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Estimation of Deflections in Cantilever and Fixed Castellated Beams with Hexagonal, Square and Circular Openings

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ABSTRACT

The majority of existing literature on castellated beams focuses on simply supported boundary conditions. But studies on cantilever and fixed boundary condition are limited in the literature. Therefore the present study provides a new experimental solution for bending of cantilever and fixed castellated beams. The experimental investigation on castellated beams with hexagonal, circular and square openings is carried out for cantilever and fixed end conditions and compared with normal beam without opening. All the beams are tested under universal testing machine and subjected to central point load. Experimental results are obtained for maximum deflections and transverse load carrying capacity and validated numerically by using finite element method. ANSYS 14.0 version is used for the finite element analysis. Finally, it is concluded that the present study will serve as a benchmark study for cantilever and fixed castellated beams.

1. INTRODUCTION

A solid web steel beam with perforation (openings) is called as a castellated beam (CB). Use of CB for various structures is increasing rapidly due to its advanced structural properties and easy construction. Also in CB, depth of the section is increased without any addition of weight, which ultimately increases moment of inertia and the load carrying capacity. The CB has less shear capacity due to effect of stress concentration at the web openings. Therefore, it is recommended to provide openings/perforations closer to neutral axis where the stresses are almost zero. Chung et al. [1] and Liu and Chung [2] presented Vierendeel mechanism in steel beams with web openings based on analytical and numerical approaches. Zirakian and Showkati [3] and Zirakian [4] performed an experimental investigation on simply supported CB subjected to central concentrated load. Many researchers have presented finite element analysis on castellated beams with and without openings such as Mohebkhah [5], Mohebkhah and Showkati [6], Wang and Chung [7], El-Sawy et al. [8], Gholizadeh et al. [9], Sweedan [10], Ellobody [11], Wakchaure and Sagade [12], Soltani et al. [13], Wong and Burgess [14], Erdal and Saka [15], Jamadar and Kumbhar [16], Wang et al. [17], Elsawaf and Hassan [18], Tsavdaridis and Papadopoulos [19], Zhou et al. [20] etc.

Harte and Baylor [21] and, Baylor and Harte [22] presented the structural behaviour of timber joists with hexagonal openings in its webs. Gandomi et al. [23] used Gene expression programming to develop a model to predict the load capacity of castellated steel beams. Erdal et al. [24] developed the design techniques to optimize solutions of three different types of beams. Durif and Bouchair [25] studied CBs with sinusoidal openings by both experimentally as well as numerically. Tsavdaridis and D'Mello [26] investigated buckling behaviour of the web in CBs with innovative shapes of opening. Showkati et al. [27] have tested simply supported CBs subjected to pure bending. Durif et al. [28] investigated behaviour of CBs with sinusoidal openings and compared with circular openings. There are some other studies available in the literature on bending and buckling behaviour of castellated beams such as Abidin and Izzuddin [29], Yuan et al. [30], Sonck et al. [31], Sorkhabi et al. [32], Wang et al. [33, 34], Ellobody and Young [35], Tsavdaridis et al. [36], Sonck and Belis [37, 38], Wang et al. [39], Najafi and Wang [40], Grilo et al. [41], Zaher et al. [42] etc.

In the present study, three groups of castellated steel beam are analyzed to show the effect of opening shape on the web post buckling behavior. The experimental investigation on castellated beams with hexagon, circle and square shapes of openings is carried out for cantilever and fixed end conditions and compared with normal beam without opening. Both the beams are tested under universal testing machine and subjected to central point load. Experimental results are obtained for critical buckling loads and validated numerically by using finite element method. ANSYS 14.0 version is used for the finite element analysis. Finally, it is concluded that the present study will serve as a benchmark study for cantilever and fixed castellated beams.

2. CASTELLATED BEAMS UNDER CONSIDERATION

Web post, castellation, throat width, throat depth, top and bottom tee etc. are the important terminologies used in the experimental work presented in this study. Figure 1 shows these terminologies for better understanding.

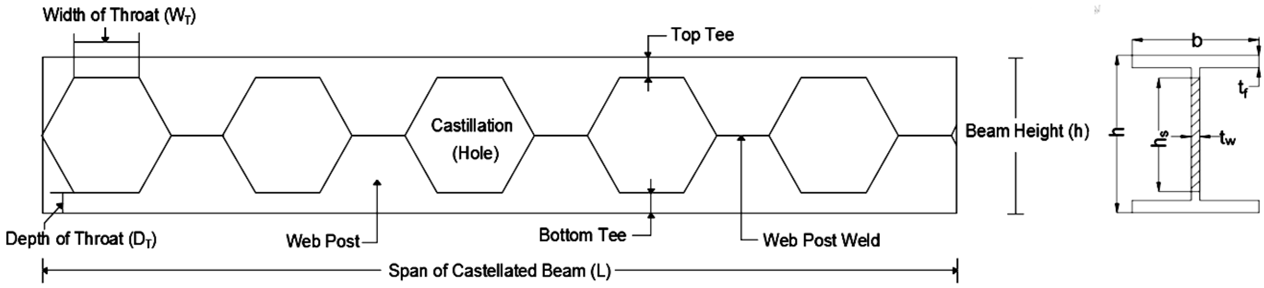


Figure 1. Terminologies of castellated beam with hexagonal opening

2.1 Fabrication of castellated beam under consideration

In the present study castellated beams are fabricated in following steps also shown in Figure 2.

Step 1: Firstly, 12 pieces of I-section having length 1m each are taken. Three shapes of web opening are chosen (hexagonal, square, circular). Hence, 3 pieces are used for each opening and 3 pieces are used for normal beam without opening.

Step 2: Then the cutting alignments are marked to each of the three pieces of hexagonal, square, circular openings.

Step 3: Then by using a gas cutter, all nine I-sections are cut in pre-determined cutting alignments.

Step 4: Two separated parts in step 3 are then welded face-to-face to get the castellated beams of required opening shapes.

Step 5: Finally, the un-aligned parts are filled by welding plates at the corner to make the stability.

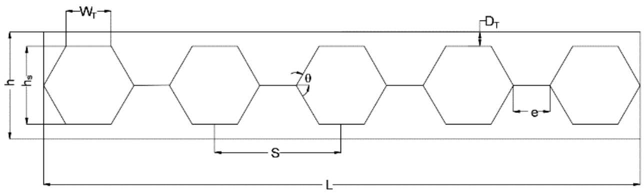


Figure 2. Design of castellated beams with hexagonal opening

2.2 Design of castellated beams

In the present study, three types of castellated beams are considered to provide a new experimental solution for bending analysis of cantilever and fixed boundary conditions.

2.2.1 Hexagonal opening

Figure 3 shows castellated beam with hexagonal opening. The angle of cut is selected to be in between 45° to 65°. Following are the parameters considered for this beam in the present study.

1. Overall Height (h)- 175mm
2. Height of perforation (h_s) -112mm
3. Total span of beam (L) - 1130mm
4. Width of throat (W_T) - 90mm
5. Spacing between two perforation (S) - 264mm
6. Angle of cut (θ) - 55°
7. Depth of throat (D_T) - 31.5mm
8. Distance between two perforation (e) - 65mm

Figure 3. Fabrication of castellated beams

2.2.2 Square opening

Figure 4 shows castellated beam with square opening. Following are the parameters considered for this beam in the present study.

1. Overall Height (h)- 153mm
2. Height of perforation (h_s)- 60mm
3. Total span of beam(L)- 1100mm
4. Width of throat (W_T)- 60mm
5. Spacing between two perforation (S)- 120mm
6. Depth of throat (D_T)- 46.5mm
7. Distance between two perforation (e)- 60mm

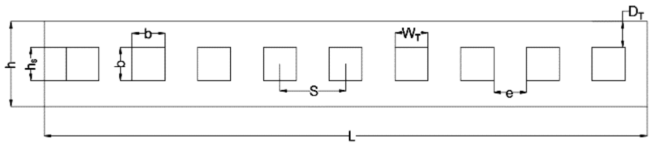


Figure 4. Design of castellated beams with square opening

2.2.3 Circular opening

Figure 5 shows castellated beam with circular opening. Following are the parameters considered for this beam in the present study.

1. Overall Height (h)- 180mm
2. Height of perforation (h_s)- 120mm
3. Total span of beam (L)- 1100mm
4. Width of throat (W_T)- 120mm
5. Spacing Between two perforation (S)- 152mm
6. Depth of throat (D_T)- 30mm.
7. Diameter of perforation ($ø$)- 120mm
8. Distance between two perforation (e)- 40mm

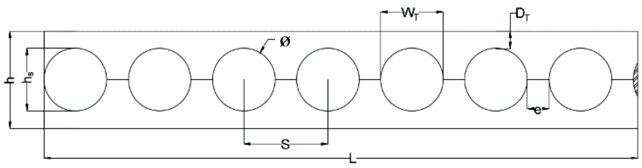


Figure 5. Design of castellated beams with circular opening

3. FABRICATION OF FIXED SUPPORT ASSEMBLY

In this study, an experimental solution for bending analysis of cantilever and fixed castellated beams is provided. Since in Universal Testing Machine (UTM) only tests on simply supported beams are possible, for the cantilever and fixed boundary conditions a new support assembly is developed by the authors. When this assembly is provided on both ends of the beams, the beam is called fixed beam whereas when only one end is supported by this assembly and other is free it is called as cantilever beam. Figure 6 shows assembly of fixed support. The procedure for preparing fixed support assembly is given below:

Figure 6. Fixed support testing assembly

Bottom plate is of size 165mm x 230mm. This bottom plate will be connected to movable cross head of a UTM. Castellated beam is resting on upper plate of size 165mm x 170mm. Stud of diameter 16 mm is used. Stud is made up of steel material of type E81. Studs are provided at the four corners of the upper and bottom plates. Total length of the stud is 500 mm out of which 350 mm from top is threaded. Pass the steel plate through stud and tight it by using rubber pad and then lock the castellated I-Section by steel plates and rubber pad using four bolts.

4. EXPERIMENTAL INVESTIGATION

4.1 Testing on castellated cantilever beams

Table 1. Deflection at center and free end of the castellated cantilever beams without and with web openings

Load (kN)	Deflection (mm)							
	Normal beam		Hexagonal opening		Square opening		Circular opening	
	Center	Free end	Center	Free end	Center	Free end	Center	Free end
10	0.132	1.245	0.027	0.232	0.093	0.789	0.055	0.412
20	0.265	2.490	0.053	0.465	0.169	1.435	0.109	0.824
30	0.397	3.735	0.159	1.394	0.254	2.152	0.164	1.237
40	0.530	4.979	0.212	1.859	0.339	2.869	0.219	1.649
50	0.662	6.224	0.266	2.324	0.423	3.587	0.273	2.061
60	0.795	7.469	0.319	2.788	0.508	4.304	0.328	2.473
70	0.927	8.714	0.372	3.253	0.593	5.021	0.383	2.885
80	1.059	9.959	0.425	3.718	0.677	5.739	0.437	3.298
90	1.192	11.204	0.478	4.182	0.762	6.456	0.492	3.710
100	1.324	12.448	0.531	4.647	0.847	7.173	0.547	4.122
110	1.457	13.693	---	---	0.931	7.891	0.601	4.534
120	---	---	---	---	1.016	8.608	0.656	4.947

Table 1 shows numerical values of deflection in cantilever normal and castellated beams subjected to central point load. Deflection is measured at two locations i.e. center and free end. Comparison of castellated beams with web opening is done with normal beam of I-section without opening. For experimental investigation, overall height of the normal beam is taken as h = 125 mm and length is taken as L = 1100 mm. Examination of Table 1 reveals that the central as well as free end deflections are minimum in castellated beam with hexagonal opening whereas those are maximum in normal beam without opening. Deflections for CBs with hexagon and circular shape of openings are more or less same. Figure 7 shows bending of flange and buckling of web in normal I-section beam without opening subjected to central point load. Variation of deflection with respect to load in cantilever normal beam is shown in Figure 8. Figures 10-12 show bending of flange and buckling of web in castellated beams with hexagonal, square and circular openings whereas Figures 13-15 show variation of deflection with respect to load in castellated beams.

Figure 7. Lateral torsional buckling and bending of cantilever normal beam (without opening)

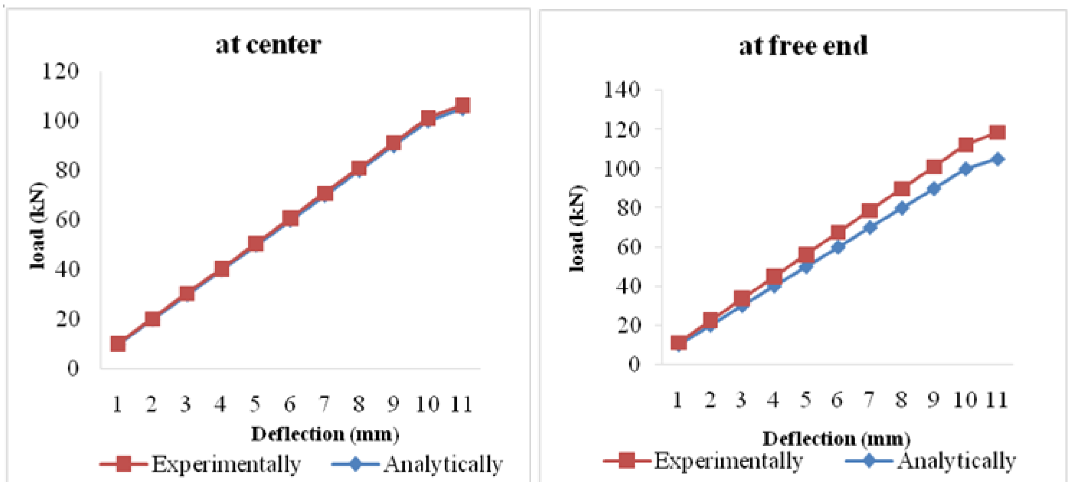


Figure 8. Load vs deflection curve in cantilever normal beam

Figure 9. Lateral torsional buckling and bending in castellated cantilever beam with hexagonal opening

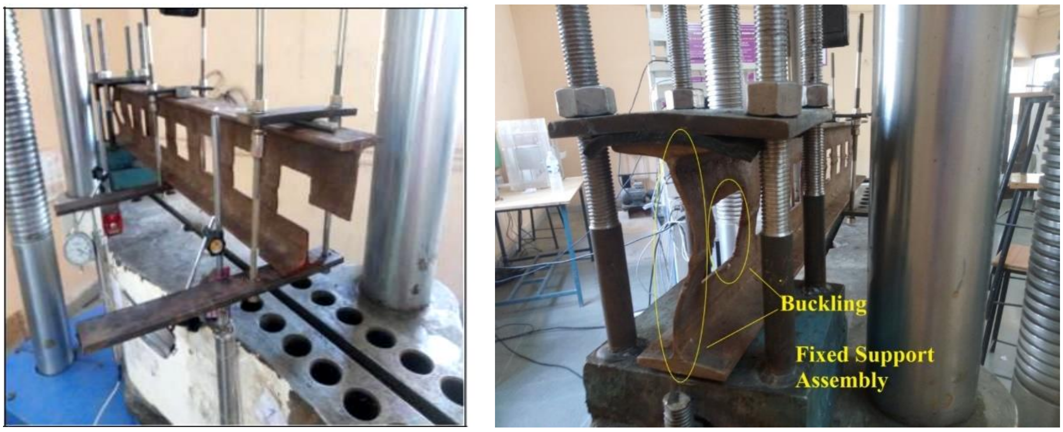


Figure 10. Lateral torsional buckling and bending in castellated cantilever beam with square opening

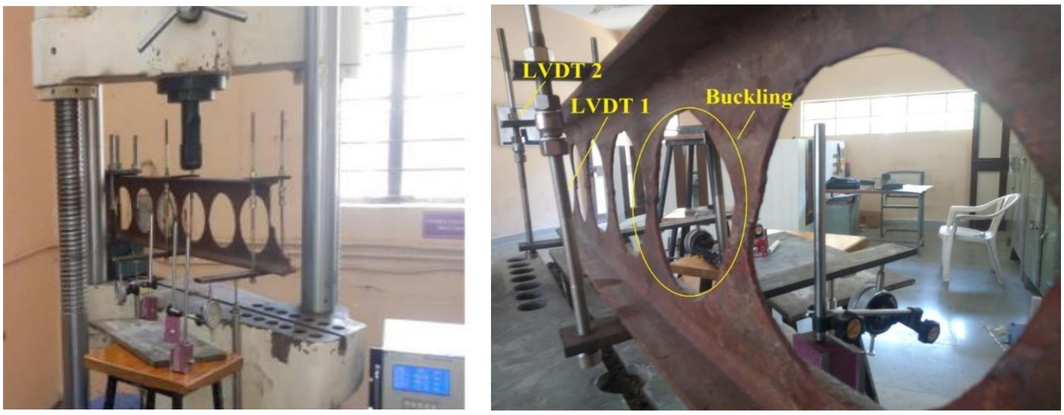


Figure 11. Lateral torsional buckling and bending in castellated cantilever beam with circular opening

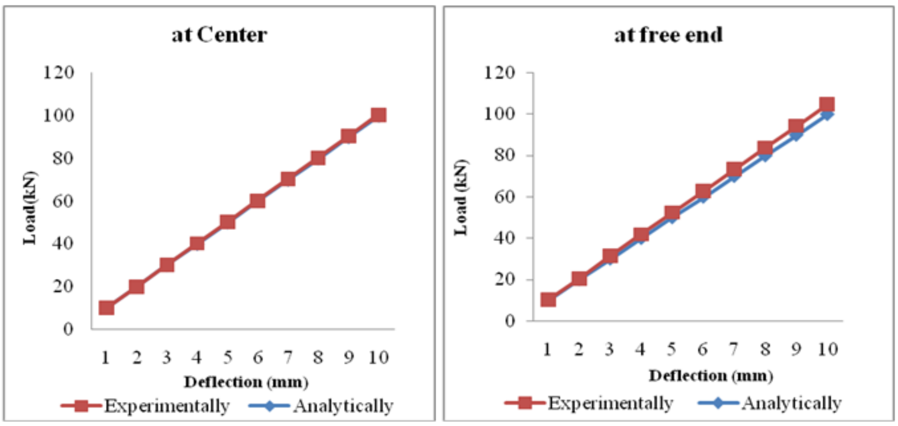


Figure 12. Load vs deflection curve in castellated cantilever beam with hexagonal opening

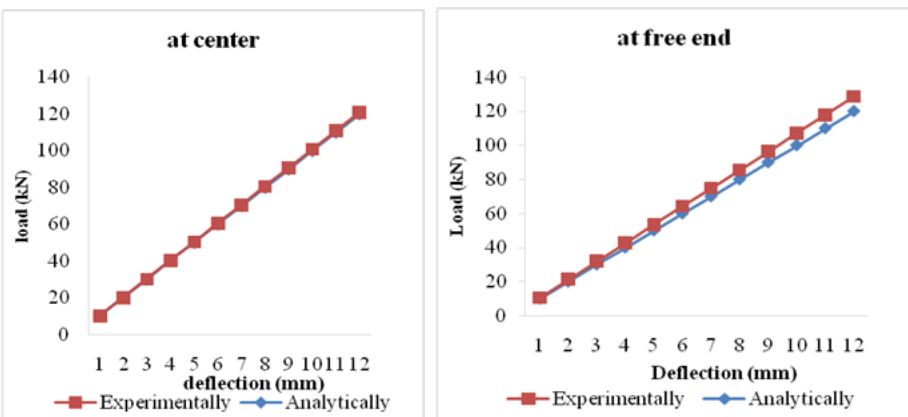


Figure 13. Load vs deflection curve in castellated cantilever beam with square opening

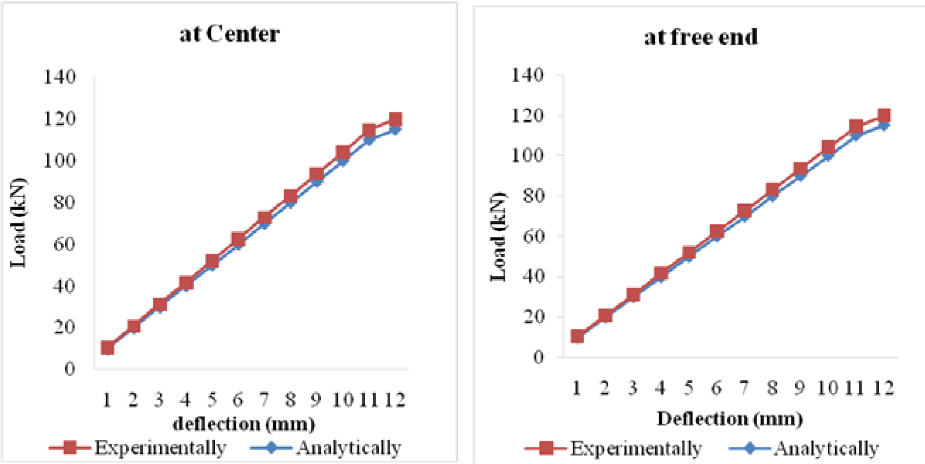


Figure 14. Load vs deflection curve in castellated cantilever beam with circular opening

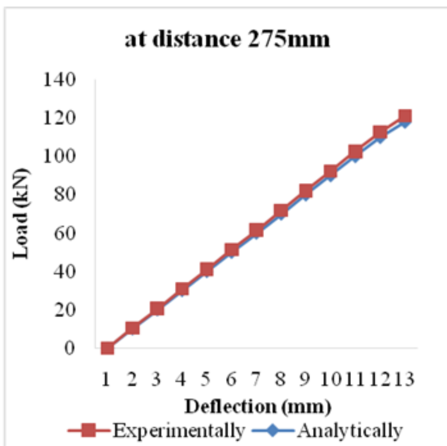
4.2 Testing on castellated fixed beams

Table 2 shows numerical values of deflection in castellated fixed beams subjected to central point load. Deflection is measured at two locations i.e. center and 275 mm from fixed end. In this study also comparison of castellated beams is made with normal beam of same dimensions (h = 125 mm, L = 1100 mm). From Table 2 it is observed that minimum deflection is observed in castellated beams (1.47 mm) with hexagonal opening whereas maximum deflection is observed in normal beam (4.40 mm) without opening. Maximum deflections in castellated beams with square and circular openings are 2.81 mm and 1.82 mm respectively. Figure 15 shows bending and buckling behaviour of normal fixed beam without opening subjected to central point load. Variation of deflection with respect to load in fixed normal beam is shown in Figure 16. Figures 17-19 show bending and torsional buckling of castellated beams with hexagonal, square and circular openings whereas Figures 20-22 show variation of deflection with respect to load in castellated beams.

Table 2. Deflections in castellated fixed beams without and with web openings

Load (kN)	**Deflection (mm)**							
	Normal beam		Hexagonal opening		Square opening		Circular opening	
	at 275 mm	at Center	at 275 mm	at Center	at 275 mm	at Center	at 275 mm	at Center
10	0.23	0.37	0.09	0.15	0.16	0.26	0.10	0.15
20	0.46	0.73	0.19	0.29	0.30	0.47	0.19	0.30
30	0.70	1.10	0.28	0.44	0.44	0.70	0.29	0.45
40	0.93	1.47	0.37	0.59	0.59	0.94	0.38	0.61
50	1.16	1.83	0.47	0.73	0.74	1.17	0.48	0.76
60	1.39	2.20	0.56	0.88	0.89	1.41	0.57	0.91
70	1.62	2.57	0.65	1.03	1.04	1.64	0.67	1.06
80	1.86	2.93	0.74	1.18	1.19	1.87	0.77	1.21
90	2.09	3.30	0.84	1.32	1.33	2.11	0.86	1.36
100	2.32	3.66	0.93	1.47	1.48	2.34	0.96	1.51
110	2.55	4.03	--	--	1.63	2.58	1.05	1.66
120	2.78	4.40	--	--	1.78	2.81	1.15	1.82

Figure 15. Bending and buckling of fixed normal beam (without opening)



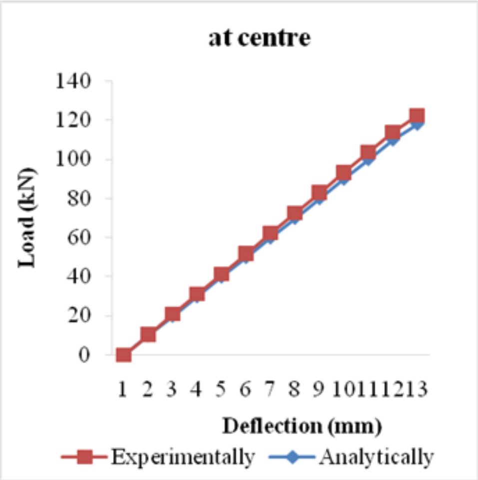


Figure 16. Load vs deflection curve in fixed normal beam

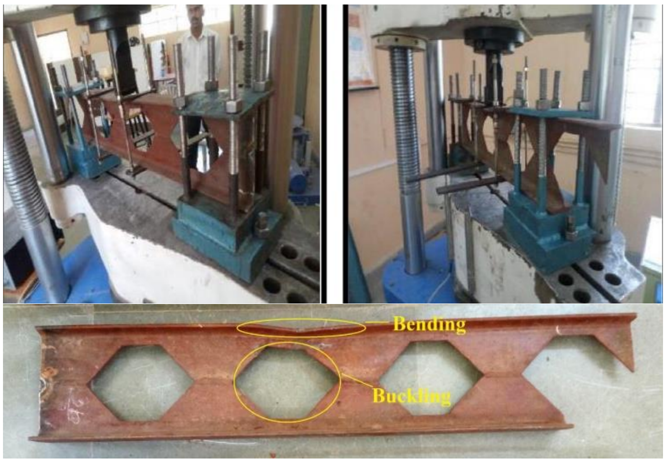


Figure 17. Lateral torsional buckling and bending in castellated fixed beam with hexagonal opening

Figure 18. Lateral torsional buckling and bending in castellated fixed beam with square opening

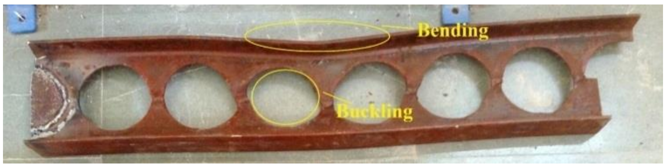


Figure 19. Lateral torsional buckling and bending in castellated fixed beam with circular opening

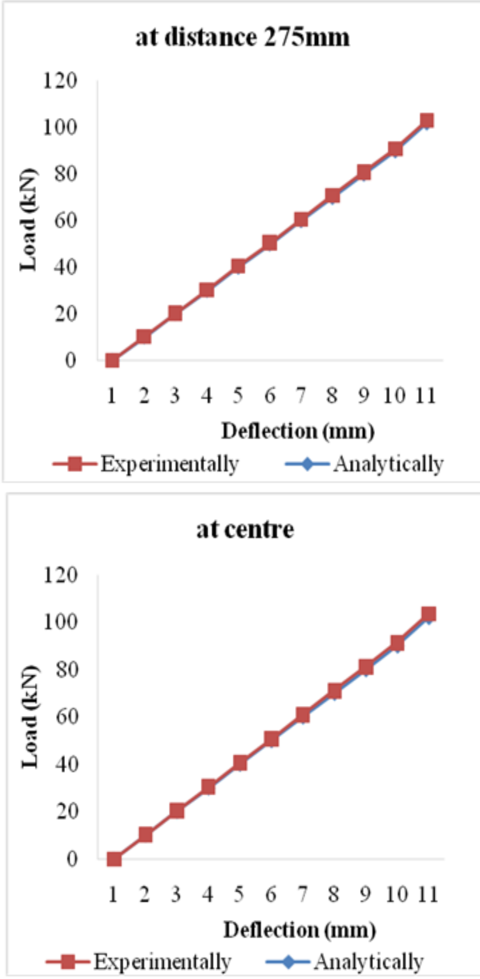
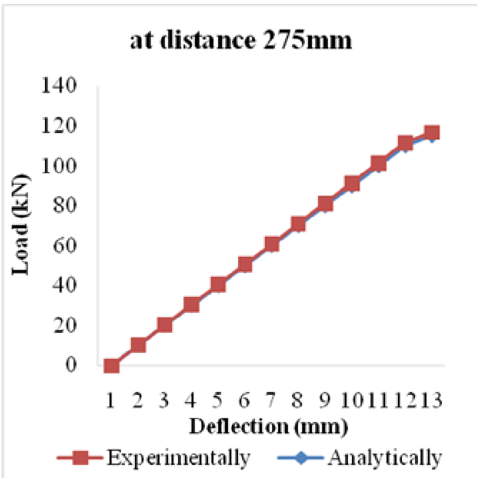


Figure 20. Load vs deflection curve in castellated fixed beam with hexagonal opening



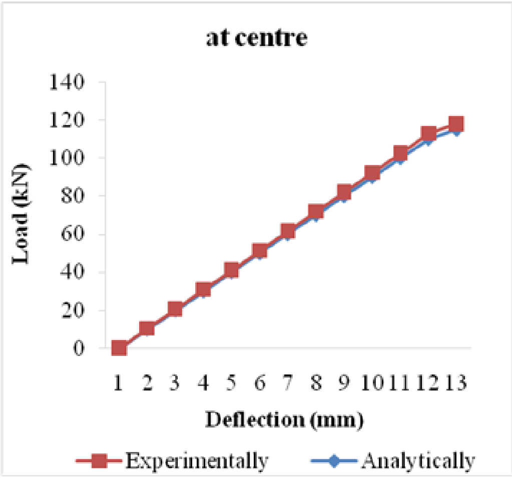


Figure 21. Load vs deflection curve in castellated fixed beam with square opening

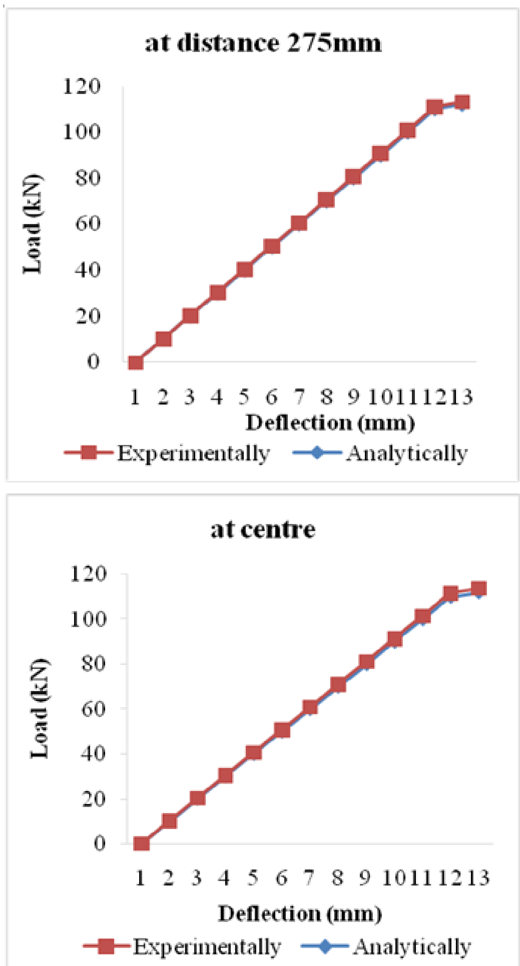


Figure 22. Load vs deflection curve in castellated fixed beam with circular opening

5. FINITE ELEMENT ANALYSIS OF CASTELLATED BEAMS

In this study, experimental results are validated by using finite element analysis of castellated beams using ANSYS 14.0 version. Figures 23 and 24 show deflection of castellated cantilever and fixed beams respectively.

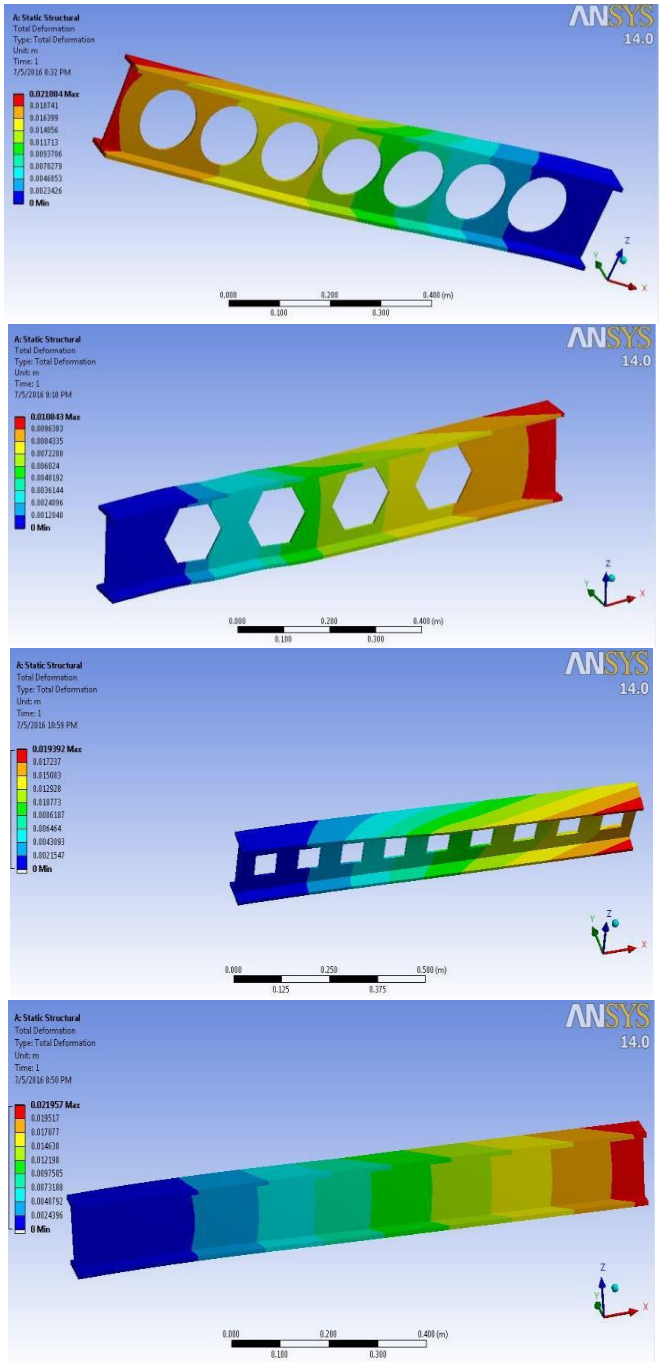
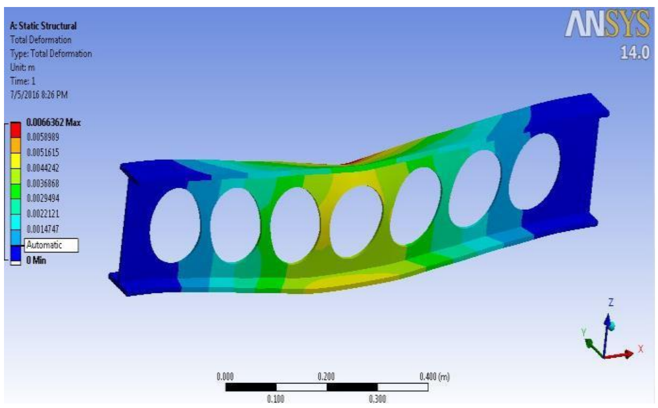


Figure 23. Finite element analysis of castellated cantilever beams using ANSYS 14.0



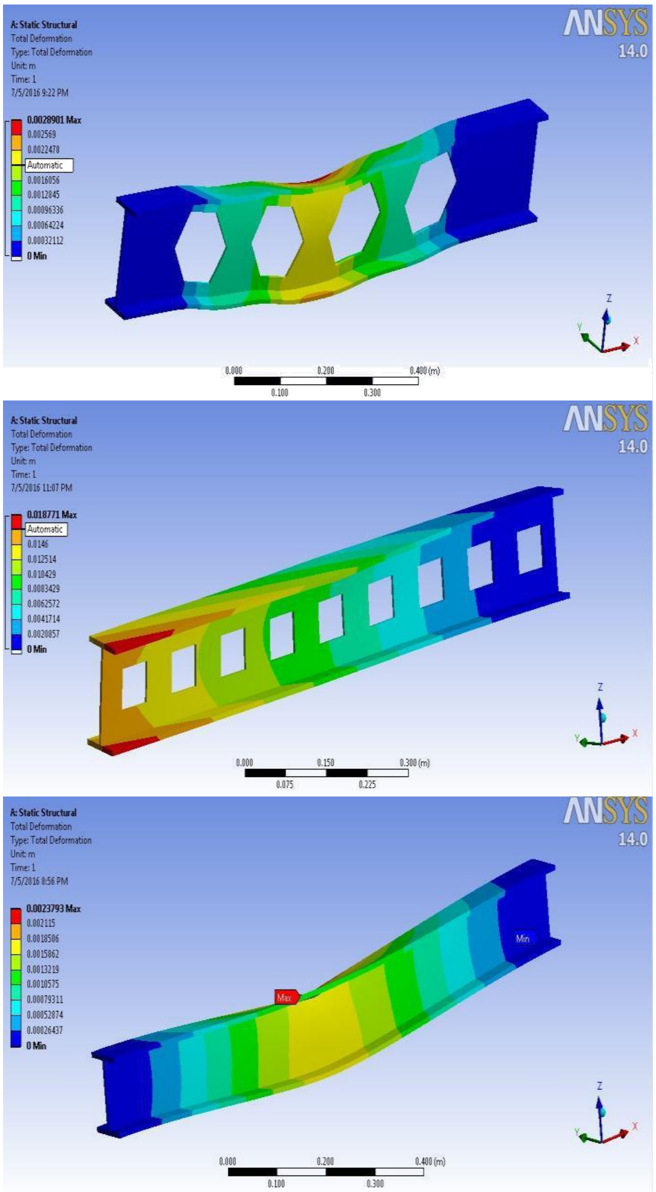


Figure 24. Finite element analysis of castellated fixed beams using ANSYS 14.0

6. CONCLUSIONS

In the present study, a new experimental solution is provided for bending of cantilever and fixed castellated beams with hexagonal, circular and square openings. Beams are tested under universal testing machine and subjected to central point load. Experimental results are obtained for maximum deflections and validated by using finite element analysis. By experimentally it was observed that the value of web shear deformation on the critical buckling load of castellated beam increase with the increase in cross sectional area of the I-section and depth of web opening, but decrease with the length and web thickness. It is also concluded that the effective opening shape in castellated beams is hexagonal as far as deflection is concern. But circular shape is more effective to avoid stress concentration at corners. Finally it is concluded that the present study will serve as benchmark study for cantilever and fixed castellated beams.

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