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Analytical and Experimental Investigation of Castellated Beam by American Standard

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ABSTRACT

Castellated beams are those beams which has openings in its web portion. Castellated beams are fabricated by cutting the web of hot rolled steel (HRS) I section into zigzag pattern and thereafter re-joining it over one another. Use of castellated beams is become very popular now days due to its advantageous structural applications. ASTM stands for American Society for Testing and Materials over 12,000 ASTM standards operate globally. They improve the lives of millions every day combined with our innovative business services, ASTM standards enhance performance and help everyone have confidence in the things they buy and use. ASTM standards use to find out ultimate moment capacity carried by given beam after castellation. The study of performance is based on deflection, moment carrying capacity of castellated beam sections like, diamond, rectangular opening .From the experimental results, it is concluded that moment carrying capacity of diamond opening is more as compared to rectangular opening.

Keywords - *Bending Moment Carrying capacity,Castellated beam,Dimond web opening Rectangular web opening, Shear stress concentration.*

I. INTRODUCTION

Castellation is a process of fabricating a section with improved section properties from virgin rolled section that is improving moment of inertia, improving depth. There by increase in moment of resistance and control on deflection.

This process increases the depth of the beam by approximately 50%, therefore increasing the strength and stiffness by about 20 to 30% without increasing the weight of the beam. Also the holes in the web allow ductwork to run through beams instead of underneath ultimately reducing the depth of the floor system. Although there are many advantages to using castellated beam, the one disadvantage is fabrication cost. The extra cost of cutting and welding the web is usually the deciding factor for their feasibility. Castellated beams are more popular in areas where the cost of steel is high and labor costs are low. The use of castellated beams in Europe has existed ever since the adoption of the fabrication process developed by Litzka Stahlbau of Bavaria, Germany (Boyer 1964). 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:

1. Flexural Failure Mechanism
2. Lateral-Torsional Buckling
3. Vierendeel Bending Mechanism
4. Weld Rupture at Web Post
5. Shear Buckling of Web Post
6. Compression Web Post Buckling

II. DESIGN EQUATIONS

Design Steps to find, ultimate load and moment carried by the beam after castellation-

Step 1) Depth of castellated section=1.5×original depth of section.

Step 2) Classification of section-

The section is classified as compact, non-compact or slender using ANSI/AISC 360-10 an American National Standard/page no 16.1-17/ table b4.1b width-to-thickness ratios: compression elements members subjected to flexure.

Step 3) Moment of inertia-

$I_{xx}=\frac{bd3}{12}$ in mm^4

$I_{yy}=\frac{db3}{12}$ in mm^4

Step 4) Radius of gyration-

$r_{xx}=\sqrt{Ixx/A}$, in mm.

$r_{yy}=\sqrt{Iyy/A}$, in mm.

Step 5) Section Modulus-

$Z_{xx}=\frac{Ixx}{Yx}$, in mm^3

$Z_{yy}=\frac{Iyy}{Yy}$, in mm^3

Step 6) Nominal Flexural Strength, M_n

6.1Yielding-

$$M_n = M_p = F_y Z_x$$

Where,
Fy = specified minimum yield stress of the type of steel being used (MPa)
Fy = $250\frac{N}{mm^2}(for\ mild\ steel)$
Zx = plastic section modulus about the x-axis, (mm^3)

$Zp = Ac.yc + At.yt$

6.2 Lateral-Torsional Buckling-

(a) When $Lb \leq Lp$, the *limit state* of *lateral-torsional buckling* does not apply.

(b) When $Lp < Lb \leq Lr$

$$M_n = C_b\left[M_p - \left(M_p - 0.7F_yS_x\right)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right] \leq$$

(c) When $Lb > Lr$

$$M_n = F_{cr}S_x \leq M_p$$

Where
Lb = length between points that are either braced against lateral displacement of the compression flange or braced against twist of the cross section, (mm).

$$F_{cr} = \frac{C_b\pi^2E}{\left(\frac{L_b}{r_{ts}}\right)^2}\sqrt{1 + 0.078\frac{Jc}{S_xh_o}\left(\frac{L_b}{r_{ts}}\right)^2}$$

And where,
E = modulus of elasticity of steel = 200 000 MPa
J = torsional constant (mm^4)
Sx = elastic section modulus taken about the x-axis, (mm^3)
ho = distance between the flange centroids, (mm)
The limiting lengths *Lp* and *Lr* are determined as follows:

$$L_p = 1.76r_y\sqrt{\frac{E}{F_y}}$$

$$L_r = 1.95r_{ts}\frac{E}{0.7F_y}\sqrt{\frac{Jc}{S_xh_o} + \sqrt{\left(\frac{Jc}{S_xh_o}\right)^2 + 6.76\left(0.\right.}}$$

Step 7) Nominal Shear strength-

$$V_n = 0.6F_yA_wC_v$$

Where,
$C_v = 1.0$
Fy = specified minimum yield stress of the type of steel being used (MPa)
Aw = area of web, the overall depth times the web thickness, dtw (mm^2)

Step 8) Maximum nominal bending capacity at the location of an opening, M_m:

$$M_m = M_p\left[1 - \frac{\Delta A_s\left(\frac{h_o}{4} + e\right)}{Z}\right]$$

in which

$M_p = F_yZ$
$\Delta A_s = h_ot_w$
h_o = depth of opening
t_w = thickness of web
e = eccentricity of opening = $|e|$
Z = plastic section modulus of member without opening
F_y = yield strength of steel

Step 9) The maximum nominal shear capacity at a web opening, V_m
The maximum nominal shear capacity at a web opening, V_m is calculated as below.

$$Vm = Vmb + Vmt$$

Where,
V_{mb}, V_{mt} = Maximum nominal shear capacity of bottom and top tees, respectively.

$$\alpha_v = \frac{V_{mb}}{V_{pb}} \text{ or } \frac{V_{mt}}{V_{pt}} = \frac{\sqrt{6} + \mu}{\nu + \sqrt{3}} \leq 1$$

in which V_{pb} or $V_{pt} = \frac{F_yt_ws}{\sqrt{3}}$

ν = aspect ratio of tee = $\frac{a_o}{s}$, use $\nu = \frac{a_o}{\bar{s}}$ when reinforcement is used

s = depth of tee, s_b or s_t

$\bar{s} = s - \frac{A_r}{2b_f}$, used to calculate ν when reinforcement is used

b_f = width of flange
a_o = length of opening

V_{pb}, Vpt is the plastic shear capacity of bottom and top tees, respectively.

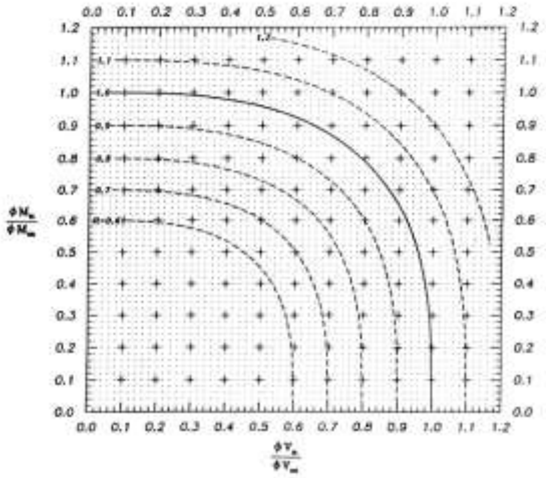
α_v, the ratio of nominal shear capacity of a tee,

For tees without concrete or reinforcement μ=0.

Step 10) Finding ratios:
Following ratios are obtained by taking values from above steps.

$$\frac{\emptyset Mn}{\emptyset Mm} \text{ and } \frac{\emptyset V\,n}{\emptyset Vm}$$

Step 11) Finding value of R from Moment-Shear Interaction curve:
The value of R is obtained from Moment-Shear Interaction Curve given below-



Graph 1. Moment- Shear Interaction curve

Step 12) Finding ultimate moment and shear strength:
The ultimate moment is calculated from following formula-

$$\emptyset M\text{n} = \frac{\text{M}_\text{u}}{\text{R}}$$

Where
Φ is 0.90 for steel members.

The ultimate shear is calculated from following formula

$$\emptyset V\text{n} = \frac{\text{Vu}}{\text{R}}$$

Where,
Φ is 0.90 for steel members.

Step 13) Check for deflection = $\frac{L}{325}$

III. FIGURES AND TABLES

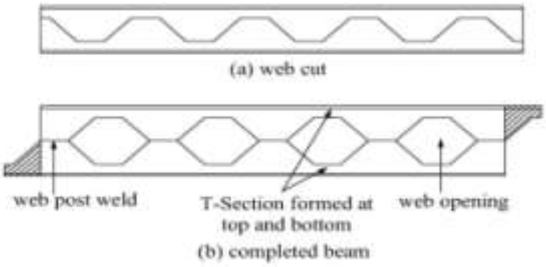


Figure 1 Fabrication Process

Details of Models

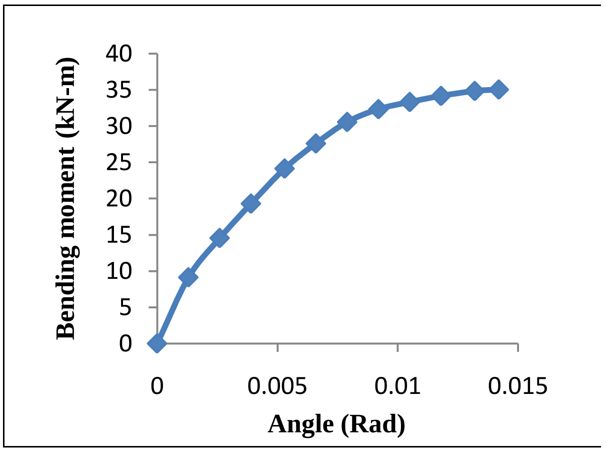
Table No.1

Name	Specification
I_P	Parent section without castellation
I_H	Section with hexagonal web opening
I_{D1}	Diamond web opening with angle of opening 30^0
I_{D2}	Diamond web opening with angle of opening 45^0
I_{D3}	Diamond web opening with angle of opening 60^0
I_{R1}	Rectangle web opening with equal length of opening for diamond 30^0
I_{R2}	Rectangle web opening with equal length of opening for diamond 45^0
I_{R3}	Rectangle web opening with equal length of opening for diamond 60^0

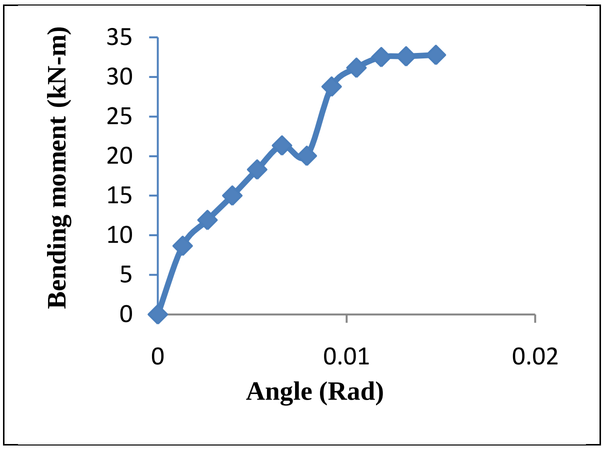
Figure. 2 Testing of Castellated beams on UTM.

Figure. 3 Web and flange buckling is observed in beam with rectangular opening.

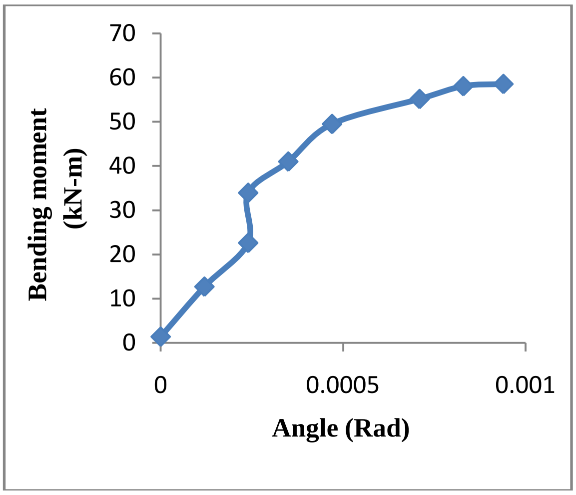
Figure. 4 Web buckling is observed in beam.



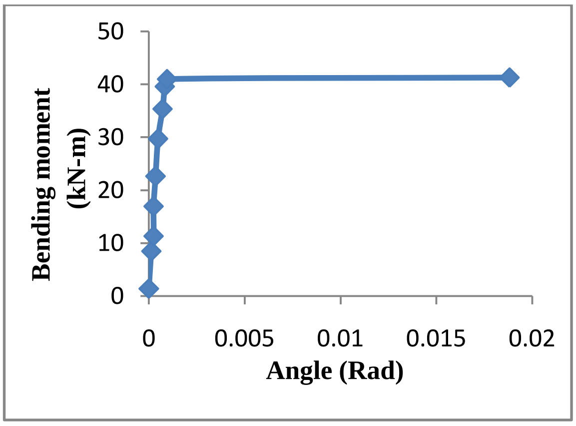
Graph 2 BM Carrying Capacity of Ip V/s Angle



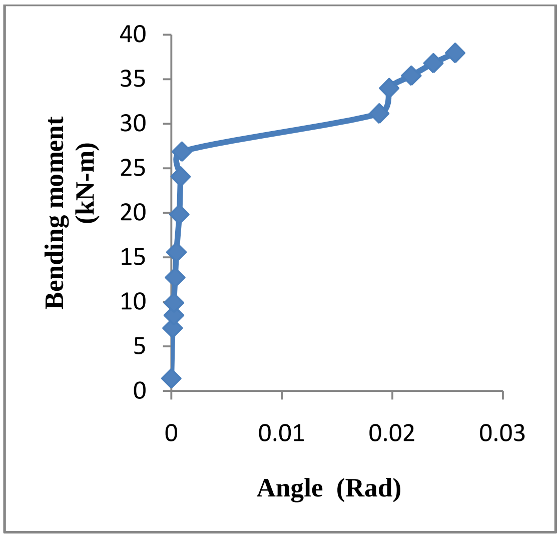
Graph 3 BM Carrying Capacity of I_H V/s Angle



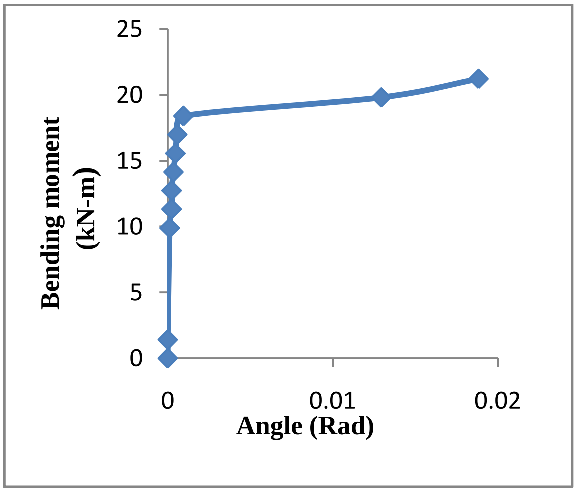
Graph 4 BM Carrying Capacity of I_{D1} V/s Angle



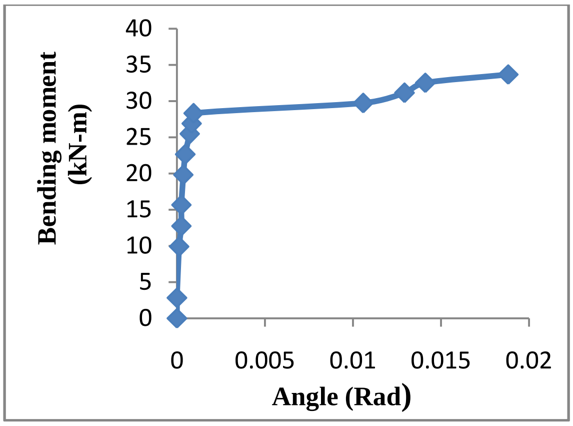
Graph 5 BM Carrying Capacity of I_{D2} V/s Angle



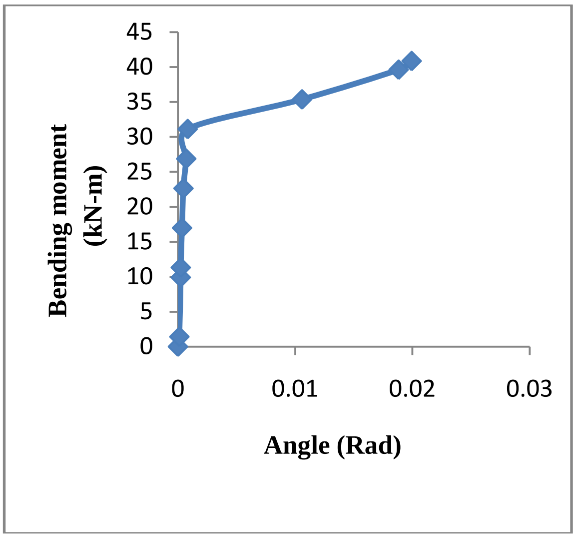
Graph 6 BM Carrying Capacity of I_{D3} V/s Angle



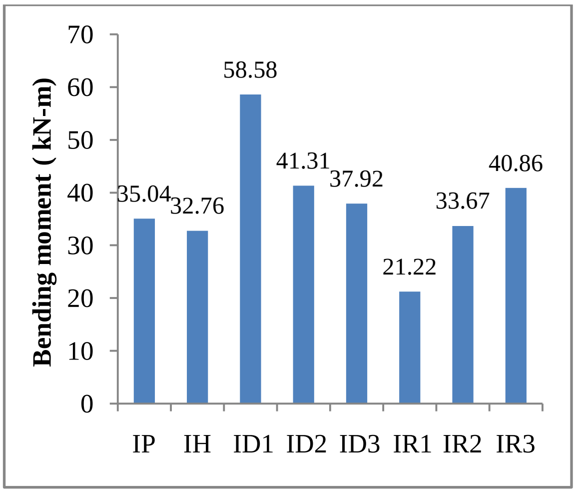
Graph 7 BM Carrying Capacity of I_{R1} V/s Angle



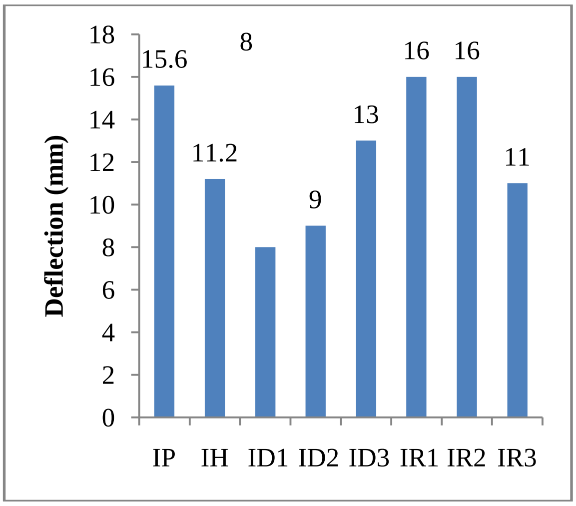
Graph 8 BM Carrying Capacity of I_{R2} V/s Angle



Graph 9 BM Carrying Capacity of I_{R3} V/s Angle



Graph 10 Comparison of BM Carrying Capacity of tested beam specimens



Graph 11 Comparison of Deflection of tested beam specimens

IV. CONCLUSION

1. Bending moment carrying capacity of castellated beam with Diamond web opening is more as compare to castellated beam with hexagonal opening.
2. Bending moment carrying capacity of I_{D1} compare to I_H is 44.08 % more, that of I_{D2} compare to I_H is 20.70 % more and of I_{D3} compare to I_H is 13.60 % more.
3. The castellated beam with Diamond web opening has as good structural performances as compare to hexagonal openings in the form of the stresses distribution, shear capacity and failure mode.
4. Castellated beams with Diamond web opening have higher shear capacity than that with hexagonal web opening.
5. Experimental analysis shows that shear stress gets easily concentrate at the corners of rectangle web opening castellated beams.
6. Hexagonal web opening castellated beam have lower shear capacity due to shear stress concentration at corner of opening
7. Diamond web opening castellated beams shows less deflection as compare hexagonal and rectangle web opening.
8. Deflection of I_{D1} compare to I_H is 28.57 % less, that of I_{D2} compare to I_H is 19.64% less and of I_{D3} compare to I_H is 13.84% more.
9. Comparing the results of all Diamond web opening castellated beams it is found that a castellated beam with Diamond web opening with angle of web opening to 30^0 shows better performance compare to castellated beam with Diamond web opening with angle of web opening to 45^0 and 60^0 both bending moment and deflection .

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