

Parametric Study on Horizontally Curved Steel I Girder Webs with Non-Central Openings

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ABSTRACT: Steel has the highest strength-to-weight ratio of any construction material, and with new construction methods, steel buildings stay a popular choice for office and multifamily developers. When the modern world is giving so much importance for architecture which is mostly blended with flawless curves, need for curved structural elements such as curved beam, domes, bridges etc. are growing essential. Curved steel beams and girders are usually used in the construction of major buildings, modern bridges, highway ramps and interchanges, ships, and air space structures. Among a range of steel sections, use of I-beams is vast in industry for bridge girders & building girders. There is a rising tendency to provide large service ducts and pipes beneath beams and girders. A solution regularly used is to give openings in the webs of the beams and girders so that the services could pass through the webs. Position, shape and size of the opening may differ according to the position, shape and size of the piping passing through webs, aesthetic demand etc. This study concentrates on the experimental and analytical parametric study of horizontally curved steel-I welded sections with web openings at various positions. The effect of shape and size of openings and other parameters such as effect of web slenderness and flange stiffness are also studied. For the study, finite element package ANSYS 15.0 is used. When the use of curved sections is becoming important in the present world, study on their modified forms will gain popularity in the near future.

KEYWORDS: Curved beam, Residual stress, Flange stiffness, Web slenderness, Ultimate load.

I. INTRODUCTION

Curved steel structures are often designed to provide the users of the structure with natural light and a sense of spaciousness and grandeur in public facilities such as airports, stations, shopping malls and leisure centres. A curved external appearance can be produced by using faceted straight members, and by varying depth connections to the secondary members, but the additional fabrication costs for the faceted solution generally mean that a curved solution is more cost effective in addition to the aesthetic considerations.

There are two methods mainly for curving of members. Rolled steel sections are usually curved by a process using rollers or an induction bending process. The induction process is generally more expensive than the cold process, although smaller radii can be achieved and lighter sections can be curved. The different processes produce different finishes, depending on the member, the material and the radius.

Provision of large service ducts and pipes beneath beams and girders in buildings may lead to unacceptably large depths between storeys. A solution frequently used is to provide openings in the webs of the beams and girders so that the services could pass through the webs. There is a tendency, nowadays, to use water pipes and air ducts of increasing sizes and, openings of dimensions up to 75% of the depth of floor beams are often required. Similarly, depths of the opening used in bridge girders are sometimes as large as 60% of the beam depth and, lengths two or three times the opening depths. Both rectangular and circular opening are commonly used.

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This paper concentrates on parametric study on the ultimate load behaviour of horizontally curved steel I girder webs with openings subjected to point load. The parameters studied are opening shape and size, position of opening, web slenderness and flange stiffness. The advantageous opening position and its critical size are determined by analytical studies using ANSYS 15.0 and experiments are carried out for different shapes.

II. RELATED WORK

Ultimate load tests on two sets of I-beams (rolled sections and welded sections) with single concentrated loading (applied at an intermediate point) were presented in [15] and the effects of residual stresses and R/L on ultimate strength were studied. Test results indicated that the load-carrying capacity decreases with the decrease in the R/L ratio. Study on the ultimate load behaviour of medium sized girders supported at the ends and subjected to a mid-span point load built using rolled steel plates were done in [14]. The test results indicated that the load-carrying capacity decreases with the increase in curvature. Ultimate strength tests on plate girders curved in plan containing centrally placed circular web openings are reported in [9]. The failure mechanism observed in the tests was similar to that observed in plate girders without web openings, the only difference being the position of plastic hinges on the flange plates. A finite element formulation for free vibration analysis of horizontally curved steel I-girder were formulated in [7]. Stiffness as well as mass matrices of the curved and the straight beam elements is formulated. [3] solved the nonlinear dynamic equilibrium equations by using numerical integration procedure.

III. MATERIAL PROPERTIES

The material used to fabricate the specimen were subjected to tension test to find the properties. Universal Testing Machine was used.

Table 1 shows the material properties of specimen. The material was made of mild steel. Fabrication was done at a local workshop.

| Property | Value |
|-----------------------|----------------------------|
| Density | 7850 kg/m ³ |
| Modulus of elasticity | 2.05 × 10 ⁵ MPa |
| Poisson's ratio | 0.3 |
| Yield strength | |
| Girder | 321 MPa |
| Stiffener | 263 MPa |
| Support | 241 MPa |

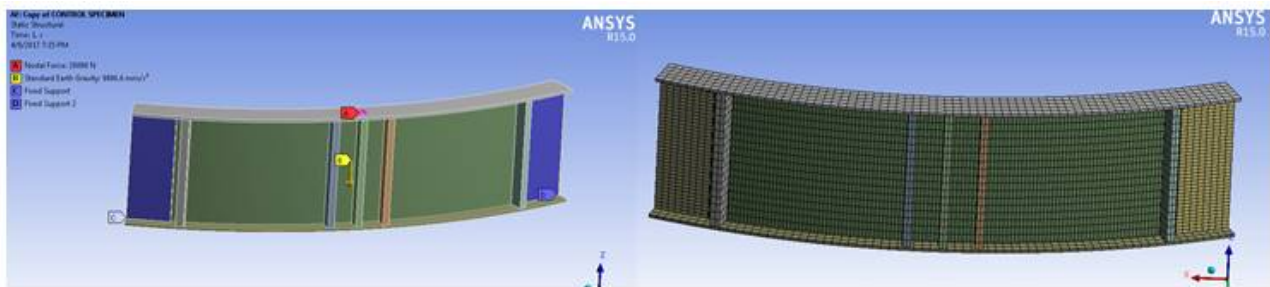
Table 1 Material properties of specimen

IV. MODEL DETAILS

A three-dimensional finite element model to predict the behaviour and ultimate load of curved plate girders with web openings, was employed in this study. Modelling was done in CATIA v5 and analysis was done using the finite element software ANSYS version 15.0. Flanges were 24 mm wide, 3.26 mm thick, 889 mm and 997 mm inner and outer radii respectively, 698.2 mm and 735.9 mm inner and outer arc length respectively. Web were 180 mm deep, 1.63 mm (14 gauge) thick with 913 mm radius and 717 mm arc length. The span of the girder was 700 mm which was the span that can be used in the laboratory machine. 5 mild steel strips of thickness 24 mm were used as stiffeners on each face of girder. On each face, one stiffener below the loading point named as Load Bearing Stiffener (LBS) were given at the mid-span in order to prevent any mode of failure not required in the study. Side stiffener of same specification were given on either side of LBS, 35 mm away from it. The end condition was fixed. For the test specimen, the ends were bolted to a support plate to prevent it from twisting and the support plate was bolted to a secondary beam beneath to achieve fixity. In ANSYS, the end faces were selected and fixed support condition was given. End stiffeners were

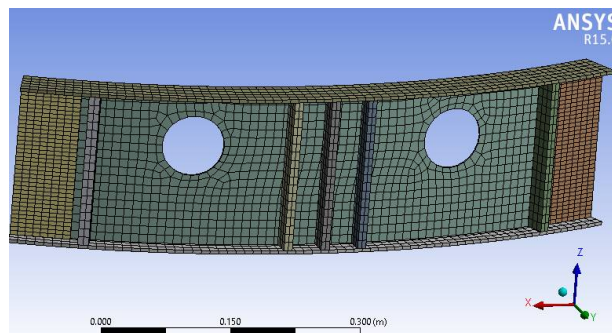
provided at each face of girder end, 10 mm away from the support plate. The end stiffeners and side stiffeners were employed to resist the tension field action of the web panel. All the parts of girder were continuously welded using gas metal arc welding. So the property provided in ANSYS was bonded property.

Figure 1(a) shows the geometry, end condition and loading condition of the control specimen CS. Figure 1 (b) shows the meshing of CS and Figure 1 (c) shows the meshing of girder with circular opening, C4DU.



1(a)

1 (b)



1 (c)

There are 2 methods of developing the model; creating a straight beam in ANSYS and curving it, and importing the same model developed in other software. For easy usage, all models were created in CATIA and imported to ANSYS, and properties were assigned. To get a smooth meshing as shown in Figure 1(c) and (d), 8 noded element was used.

V. EFFECT OF POSITION OF OPENING

Circular opening was used for the study the effect of position of opening as it is the most commonly used shape. The circular opening of size $0.4D$ (72 mm) is used. The ultimate loads are compared to determine the effect of position of web opening in the ultimate load behaviour of a horizontally curved girder. Point load of 100 kN were applied gradually in 10 steps.

Notations used for the models are:

| | | |
|------------|---|--|
| L3, L4, L5 | → | L/3, L/4, L/5 (Distance from web panel end). |
| 4D | → | 0.4 X Depth of web |
| C | → | Near load centre |
| D3 | → | D/3 (Distance from the web bottom or top) |
| S | → | Near support |
| U | → | Up opening |

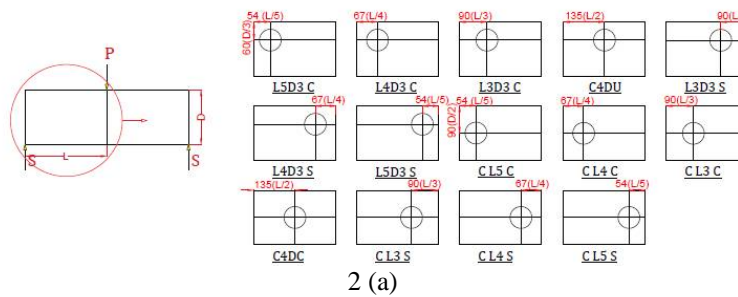
Figure 2 (a) shows the different positions of opening considered for study, all referred dimensions in mm.

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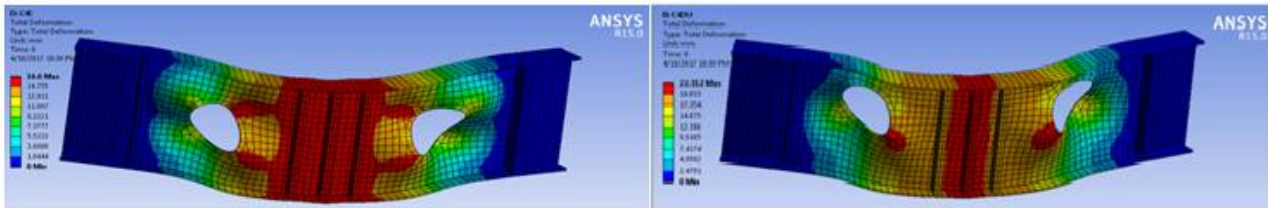
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2 (a)

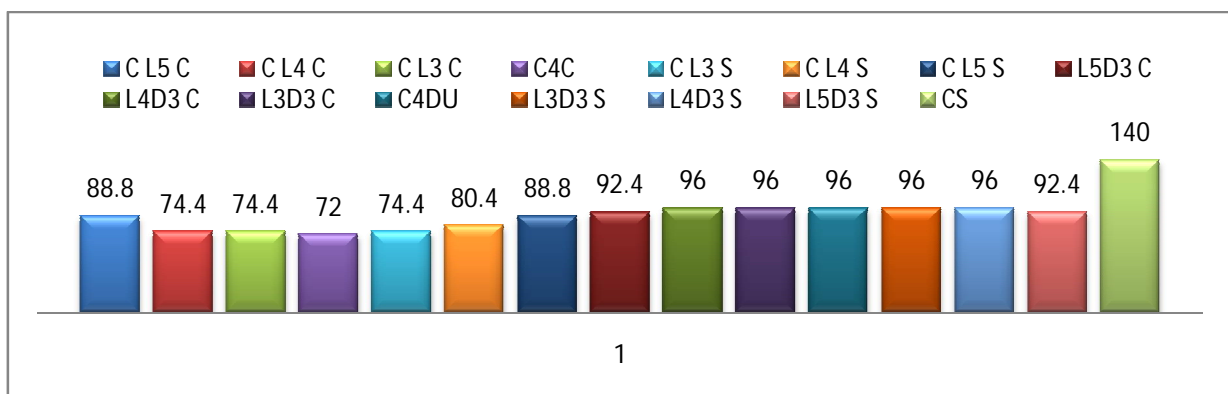
For each model, position of opening in a web shown in Figure 2 (a) had its opening mirrored in the adjacent web of the girder. The position varied in depth and width to study the variation of ultimate load capacity and find its safest and critical positions. The various positions adopted along the length of panel are $L/2$, $L/3$, $L/4$ and $L/5$ whereas along the depth of panel are $D/3$ (from top of web and bottom of web) and $D/2$.

Figure 3 (a)-(c) shows the deflection diagrams of C4DC and C4DU and comparison of ultimate load at various positions respectively.



3 (a)

3 (b)



3 (c)

It was observed that as the position is varied from one load end of web panel to the support end at web depth $D/3$, the load carrying capacity is unaffected except at a position near web panel ends. The drop in ultimate load carrying capacity at the web panel ends are 4.3 %. It can be seen from Figure 3(c), as the position is varied from one load end of web panel to the support end at web depth $D/2$, the load carrying capacity is affected depending on the position of the opening. Comparing all the positions, the ultimate load carrying capacity is significantly dropped for C4DC ($L/2$, $D/2$) compared to C4DU. The variation between C4DC and C4DU are 25%.

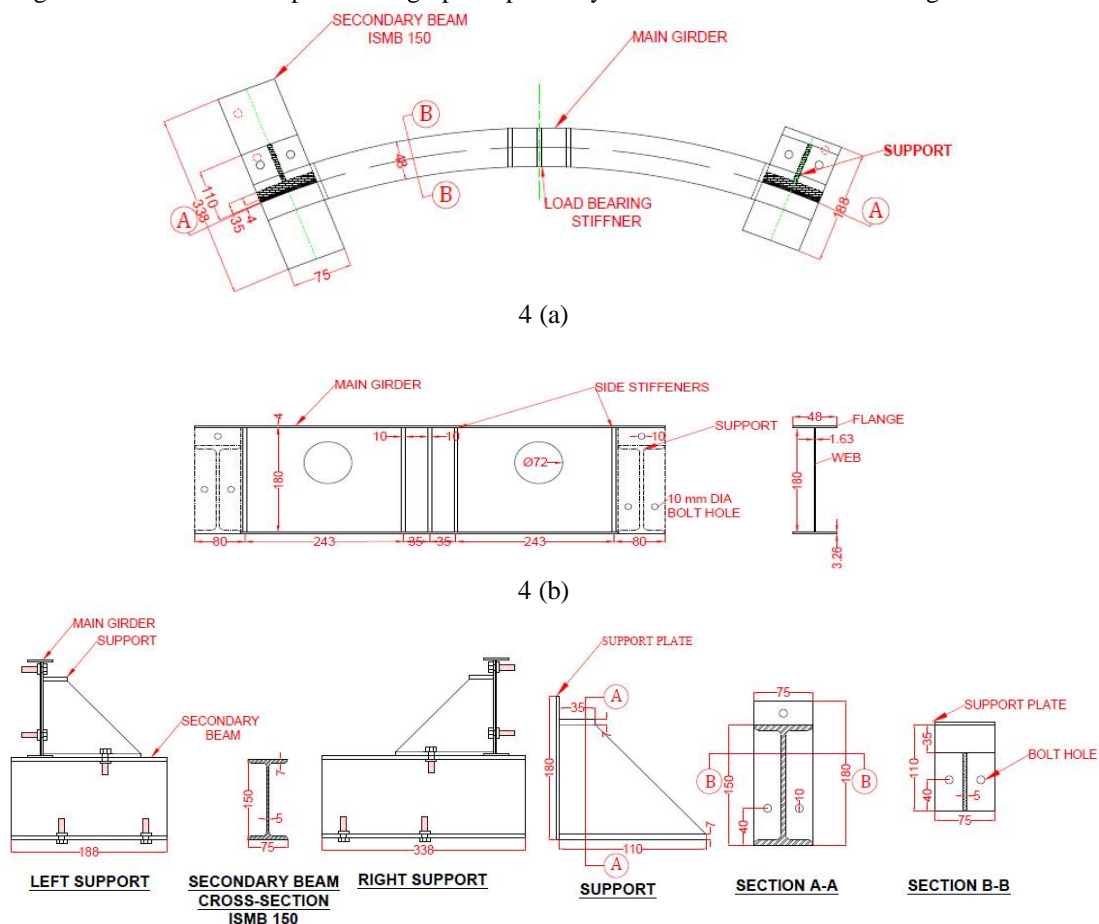
Based on the observations made from the ANSYS results obtained (Figure 3(a) and (b)), it was inferred that giving an opening at D/3 position is advantageous than at D/2 position as the load carrying capacity is significantly low for C4DC than for C4DU, the ultimate load carrying capacity is less affected along the length of the panel at D/3 depth.

The modelling was done only for girders with opening at D/3 from top. To check how it differs for girder with opening at D/3 from bottom, analysis for C4DD is done. Then the ANSYS results of C4DU and C4DD were compared with experiment results.

VI. EXPERIMENT DETAILS

The girder was fabricated at steel workshop and the support section was fabricated at Machine Lab. Girder was bolted to support section using 3 bolts on each end and the support section was bolted to bottom secondary beam. The secondary beam was in turn bolted to the UTM groove to achieve fixity.

Figure 4 (a)-(h) gives the plan of the girder, sectional view, support details, before and after testing of C4DU and C4DD of the girder and their load-displacement graph respectively. All dimensions in the drawing are in mm.



4 (c)

Support plate was given was given only on one face at each of girder (as in Figure4 (a)) because the twist of girder was expected on that side due to the curvature of the girder. Instead of giving eccentric loading, the supports were eccentrically placed on the UTM. The secondary beam and support plate in Figure 4 (c) was made from ISMB 150.

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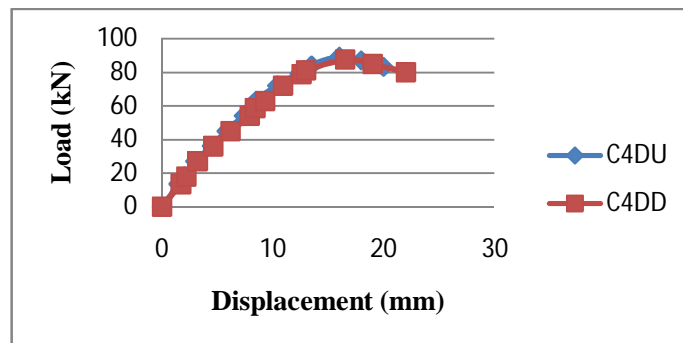
4 (d)

4 (e)



4 (f)

4 (g)



4 (h)

After the experiments conducted, it was observed that the girders C4DU and C4DD behaved similarly during the experiment as shown in Figures 4 (g) and (e). C4DU failed at 89 kN with 16 mm deflection and C4DD failed at 87.6 kN with 16.5 mm deflection (Figure (h)). The ultimate load and corresponding deflection of C4DU and C4DD are close enough that they are almost overlapping as in Figure 4 (h). So it can be concluded that behaviour of girder with down opening at any position will behave similar to that of UP opening.

VII. EFFECT OF SHAPE OF OPENING

3 shapes were considered: circle, square and oval. Shapes of same area are considered for the study. For this, circle was taken as the control shape and a diameter of $0.4 \times \text{Depth}$ was considered and whose study was done in the previous section. Experimental study was done and then it was compared with analytical results.

For the girder with square opening S4DU, the opening was given $D/3$ from top. The dimension of side are calculated as follows;

$$\text{Area} = d^2$$

$$4071.5 \text{ mm}^2 = d^2; \text{ Side, } d = 64 \text{ mm}$$

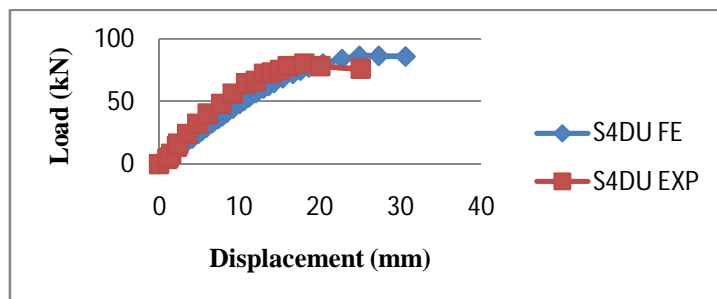
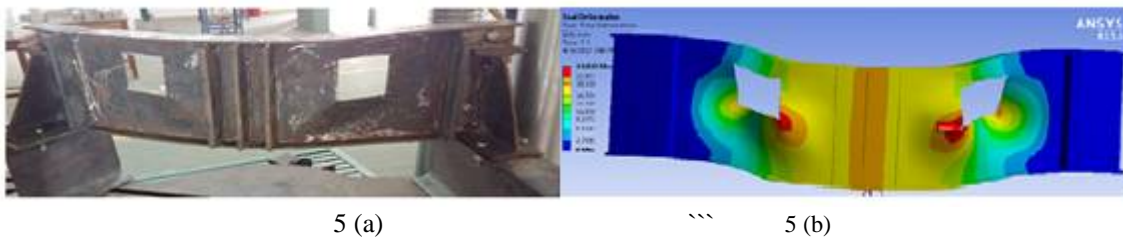
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Figure 5 (a)-(c) gives experimental details, ANSYS details and load vs displacement graph of S4DU.



5 (c)

It can be seen in figure 5 (c) that the ultimate load of S4DU obtained from ANSYS (86.4 kN, 24.8 mm deflection) match the experimental results (80 kN, 18 mm deflection). The specimen failed at lesser deflection compared to the analytical result. The torn corners prove the concentration of stress at the corner of openings in Figure 5 (a).

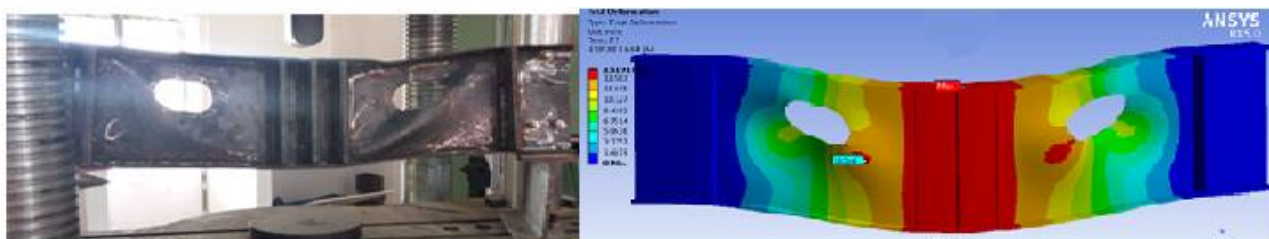
For the girder with oval opening O4DU, the opening was given D/3 from top. The dimension of side *a* are calculated as follows;

$$\text{Area} = \frac{\pi}{4} \times a^2 + \left(\frac{a}{2}\right)^2$$

$$4071.5 \text{ mm}^2 = \frac{\pi}{4} \times a^2 + \left(\frac{a}{2}\right)^2$$

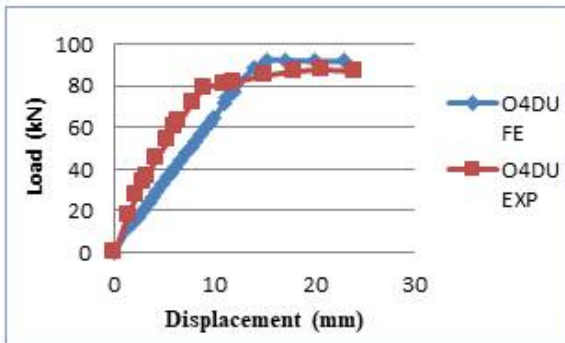
$$a = 48 \text{ mm}$$

Figure 6 (a)-(d) gives experimental details, ANSYS details, load vs displacement graph of O4DU and comparison of ultimate load behaviour of different shapes.

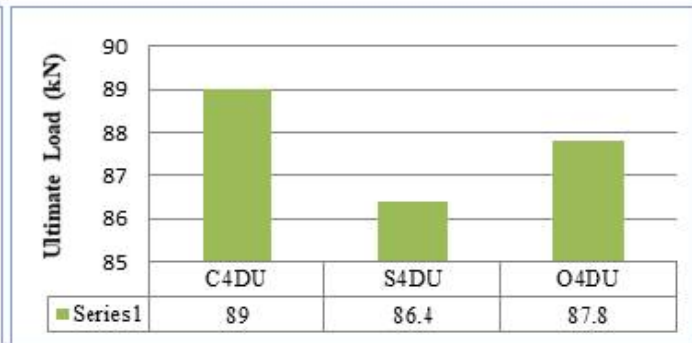


6 (a)

6 (b)



6 (c)



6 (d)

It can be seen from graphs 4 (c), 5(c), 6(c) and 6 (d) that the experiment values match with the ANSYS results. The square and circle shape has the least and greatest load carrying capacity respectively and the oval shape displays a load carrying capacity between them. Torn corners were seen for the square shape after experiment. This must be due to the stress concentration at the corners of the opening. Though O4DU showed higher load carrying capacity than square, the displacement was comparatively large. The ultimate load of S4DU is 2.92% lesser than C4DU & that of O4DU is 1.3% lesser than C4DU. The minute difference shows that at D/3 position, varied shapes can be safely employed.

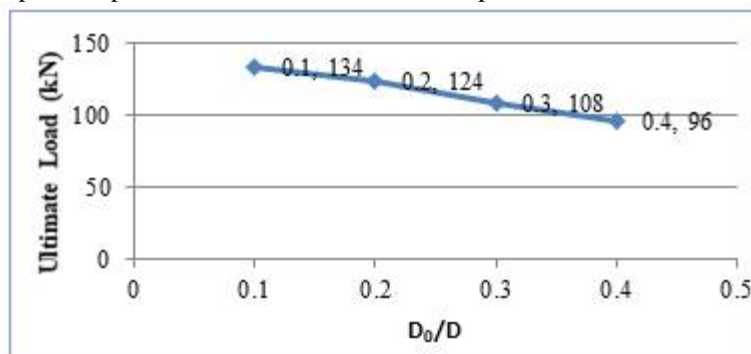
VIII. EFFECT OF SIZE OF OPENING

4 sizes of opening were used in the study as shown below.

- C = Circular opening
- U = Up opening
- 1D, 2D, 3D, 4D = $0.1 \times \text{Depth}, 0.2 \times \text{Depth}, 0.3 \times \text{Depth}, 0.4 \times \text{Depth}$
= 18 mm dia, 36 mm dia, 54 mm dia, 72 mm dia.
- D_0 = Diameter of opening.
- D_0/D = 0.1 (for 1D), 0.2 (for 2D), 0.3 (for 3D), 0.4 (for 4D).

The models used in the study were C1DU, C2DU, C3DU and C4DU. The dimension of opening was limited to 0.4 times depth as bigger size than that wouldn't fit the web at D/3 position. Models at up position was only analyzed since it was found in the previous section that for a position, girder behave similarly in up and down position.

Figure 7(a) shows the graphical representation for ultimate load comparison of the models after analysis.



7 (a)

From the analysis results, it was observed that as the size of the opening increases, the load-carrying capacity of specimen decreases. The concentration of stress was seen at the opening. From the section discussed on position of opening, it was obtained that the ultimate load capacity of CS was 140 kN and that of C1DU was 134 kN which are very close that the presence of opening is less affected (4.28% difference). The largest opening C4DU has the least load

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carrying capacity of 96 kN (31.42% difference compared to CS). From Figure 7 (a) it can be seen that the load against d_o/d relationship is approximately linear.

IX. EFFECT OF FLANGE STIFFNESS AND WEB SLENDERNESS

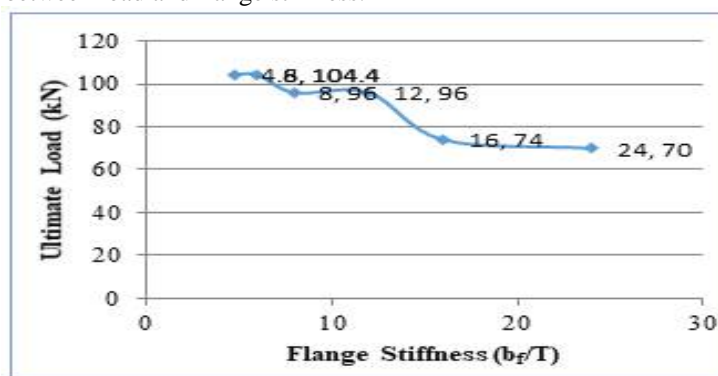
This section deals with how the parameters such as web slenderness ratio and stiffness of flange influence the behaviour of a horizontally curved girder with openings. Flange stiffness is taken as the ratio of width of flange to its thickness, (b_f/T) . The lower the value, the stiffer the flange is. Analyses are done to see the effect of flange stiffness and variation in ultimate load, displacement and torsional moment and graphs are plotted to draw conclusions. For the study, 6 models were analysed, F2 (2mm thick flange), F3 (3mm thick flange), F4 (4mm thick flange), F6 (6mm thick flange), F8 (8mm thick flange) & F10 (10mm thick flange) where F4 was taken as the control size. All other specifications are as same as C4DU.

Table 1 shows the results and percentage variation of the models used to study flange stiffness.

| Flange Width (mm) b_f | Flange Thickness, T (mm) | Flange Stiffness b_f/T | Ultimate Load, P (kN) | % Difference of P | Torsional Moment, M (kNm) | % Difference of M | Displacement (mm) |
|-------------------------|--------------------------|--------------------------|-----------------------|-------------------|---------------------------|-------------------|-------------------|
| 48 | 2 | 24 | 70 | 27.08 | 3.03 | 38.16 | 21.129 |
| | 3 | 16 | 74 | 22.91 | 3.45 | 29.59 | 22.569 |
| | 4 | 12 | 96 | - | 4.9 | - | 22.312 |
| | 6 | 8 | 96 | - | 5.16 | 5.3 | 18.895 |
| | 8 | 6 | 104.4 | 8.75 | 5.62 | 14.69 | 21.087 |
| | 10 | 4.8 | 104.4 | 8.75 | 5.64 | 15.1 | 18.41 |

Table 1 Percentage difference of corresponding values

Figure 8 shows the graph between load and flange stiffness.



8 (a)

From the table and figure 8, it was observed that as the flange thickness is increased, it becomes stiffer and fails with a lower displacement. Table 1 showed the percentage difference of P and M for different models where lower the value of flange stiffness is, stiffer the flange is. It can also be seen in Table 1 that displacement is less affected due to flange stiffness. Ultimate load carrying capacity is directly proportional to flange stiffness. Torsional moment capacity is less affected due to flange thickness.

Considering the web slenderness, it is the ratio of depth of web to its thickness, D/T . The thinner the web is, the higher the value is. The necessity for study of web slenderness ratio arises in this field because of the extensive use of thin webs. Analyses are done to see the effect of web slenderness and variation in ultimate load, displacement and

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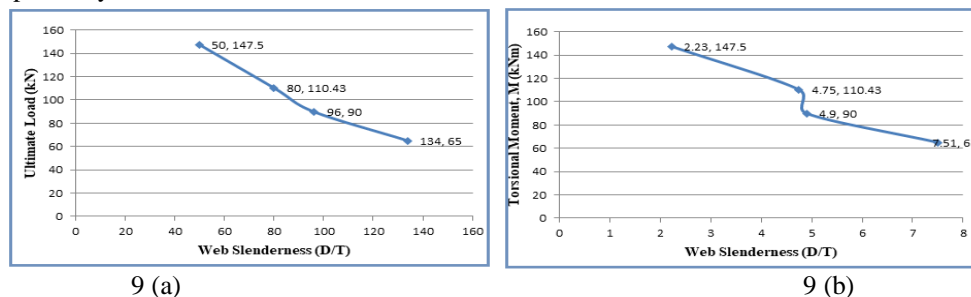
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torsional moment and graphs are plotted to draw conclusions. For the study, 4 models were analysed, W1.22 (1.22mm thick web), W1.63 (1.63mm thick flange), W2 (2mm thick flange), W2.77 (2.77mm thick flange), & where W2 was taken as the control size. All other specifications are as same as C4DU.

Figure 9 (a) and (b) shows the graph between ultimate load and web slenderness & torsional moment and web slenderness respectively.



From figure 9 (a) and (b), it can be concluded that ultimate load carrying capacity is inversely proportional to the web slenderness of the web. The variations of values are almost linear as it can be seen in the graph. There is considerable change in the torsional moment with respect to the web slenderness which shows that the performance of web directly influences the torsional moment capacity than the flange.

X. CONCLUSIONS

This paper dealt on parametric study on horizontally curved steel I girders (HCG) with web openings. Based on the experimental and analytical studies done, the following conclusions are made. The most advantageous position for opening in HCG is at D/3 position from web bottom or top and the critical position is at the centre. Different shapes of opening can be employed without greatly affecting the ultimate load carrying capacity. The ultimate load carrying capacity is less affected along the length of the panel at D/3 depth. As the size of the opening increases, the load-carrying capacity of specimen decreases. Ultimate load carrying capacity is directly proportional to flange stiffness. Torsional moment capacity is less affected due to flange thickness. There is considerable change in the torsional moment with respect to the web slenderness which shows that the performance of web directly influences the torsional moment capacity than the flange.

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