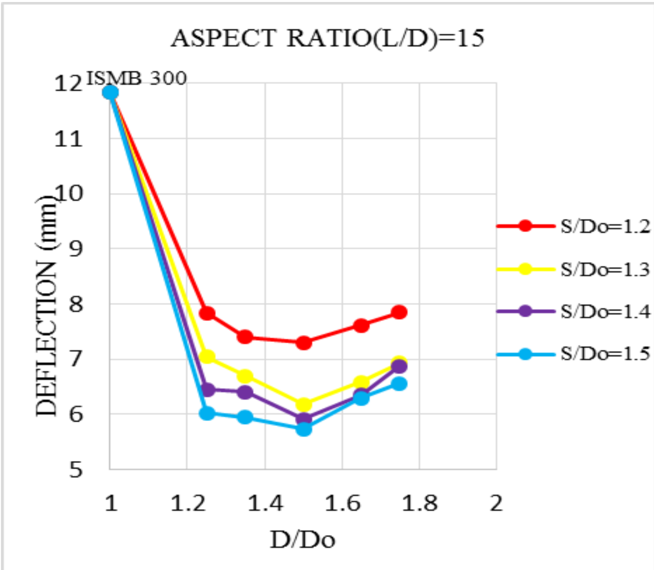

Chart-4: Opening ratio-deflection curve with aspect ratio 15

From the graphs it is clear that the cellular beams have less deflection compared with normal steel beam in all aspect ratios. The results obtained in parametric study implies that, the opening ratio 1.5 perform the better results. That is the deflection decreases from opening ratio 1.25 to 1.5 and then increases till 1.75. The increases of total depth of the beam decease the deflection up to 1.5. After that deflection increases because even though the depth of beam increases, the depth of opening also increases with that and its play the major role. In the case of spacing ratio, the deflection decreases with decrease of spacing ratio due to the increase of stability with spacing. Also the deflection increases with increase of aspect ratio.

6. CONCLUSIONS

In this study the structural behaviour of castellated steel beams with different parameters has been investigated. The following conclusions are obtained from the investigations.

1. Value of defection is minimum for circular web opening of same section of beam compared to other shapes of cuts. Also the load carrying capacity is high for cellular beams. Therefore it is concluded that cellular beam is best for structural applications.
2. Finite element analysis hold good agreement with the experiment results. FEA can accurately predict the load carrying capacity and deformation in line with the experimental study.
3. Cellular beam has less deflection due to increase of depth compared to its parent standard solid steel beam.
4. The parametric study of cellular beam shown that the deflection decreases with the increase of opening ratio up to 1.5 and then deflection increases.
5. The parametric study of cellular beam shown that the deflection decreases with increase of spacing ratio due to the increase of stability with spacing.
6. The deflection increases with increase of aspect ratio of cellular steel beams.

REFERENCES

[1] A. Bouchaïr, M.R. Soltani, and M. Mimoune (2012): *"Nonlinear FE analysis of the ultimate behavior of steel castellated beams",* Journal of Constructional Steel Research 70 (2012) 101–114, Science Direct

[2] Amr M.I. Sweedan (2011): *"Elastic lateral stability of I-shaped cellular steel beams"* Journal of Constructional Steel Research 67 (2011) 151–163,Science Direct

[3] Cedric D'Mello and Konstantinos Daniel Tsavdaridis(2012): *"Vierendeel Bending Study of Perforated Steel Beams with Various Novel Web Opening Shapes through Nonlinear Finite-Element Analyses"* Journal of Structural Engineering, Vol. 138, No. 10, October-2012, ASCE

[4] Ferhat Erdal and Mehmet Polat Saka (2013): *"Ultimate load carrying capacity of optimally designed steel cellular beams",* Journal of Constructional Steel Research 80 (2013) 355–368, Science Direct

[5] J. R. Yost, D. W. Dinehart, R. M. Hoffman, S. P. Gross and M. Callow (2013*):"Experimental and Analytical Investigation of Service-Load Stresses in Cellular Beams"*, Journal of Engineering Mechanics, Vol. 138, No. 8, August -2012, ASCE

[6] K. Jagadeesan and B. Anupriya (2014): *"Strength study on castellated beam"*, International Journal of Engineering Research & Technology (IJERT) Vol. 2 Issue 12, August- 2014

[7] K.F. Chung, C.H. Liu and A.C.H. Ko (2003): *"Steel beams with large web openings of various shapes and sizes"*, Journal of Constructional Steel Research 59, February 2003, 1177–1200, Science Direct

[8] Mara Junus, Parung Herman, Tanijay Jaonie and D jamaluddin Rudy (2014): *"Behavior of Castellated Beam Column Due to Cyclic Loads"*, International Conference on Advances in Civil and Structural Engineering, Research Gate, Institute of Research Engineers, USA, December 2014

[9] Oliver Hechler, Christian Muller (2006): *"Investigations on beams with multiple regular openings"* Composite Construction in Steel and Concrete, ASCE

[10] P.D. Kumbhar and A.M. Jamadar (2015): *"Optimization of opening size for castellated beam with sinusoidal openings"*, International journal of optimization in civil engineering, June 2015 5(3):301-313

[11] Puchpor P.D and Deshpande N, V (2014): *"Analysis and design of cellular beam and its verification"*, International conference of applied computing, IERI Procedia 7 (2014) 120 – 127, Science Direct

[12] R. P. Smoke, and J. R. Yost (2010): *"Seismic Performance of Connections for Cellular Beams in Steel Moment Frames*", Structures Congress, ASCE

[13] R. R. Jichkar, N. S. Arukia and P. D. Pachpor (2014): "*Analysis of Steel Beam with Web Openings Subjected to Buckling Load*",International Journal of Engineering Research and Applications, Vol. 4, Issue 5, May 2014, pp.185-188

[14] Samadhan G. Morkhade and Laxmikant M. Gupta (2015): "*An experimental and parametric study on steel beams with web openings*" International journal of advanced structural engineering, Springer, July 2015 7:249–260

[15] Walid Zaarour and Richard Redwood(1996): "*Web buckling in thin webbed castellated beams*", Journal of structural engineering, August 1996.122:860-866,ASCE