

Analytical and Experimental Investigation of Castellated Beam by Using British Standard

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Abstract

Castellated beams are those beams which have openings in their web portion. Castellated beams are fabricated by cutting the web of hot rolled steel I section into zigzag pattern and thereafter rejoining it over one another. Use of castellated beams is become very popular now a day due to its advantageous structural applications. 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. In this research we have used the British Standard Code based methodology for designing of castellated beam.

In this research we have used the British Standard Code based methodology for designing of castellated beam. So the first objective of this research is to investigate the performance of castellated beam designed by BS code method. The study of performance is based on deflection, moment carrying capacity of castellated beam.

We compare the different types castellated beams design by British Standard based on their moment carrying capacities. The openings made in the webs are of generally hexagonal, diamond, rectangular or square in shape. By studying the different research paper it found that castellated beams with hexagonal, rectangular or square opening mostly fails due to shear stress concentration at the corner of opening

Second objective of this research is to provide new web opening shape by considering different angle of opening to avoid failure of castellated beam due to shear stress concentration at the corner of opening, and avoiding Vierendeel Bending failure which is commonly observed in rectangular opening.

From the experimental results, it is concluded that, the castellated steel beam design by British Standard code with different angle of opening there is improvement in moment carrying capacities. At the same time it is found that moment carrying capacity of hexagonal web opening shape castellated beam is more

as compare to with rectangular web opening due to shear stress redistribution at corner.

Keywords—*Rectangular & Hexagonal web opening, Angle of opening, Length of opening, Moment carrying capacity, Shear stress concentration.*

I. INTRODUCTION

Castellation is a process of fabricating a section with improved section properties from virgin rolled section by increasing depth ultimately improving moment of inertia. There by increase in moment of resistance and controlled on deflection. Steel offers much better compressive and tensile strength than concrete and enables lighter constructions. Also, unlike masonry or reinforced concrete, steel can be easily recycled. Beams are flexural members that support loads which are applied transverse to their longitudinal axes. Beams have a far more complex load carrying action than other structural elements such as trusses and cables. The load transfer by a beam is primarily by bending and shear.

The web resists shear forces, while the flanges resist most of the bending moment experienced by the beam. Beam theory shows that the I-shaped sections is a very efficient form for carrying both bending and shear loads in the plane of the web.

A beam with a perforated web is called castellated beam. It is an open web beam but made up of single rolled wide flange beam section and is formed by flame cutting the beam section in the predetermined pattern and rejoining the segment by welding to produce a regular pattern of holes in web. The beam section obtained in such way can be even 50% dipper than the original section. By increasing the depth, the section modulus is increased by about 2.25 times the section modulus of the original beam section.

II. TERMINOLOGY IN CASTELLATED BEAM

The various basic terms involved in the analysis and design of castellated beams are illustrated given below.

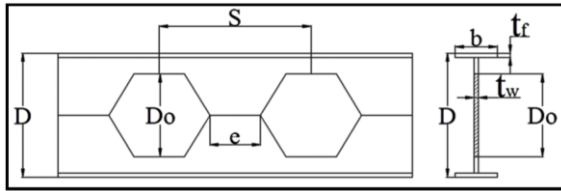


Fig.1. Typical cross section of the beam

Where,

D_o = Depth of opening provided.

D = Overall depth of the opening.

S = C/C spacing between the two opening

e = Clear distance between two opening

b = Width of flange of I beam

t_f = Thickness of flange of I beam

t_w = Thickness of web of I beam

Objective of the research work

The aim of the research is to determine the most suitable castellated beam section that can produce of desirable strength without compromising engineering performance and minimum possible self-weight.

To investigate and compare, through an experimental program, the flexural behavior of castellated steel beams with hexagonal and rectangular web opening shape configurations with universe.

To examine both the moment carrying capacities and the failure modes of castellated sections and positions of high stress concentration points in the vicinity of the web openings.

To invent an effective opening configuration for a wide variety of beam cross-sections found in practice through an extensive parametric study.

To parametrically investigate the local buckling behavior of such thin-walled perforated webs while changing the geometric characteristics of the new web opening architecture and compare with existing web opening design structural behavior in terms of buckling load/moment, stress distribution and failure mode.

A. Problem statement

A lot of research work has been carried out for analysis and design of castellated beams, especially with hexagonal openings. There is no universally accepted design method for castellated beam because of complexity in geometry accompanied by complex mode of failure.

There is lot of study has been done in optimizing sizes of castellated beams with hexagonal openings, and hence there is need to optimize the beams with

other shaped openings. While the local failure associated with the castellated beam can be minimized by providing other shaped openings like hexagonal (300,450,600) and rectangle shapes.

B. Failure mode

The design concept for castellated beams is based on typical beam limit states, but the presence of web openings and welds can cause other modes of failure. The potential modes of failure associated with castellated beams are:

Flexural Failure Mechanism

Lateral-Torsional Buckling

Vierendeel Bending Mechanism

Rupture of the Welded Joint in a Web Post

Shear Buckling of Web Post

III. BRITISH STANDARDS METHODOLOGY

ISMB150 is selected as a parent section for fabricating castellated beam. Following guidelines are followed for fabrication-

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 experimental investigations carried out on the test specimen to study the flexural behavior of Hot rolled I sections and castellated beam sections. Test specimen's span = 2 m. The beams were simply supported at the ends and subjected to a two point load applied at the one third span. The deflection at Centre of beam and various failure patterns are studied.

$$1.08 < S/D_o < 1.5$$

$$1.25 < D/D_o < 1.75$$

$$D_o < 0.8 D \quad e < 0.4 D_o$$

$$\text{Width of end post} > 0.5 D_o$$

C. Design of moment (flexural) capacity of the beam:-

In this check, we have to ensure that maximum moment induced in the beam due to external loads

should be less than moment capacity of the upper and lower Tee.

$$M_u < M_{pTee}$$

$$M_{uTee} = A_{Tee} \times P_y \times z$$

Where,

M_u = Maximum moment induced in the beam as per loading conditions.

M_{pTee} = Moment capacity of the upper or lower Tee.

A_{Tee} = Area of upper or lower Tee.

P_y = Yield stress of steel. (250 N/mm²)

z = Lever arm (Distance between the centroid of upper and lower Tee).

D. Design of shear capacity of the beam:-

Maximum vertical and horizontal shear induced in the beam due to external loading should be less than vertical and horizontal shear capacities of the beam respectively.

$$V_{vmax} < P_u$$

$$P_v = 0.6 \times P_y \times A_v$$

$$V_{vmax} < P_{vy}$$

$$P_{vy} = 0.6 \times 0.9 \times A_{wt}$$

$$V_{Hmax} < P_{vh}$$

$$P_{vh} = 0.6 \times P_y \times A_{mwt}$$

$$V_H = T_i + 1 - T_i$$

$$T = M/z$$

Where,

V_{vmax} = Maximum vertical shear.

V_{Hmax} = Maximum horizontal shear.

P_v = Shear strength of castellated beam

A_v = Shear area (shear area of whole cross section)

$$= (D - 2t_f) \times t_w$$

P_{vy} = Vertical shear capacity.

A_{wt} = Shear area of Tee

$$= (D - 2t_f - D_o) \times t_w$$

P_{vh} = Horizontal shear capacity.

A_{mwt} = Horizontal shear area

$$= e \times t_w$$

V_H = Horizontal shear.

T = Axial load at different point.

M = Bending moment at different point.

E. Check for Vierendeel bending of tee:-

Vierendeel bending moment of the lower or upper Tee should be less than the local bending resistance of respective Tee.

$$M_{pTeeLocal} = \frac{A_{Tee} \times P_y \times Z_{Tee}}{2}$$

$$M_{pv} = V_{max} \times l_{eff}$$

$M_{pTeeLocal}$ = Bending resistance of Tee of beam.

M_{pv} = Vierendeel bending moment.

l_{eff} = Effective length of opening.

Effective length of opening is depends on the type of opening provided.

For other opening effective length is width of opening.

F. Check for fracture in welding

Strength of weld should be more than maximum horizontal shear force in the section.

$$\text{Shear strength of the weld} = \frac{e \times t_w \times P_y}{\sqrt{3}}$$

G. Check for deflection

Deflection of beam is calculated as per standard formulae for perforated depth of the beam. Additional deflection due to openings is calculated by adding 15% to 25% deflection in above calculated deflection.....

Required deflection $\geq$ calculated deflection

$$\text{Required deflection} = \frac{L_{eff}}{325}$$

$$\text{Calculated deflection} = \frac{W l^3}{48EI}$$



Fig.2. Testing Arrangement of (Ip)



Fig.3. Testing Arrangement (I_{H1})



Fig.6. Testing arrangement of (I_{R1})



Fig.4. Testing Arrangement (I_{H2})



Fig.7. Testing arrangement (I_{R2})



Fig.5. Testing Arrangement of (I_{H3})



Fig.8. Testing arrangement of (I_{R3})

IV. EXPERIMENTAL RESULTS AND DISCUSSION

TABLE.1. MOMENT CARRYING CAPACITY OF I_p

Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	0	0	0	0
1	36.1	1	9.13	0.0013
2	57.5	2	14.55	0.0026
3	76.3	3	19.30	0.0039
4	95.4	4	24.14	0.0053
5	109.1	5	27.60	0.0066
6	120.8	6	30.56	0.0079
7	127.8	7	32.33	0.0092
8	131.7	8	33.32	0.0105
9	135	9	34.16	0.0118
10	137.7	10	34.84	0.0132
11	138.5	15.6	35.04	0.0200

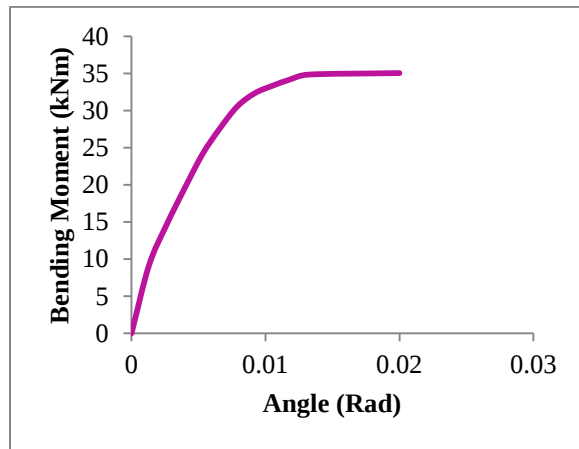


Fig.9. Moment carrying capacity of I_p V/s Angle

TABLE. 2. MOMENT CARRYING CAPACITY OF I_{H1}

Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	0	0	0	0
1	5	0	2.45	0.00000
2	35	1	8.58	0.00012
3	50	2	12.25	0.00024
4	80	3	19.6	0.00035
5	100	4	24.5	0.00047
6	120	5	29.4	0.00058
7	135	6	33.0	0.00071
8	139.2	7	34.10	0.00084
9	141.5	8	34.66	0.00094

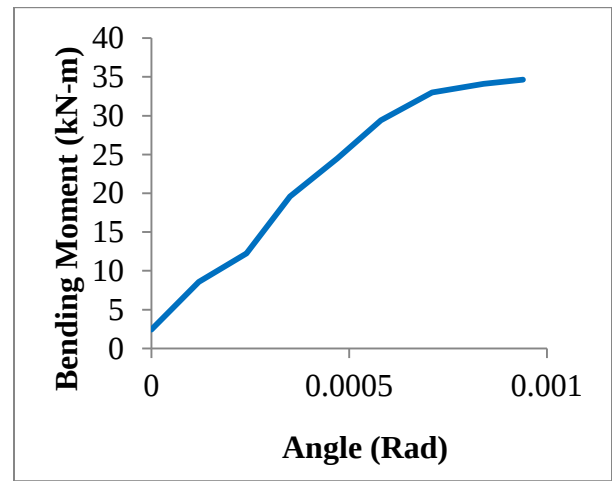


Fig.10. Moment carrying capacity of I_{H1} Angle

TABLE.3. MOMENT CARRYING CAPACITY OF I_{H2}

Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	0	0	0	0
1	34.2	1	8.65	0.00132
2	47.1	2	11.92	0.00263
3	59.3	3	15.00	0.00395
4	72.3	4	18.29	0.00526
5	84.3	5	21.33	0.00658
6	98.9	6	20.02	0.00789
7	113.7	7	28.77	0.00921
8	123.1	8	31.14	0.01053
9	128.4	9	32.49	0.01184
10	128.8	10	32.59	0.01316
11	129.5	11.2	32.76	0.01474

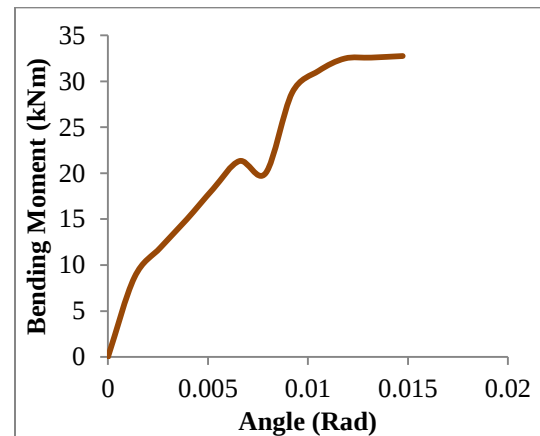
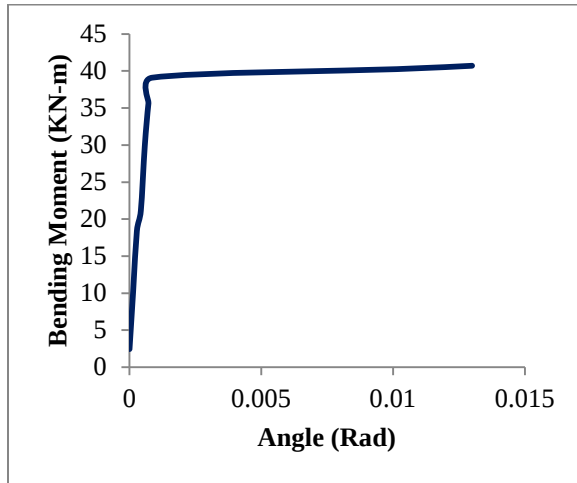


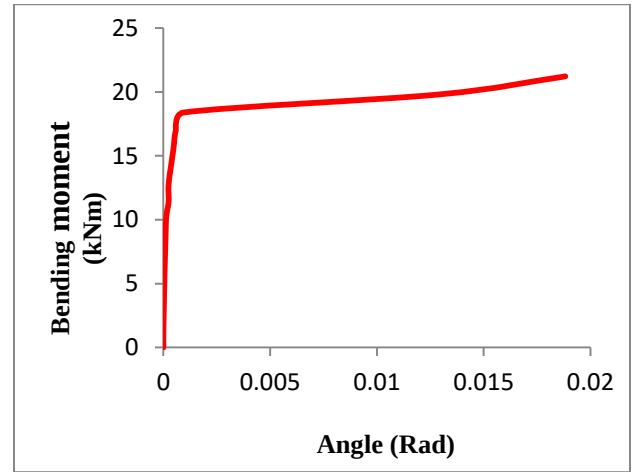
Fig.11. Moment carrying capacity of I_{H2} V/s Angle

TABLE.4. MOMENT CARRYING CAPACITY OF I_{H3}

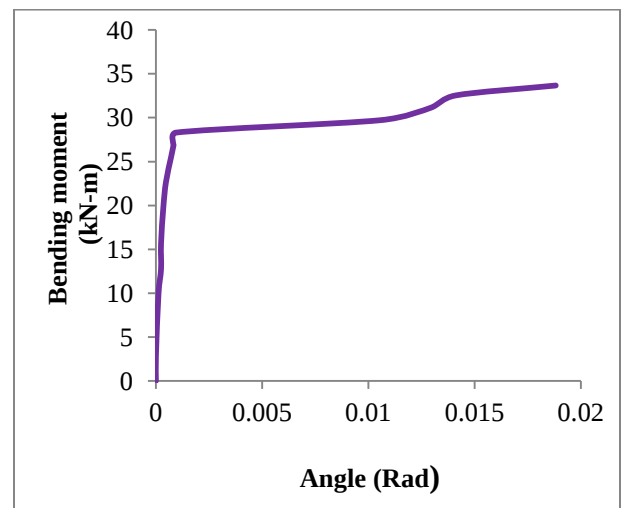
Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	0	0	0	0
1	5	0	2.45	0.00000
2	45	1	10.35	0.00014
3	80	2	18.4	0.00028
4	105	3	21.15	0.00043
5	130	4	29.9	0.00058
6	155	5	35.65	0.00072
7	170	6	39.1	0.00086
8	175	7	40.25	0.01014
9	177	9	40.71	0.01300

Figure.12. Moment carrying capacity of I_{H3} AngleTABLE.5. MOMENT CARRYING CAPACITY OF I_{R1}

Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	0	0	0	0
1	5	1	1.41	0
2	35	2	9.905	0.00012
3	40	3	11.32	0.00024
4	45	4	12.73	0.00024
5	50	5	14.15	0.00035
6	55	6	15.56	0.00047
7	60	7	16.98	0.00058
8	65	8	18.39	0.00094
9	70	9	19.81	0.01293
10	75	9.91	21.22	0.01882

Figure.13. Moment carrying capacity of I_{R1} V/s AngleTABLE.6. MOMENT CARRYING CAPACITY OF I_{R2}

Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	0	0	0	0
1	10	1	2.83	0
2	35	2	9.9	0.00012
3	45	3	12.74	0.00024
4	55	4	15.66	0.00024
5	70	5	19.81	0.00035
6	80	6	22.64	0.00047
7	90	7	25.47	0.00071
8	95	8	26.88	0.00083
9	100	9	28.3	0.00094
10	105	10	29.72	0.01058
11	110	11	31.13	0.01293
12	115	12	32.54	0.01411
13	119	13	33.67	0.01882

Figure.14. Moment carrying capacity of I_{R2} V/s Angle

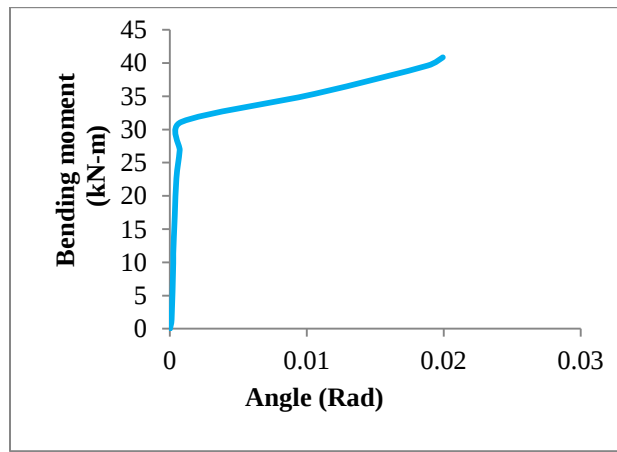


Fig.15. Moment carrying capacity of I_{R3} V/s Angle

TABLE.7. MOMENT CARRYING CAPACITY OF I_{R3}

Sr. No	Load (kN)	Deflection (mm)	Moment (kN-m)	Angle (Rad)
0	5	0	0	0
1	35	1	1.415	0.00012
2	40	2	9.905	0.00024
3	60	3	11.32	0.00024
4	80	4	16.98	0.00035
5	95	5	22.64	0.00047
6	110	6	26.88	0.00071
7	125	7	31.13	0.00083
8	135	8	35.37	0.01058
9	140	9	39.62	0.01882
10	144.4	10	40.86	0.01993

A. Moment Study

With reference to test result the moment carrying capacity of all Hexagonal Web Opening Castellated Beams is more as compare moment carrying capacity of Rectangular Web Opening Castellated Beam.

TABLE.8. COMPARISON OF MOMENT CARRYING CAPACITY OF HEXAGONAL AND RECTANGULAR WEB OPENING

Sr. No	Moment (kN-m)						
	I_p	I_{H1}	I_{H2}	I_{H3}	I_{R1}	I_{R2}	I_{R3}
1	35.04	34.66	32.76	40.71	21.22	33.67	40.86

TABLE.9. COMPARISON OF MOMENT CARRYING CAPACITY OF HEXAGONAL AND RECTANGLE WEB OPENING CASTELLATED

Sr. no	BEAMS				% increase in Moment of Rectangular Web Opening Castellated Beam		
	Moment (kN-m)				I_{R1}	I_{R2}	I_{R3}
1	I_{H2}	I_{R1}	I_{R2}	I_{R3}	I_{R1}	I_{R2}	I_{R3}
2	32.76	21.22	33.67	40.86	35.22*	2.77	24.72

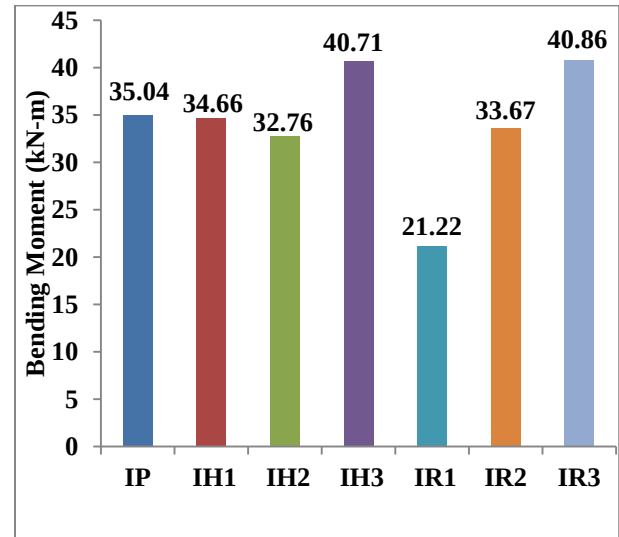


Fig.16. Comparison of Moment carrying capacity of tested beam specimens

B. Deflection Study

The deflections of solid web beam, hexagonal and rectangle web opening castellated beam are recorded in following table 9. It is observed that deflection of Hexagonal web opening castellated beam with angle of opening 300 IH1 is less as compare to deflection of Rectangular web opening . The deflection of all hexagonal web opening castellated beams is less as compare to deflection of rectangle web opening castellated beam.

TABLE.10. COMPARISON OF DEFLECTION OF TESTED BEAM SPECIMENS.

Sr. No.	Deflection (mm)						
	I_p	I_{H1}	I_{H2}	I_{H3}	I_{R1}	I_{R2}	I_{R3}
1	15.60	8	11.2	9	9.11	13	10

TABLE.11. COMPARISON OF DEFLECTION OF HEXAGONAL AND RECTANGLE WEB OPENING CASTELLATED BEAMS

Sr. No.	Deflection (mm)				Percentage Decrease In Deflection of Rectangular Web Opening Castellated Beam (%)		
	I_{H2}	I_{R1}	I_{R2}	I_{R3}	I_{R1}	I_{R2}	I_{R3}
1							
2	11.20	9.91	13	10	22.94	13.84*	10.71

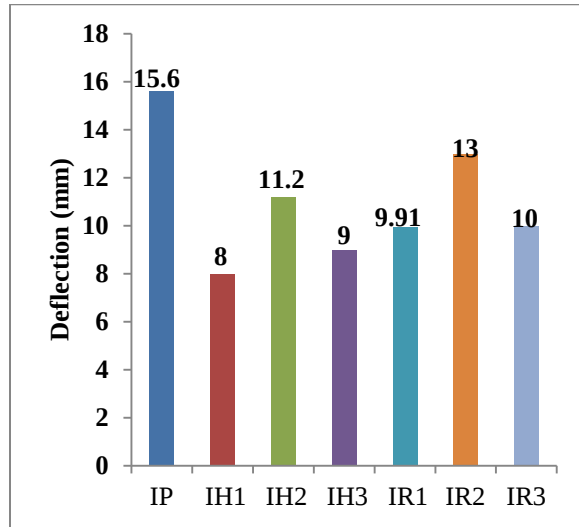


Fig .17. Comparison of Deflection of tested beam specimens

V. CONCLUSIONS

From the above discussed results it can be concluded that:

1. Moment carrying capacity of castellated beam with hexagonal opening is more as compare to castellated beam with rectangular opening.
2. It is observed from experiment of castellated beams hexagonal web opening shows better performance compare to rectangular web opening castellated beams.
3. Hexagonal web opening castellated beam have lower shear capacity due to shear stress concentration at corner of opening.
4. A hexagonal shaped opening more share transfer area is available, therefore castellated beam with hexagonal openings proves to be better.
5. Moment carrying capacity of I_{H2} compare to I_{R2} is 2.770 % more, that of I_{R3} is 24.07 % more.
6. Deflection carrying capacity of I_{R1} compare to I_{H2} is 22.94 % more, that of I_{R3} compare to I_{H2} is 10.71 % more.
7. Hexagonal web opening castellated beams shows less deflection as compare rectangular web opening castellated beam.

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