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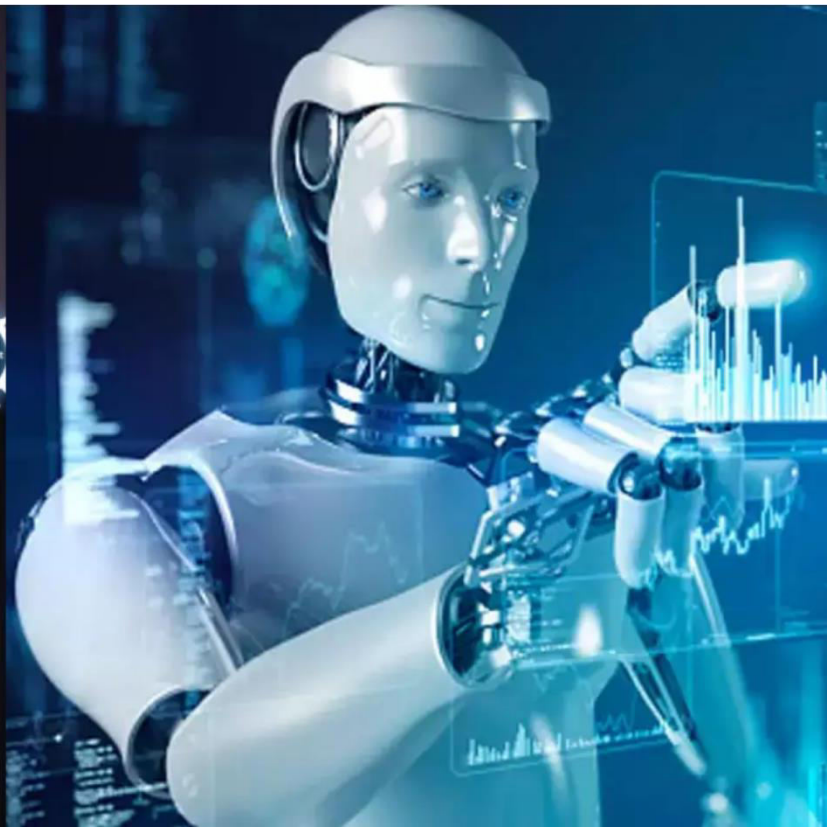

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Structural Behavior of Steel Beams for Elliptical Openings with Variable Spans and Loads

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ABSTRACT: Integrating building utilities within the structural floor zones was essential for modern high rise commercial construction to reduce the storey height and material cost. Web perforations allows the duct work and conduits to pass directly through steel beams. However, creating openings, alters internal stress distribution, reduces shear capacity and impacts serviceability deflections. The paper presents the comprehensive parametric investigations, evaluating the structural performance and serviceability behavior of bare steel beam featuring central single elliptical web openings as per the required spacings throughout the length of beam. The full factorial analysis matrix, comprising full 36 distinct structural models were evaluated across three Indian Standard medium weight beams as ISMB 400, ISMB 500 and ISMB 600, with three types of depth ratio as 0.5 D, 0.6 D, 0.7D where D is the overall depth of beam. Analysis was carried out for two different spans as 6.0 m and 9. 0 m These parameters were analyzed the structures for two uniformly distributed loads as 10 Kn/m and 15 Kn/m

For each structural model, three primary parameters were evaluated (1) Design Bending Moment (Md), (2) Design shear force (Vd) and (3) Mid span deflection Thus generating a complete data set of 108 results. All the defections were checked against permissible limit of Span / 325 in accordance with IS Code 800-2007.For opening, Elliptical shape was considered. The C G of the beam coincides with the C G of the Elliptical shape of the opening.

The results indicate that the elliptical opening provides a smooth stress transition around the perforation parameters, mitigating local stress concentration factors observed in sharp corner engineering out-outs. While increasing opening depths from 0.5 D to 0.7 D, leads to a progressive in web shear resistance and net Moment of Inertia. maintaining the structural integrity. Practical design guidelines and section selection were established to assist structural engineers and Architects to select the section.

KEYWORDS: Elliptical Opening, Bending capacity, Shear capacity, Web Perforation, ISMB Sections

I. INTRODUCTION

In modern structural engineering and commercial building construction, integrating building services - such as HVAC duct work, electrical conduits, plumbing lines and fire protection piping -within the structural flooring zones were essential for optimizing storey height and reducing total building volume. Traditional solid web steel sections often required suspended utility networks underneath the bottom flange, which increases the floor-to-floor height and leads to higher material costs for claddings, columns, and structural wall systems. To overcome these architectural and spatial constraints, perforated steel beams featuring web openings became an established structural solution. Web perforations allow building utilities to pass directly through the structural depth of beam, significantly saving vertical space without increasing overall vertical building height. However, creating openings in the web of steel beams alters its structural behaviour introducing local stress concentration, reducing cross sectional shear capacity (Vd), and decreasing flexural stiffness, which directly impacts mid span deflections.

The geometric profile of web opening plays a critical role in dictating the stress field around the perforation. While rectangular and castellated hexagonal openings were widely utilized due to ease of fabrication, they exhibit sharp geometric corners that generate severe stress concentration, secondary bending and localized web buckling under heavy shear loadings. Conversely, continuous curved profiles -such as circular and elliptical geometries -distribute internal shear and flexural stress fields far more smoothly along their parameters. Ellipticals opening in particular, offer a distinct advantage, they provide wider horizontal clearance for utility routing while maintaining the controlled vertical opening depth. (0.5 D ,0.6 D ,0.7 D) minimizes the loss of moment of inertia (Inet) compared to large circular or rectangular cutouts The details of elliptical openings were shown in Fig 1.

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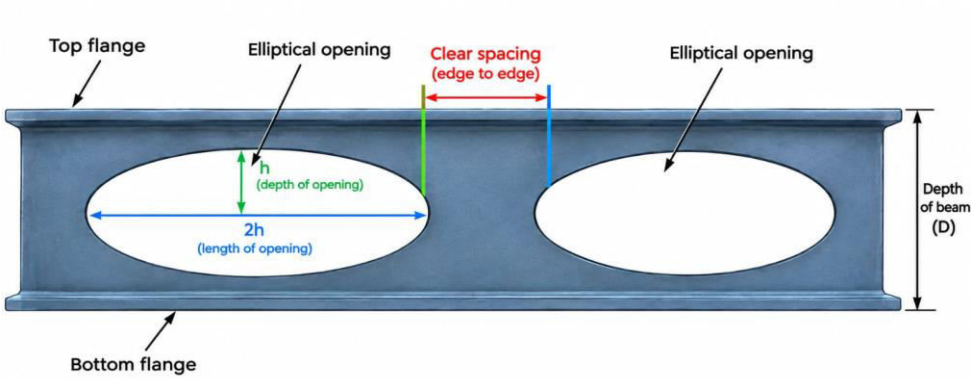

Fig.1. Showing the detail of opening

Furthermore, maintaining practical minimum height of openings at least 150 mm ensures sufficient utility clearance for building services

To analyze the structure, various parameters were considered. Total two spans of 6.0m (Residential building span) and 9.0 m (Industrial structure span) were opted. For these spans uniformly distributed loads as 10 kn/m and 15 kn/m were considered To analyze the structures three beams (ISMB 400, ISMB 500, ISMB 600) were considered.The primary object of this study was to evaluate the effect of elliptical web openings. To analyze the castellated beam, Elliptical shape openings were selected, with an aspect ratio of 0.5D, 0.6D and 0.7D. Where D is the overall depth of the selected beams. To avoid the stiffeners, adequate clear spacing between two openings were maintained. To quantify changes across 36 distinct structural models yielding 108 primary outputs were selected. Using three beams x three openings x two spans x two loads x three design parameters (Md, Vd, Deflection) total 108 designed data were calculated, = 3 x 3 x 2 x 2 x 3 = 108. To verify all mid span deflections, a permissible limit of L/325 as per IS code 800 -2007, was considered where L is the span length.

The results thus obtained were displayed in tabular form. Similarly, to study the deflections for two spans and two loads with three distinct openings, three graphs were also shown. The results thus obtained will act as ready reckoner for field and structural Engineers and Architects.

II. METHODOLOGY

This study employs a rigorous full factorial parametric framework to evaluate the structural behaviour and serviceability performance of bare steel I section beams featuring central single Elliptical web openings. The analytical methodology is structured to systematically isolate the effect of beam sections depth, opening ratio, span length and load magnitude under the codal provision of IS Code 800- 2007. To establish a compressive data base of structural responses, a total 36 distinct parametric models were formulated. The matrix form four independent variables

Beam cross sections * ISMB 400, ISMB 500, ISMB 600. Elliptical opening depth ratio as 0. 5 D, 0.6 D, 0.7 D

D = Over depth of selected beam Standard spans of 6.0 m and 9 .0 m were selected to analyse the structure

Uniformly distributed load of magnitude 10.0 Kn/m and 15.0 Kn/m the combinations of these parameters 108 primary output data points as design bending moments (Md), Design shear force (Vd) and mid span deflection were selected. Analysis was completely based on structural steel configurations without composite concrete floor slab to evaluate the isolated performance of perforated steel profile. The results thus obtained were displayed in tabular forms and graphs.
To analyze the structures, the following sequence was adopted for all three beams. An attempt was made to carry out the working method for the beam as a sample.

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Beam span = 6.0 m and 9.0m. Loading: uniformly distributed load = 10 Kn/m and 15 Kn/m Beam section:: ISMB 400 @ 61.5 Kg/m.
Depth of opening = 0.5 D ,o.6 D , 0.7 D , Where D = Over all depth of beam
For o.5 D =0.5 x 400 = 200 mm
Total three output = Md , V d , actual deflection. (3)
Same beam, same span and same loading for opening depth = 0.6 D
Total three Out put = Md , V d , and actual deflection (3)
Same beam, same span and same loading for opening depth = 0.7 D
Total three Output = Md , V d , and actual deflection (3)
Total results were 3 + 3 + 3 = 9
Similar results for span = 9.0 m
All such results thus obtained, were also shown in three tables of observation chapter

III. OBSERVATIONS

To analyze the castellated beam with elliptical openings and different spans and loadings, it was decided to select three beams as ISMB 400, ISMB 500, ISMB 600.The required details were available in IS code as well as in standard steel tables. The beams were analyzed for spans as 6.0 m and 9.0 m with 10 Kn /m and 15.0 Kn / m uniformly distributed loads. The Elliptical shape openings were selected. The depth of openings was created as per the ratio of depth of concerned beams. Three openings were selected as 0.5 D, 0.6 D ,0.7 D where D is the overall depth of the beam as shown in Table 1

Table.1. Showing the design details

Sr. No.	Beam	Depth of Beam	Ratio	Opening Depth
1	ISMB 400	400 mm	0.5 D	200 mm
			0.6 D	240 mm
			0.7 D	280 mm
2	ISMB 500	500 mm	0.5 D	250 mm
			0.6 D	300 mm
			0.7 D	350 mm
3	ISMB 600	600 mm	0.5 D	300 mm
			0.6 D	360 mm
			0.7 D	420 mm

For ISMB 400 with all the three elliptical opening depths, mentioned above, for two spans as 6 m and 9 m with uniformly distributed load of 10 Kn/m and 15 Kn/m, analysis was carried out to find out the design moments (Md), design shear (Vd) and actual deflections. The results thus obtained were displayed in Table 2

Table 2: Showing design parameters for ISMB 400

Design details for ISMB 400						
Overall beam depth = 400 mm						
Beam	Overall depth (mm)	Opening ratio	Opening depth (mm)	Zp open (cm^3)	Vd (kN)	Md (kN·m)
ISMB 400	400	0.4D	160	1113.04	280.28	252.96
ISMB 400	400	0.5D	200	1081.40	233.56	245.68
ISMB 400	400	0.6D	240	1041.84	186.85	236.78
ISMB 400	400	0.7D	280	995.55	140.14	226.26
ISMB 400	400	0.8D	320	942.16	93.43	214.13

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The deflection Vs opening depth ratio for the castellated beam ISMB 400 for 6 m and 9 m spans with uniformly distributed loads of 10 Kn / m and 15 Kn /m over an entire span were shown in Fig 2

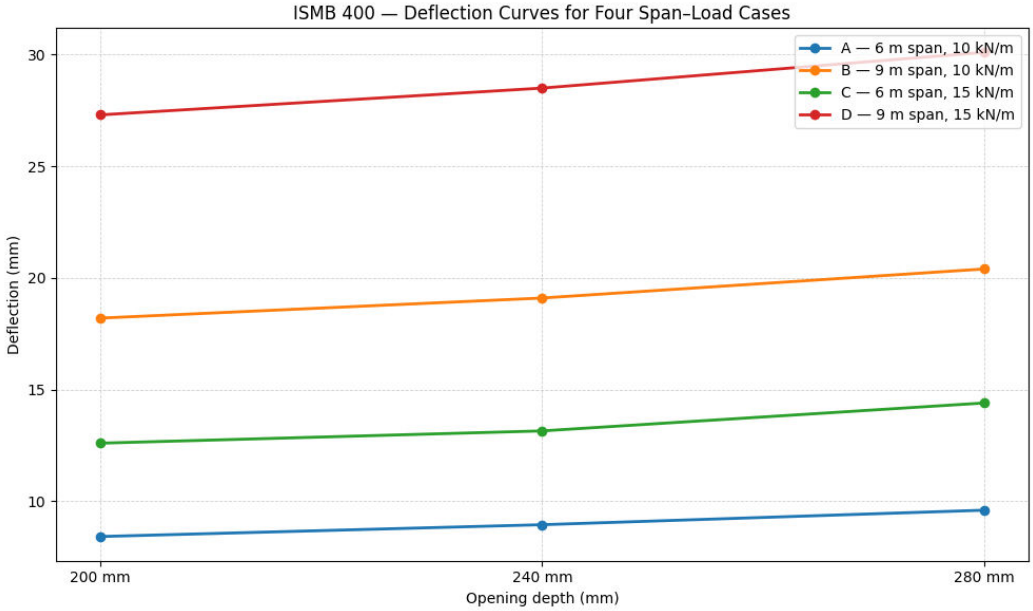

Fig.2. Showing deflection Between opening Vs Deflections

For ISMB 500 with all the three elliptical opening depths, mentioned above, for two spans as 6 m and 9 m with uniformly distributed load of 10 Kn/m and 15 Kn /m, analysis was carried out to find out the design moments (Md), design shear (Vd) and actual deflections. The results thus obtained were displayed in Table 3

Table3: Showing design parameters for ISMB 500

Design details for ISMB 500

Overall beam depth = 500 mm

Beam	Overall depth (mm)	Opening ratio	Opening depth (mm)	Zp open (cm^3)	Vd (kN)	Md (kN·m)
ISMB 500	500	0.4D	200	1979.00	401.52	449.77
ISMB 500	500	0.5D	250	1921.63	334.66	436.73
ISMB 500	500	0.6D	300	1851.50	267.68	420.80
ISMB 500	500	0.7D	350	1768.63	200.76	401.96
ISMB 500	500	0.8D	400	1673.00	133.84	380.23

The deflection Vs opening depth ratio for the castellated beam ISMB 500 for 6 m and 9 m spans with uniformly distributed loads of 10 Kn / m and 15 Kn /m over an entire span, were shown in Fig 3

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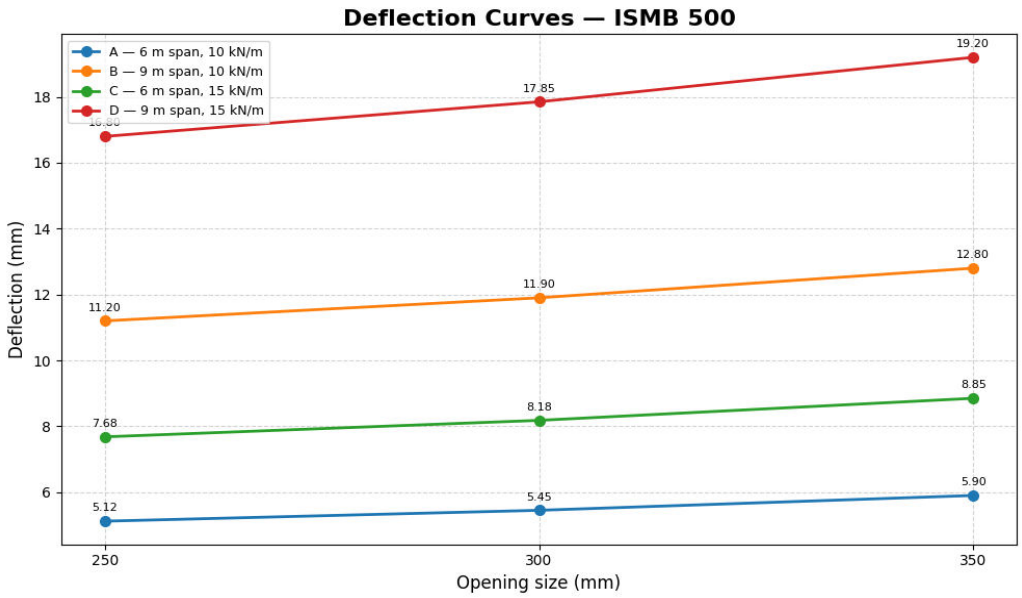

Fig 3 Showing deflection Between opening Vs Deflections

For ISMB 600 with all the three elliptical opening depths, mentioned above, for two spans as 6 m and 9 m with uniformly distributed load of 10 Kn/m and 15 Kn /m, analysis was carried out to find out the design moments (Md), design shear (Vd) and actual deflections. The results thus obtained were displayed in Table 4

Table 4: Showing design parameters for ISMB 600

Design details for ISMB 600

Overall beam depth = 600 mm

Beam	Overall depth (mm)	Opening ratio	Opening depth (mm)	Zp open (cm^3)	Vd (kN)	Md (kN·m)
ISMB 600	600	0.4D	240	3327.20	566.85	627.00
ISMB 600	600	0.5D	300	3180.00	472.38	666.82
ISMB 600	600	0.6D	360	3061.00	377.90	695.73
ISMB 600	600	0.7D	420	2920.80	283.43	722.73
ISMB 600	600	0.8D	480	2758.50	188.95	744.82

The deflection Vs opening depth ratio for the castellated beam ISMB 600 for 6 m and 9 m spans with uniformly distributed loads of 10 Kn / m and 15 Kn /m over an entire span were shown in Fig 4

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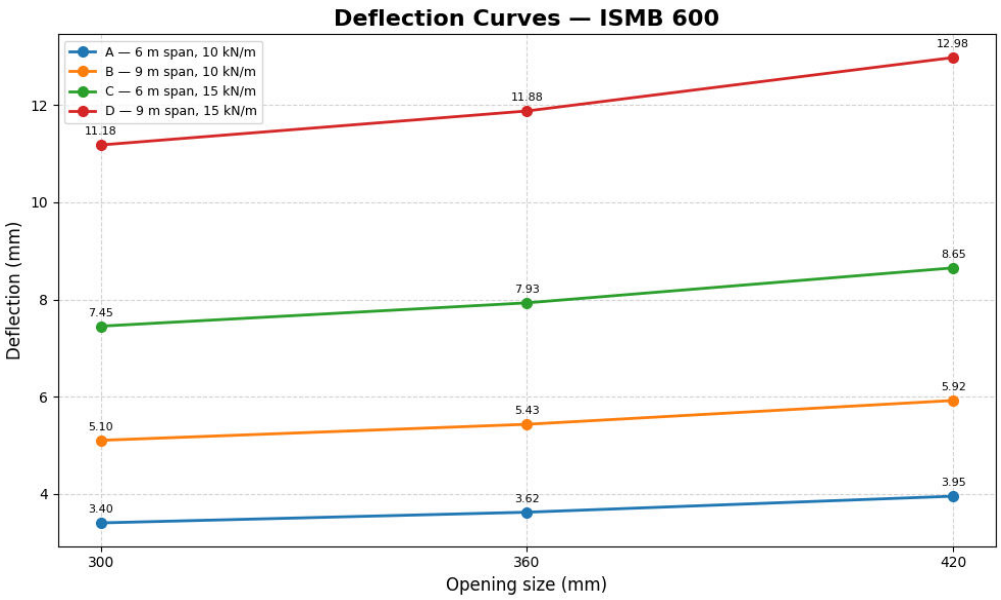

Fig 4 Showing deflection Between opening Vs Deflections

IV. RESULTS

In ISMB 400, for 6 m and 9 m spans, under uniformly distributed load of 10 kn/m and 15 Kn/m, it was observed that the actual deflection increases with increase in opening ratio 0.5 D to 0.7 D where D= over all depth of beam. For 6 m span under 10 Kn/ m udl, the deflection increases from 8.42 mm to 9.60 mm ie 14.0 % increase. For 9.0 m span, under 15 Kn/m udl, the deflection increases 27.30 mm to 30.10 mm. The rate of increase is more pronounced for larger span and higher loads.

For ISMB 500 Castellated beam with elliptical openings, follows the similar path as observed in ISMB 400 beam loading but the magnitude of deflection was found to considerably reduce the deflection. For a 6.0 m span with 10 Kn/m udl, the deflection decreases from 5.12 to 5.9 mm. For a 9.0 m span, under 15 Kn/m udl, the variation of deflection varies from 16.80 mm to 19.20 mm. This indicates that beam ISMB 500 was stiffer than ISMB 400, due to higher moment of inertia.

Beam ISMB 600 shows the minimum deflection was observed among all other two beams. For 6m span and 10 Kn /m udl, the deflection observed to be only 3.40 mm to 3.95 mm. For 9.0 m span, with 15 Kn/ m udl, deflection was 11.18 Mm to 12.98 mm. These results indicate that this beam provide better resistance as compared to cellular beam as for the design aspect was concerned, it was recommended that the ratio of 0.5 D is suitable to keep the deflection within limit. It was a fact that Deeper sections were more efficient to control the deflections. For ISMB 400 when depth ratio increases from o.5 D to 0.6 D and o.7 D It was observed that the shear capacity (Vd) decreases by 46 Kn for every 0.1 D increase of opening ratio. It was observed that due to an increase of opening ratio by 0.1 D, the net plastic modulus of ISMB 400, reduced by magnitude of 6o Cm ^4. These results were applicable to castellated beams for elliptical openings. When focused on effective shear areas of ISMB 400, it was observed that shear area decreases by 365 mm^2 for every increase of opening ratio by 0.1 x D where D is the overall depth of selected castellated beam.

ISMB 500: When carefully observed, it was seen that for every 0.1D increase of elliptical opening depth, an effective shear area of beam decreases by 510 mm^2 .For the same beam, it was found that for the same beam value of Zp decreases by 100 cm^3 . Similarly, the design shear capacity, Vd, decreases by 68 Kn for every 0.1 D increase of opening depth ratio, In the same pattern, it was seen that for the same 0.1 D incremental depth of opening the design capacity of moment, Md, decreases by 68 Kn m

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ISMB 600: To study the effect on various design parameters, by making the Changes in opening depth ratio, for every increase of opening by 0.1 D, an effective shear area decreases by 72 mm^2. The design moment capacity (Md) decreases by 41 Kn m.

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