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# Parametric Investigation of Shape and Size of Openings on Serviceability Performance of Castellated Beams

**Dr Vikas Gandhe** Structural Engineer
251 B Silicon city, Indore (M. P.) India

**Abstract - This paper introduces a significantly rigorous parametric framework for evaluating the structural performance and efficiency of hot rolled steel beams featuring diverse web perforations. Utilizing standard profiles as ISMB 300 , ISMB 400 and ISMB 500 as parent sections , a comparative analysis isolates the behaviour of the five opening, ,topologies as circular , hexagonal,trapezoidal , rectangular and diamond shapes .The web perforation depths was systematically scaled across four distinct ratios as 0.5 D, 0.6 D, 0.7 D, and 0.8 D (Where D is the overall depth of beam ). The cross sectional areas of material removed was kept strictly constant across within each parametric series for all five shapes It clearly indicates that the cutting volume of all the five shapes remains the same .The parametric analysis was carried out ;selecting a simply supported beam with a span of 6.0 m, provided with uniformly distributed load of 10 kn/m over the entire span . The structural response was evaluated in terms of moment capacity, shear capacity and magnitude of deflection, in accordance with codal provisions .Castellated beam showed relatively better stiffness performance, compared to cellular beam ,specially for large openings All the three beams, mentioned above, were analysed for all types of openings ,and four aspect ratios,keeping the span of 6.0 m and uniformly distributed load of 10 Kn /m. The study establishes that the deflection was the governing factor with web openings, with magnitude of 0.6 D. All the results were shown in a tabular form and the deflections with respect to openings were shown in graphical form .**

**Keywords - Opening Geometry, Deflection, moment capacity, structural performance, shear strength.**

## INTRODUCTION

In house and long span building frame work, minimizing the dead load of the structural floor system while maintaining strict serviceability control is a primary design objective .Traditional hot rolled steel sections ,while highly robust,frequently introduce a weight penalty when web depth are increased to handle large bending moments. To address these limitations, structural engineering practices were heavily opted for the perforated web. The beam web drastically reduce the dead weight of the section, provides conventionally convenient conduits for building utilities and eliminates the need for increased floor height .Perforated members are generally classified in two categories , based on manufacturing and cutting pattern/ profiles as cellular beam and castellated beam. Cellular beams were provided with a series of circular openings at required spacings. A castellated beam was provided with openings with different shapes as trapezoidal, rectangular , hexagonal ,circular and diamond type with required spacing , over an entire span length. See **Fig 1**

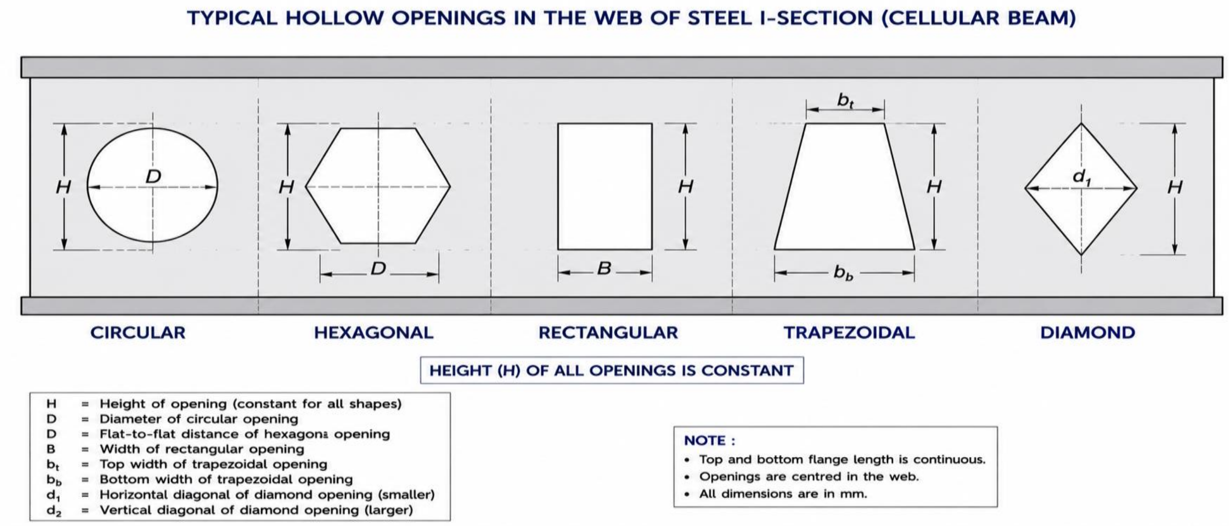


**Fig 1 : Showing Shape Of Openings**

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Expanding the depth of these openings , allows for greater material dead weight saving . But it simultaneously triggers complex structural problems within the web itself. As the steel was stripped away, the beam ceased to act purely as a solid and flexural members.Instead it transforms into a complex formwork ,assembling a Veerendeel truss and the remaining solid strip of steel above and below the holes.(Top and Bottom section) must independently resist localized secondary bending and horizontal shear.
The basic limitations, within existing literature, ware the manner in which the different opening geometries are evaluated . Most conventional studies compare shapes by fixing a single maximum boundary dimensions such as constant height if cut to out across all configurations . While mathematically simple. This direct sizing methodology alters the total volume of steel, removed from shape to shape , failing to isolate whether a beam structural degradation is driven as the volume of material lost by the geometric profile of boundary cut itself. It is important to note that all the openings for all the five shapes have the same area . It clearly indicates that cutting volume of steel in all the indicated beams are equal Similarly ,the depth of openings of all shapes of openings were equal .when depth of cutting is equal as well as total cutting volume is also equal hence cutting of web becomes an easy task for fabricators .In one line concept was defined as

**Equal areas = Equal height = Equal volume displacement**

To resolve this problem , this research introduces Engineered constant area parametric study. By fixing all alternative shapes (Circular , trapezoidal ,rectangular ,hexagonal ,and Diamond) to look on to and match the exact cross sectional area of base line circular cellular cut out ,the volume of the steel removed , remains the strict control variable To observe this mechanism under realistic services environments , this paper evaluates s the profile across the 6.0 m span , carrying an uniformly distributed load of 10 Kn/ m over the entire span , as per the details from IS CODE 800 -2007.Considering three beams as ISMB 300 ,ISMB 400 and ISMB 500, For this analysis ,total four .openenings considered as 0.5 D,0.6 D,0.7D ,0.8 D, . Where D = over all depth of selected beams . All the three beams were analysed for all opening depths
The results thus obtained for SIXTY parameters .These 60 results were displayed in tabular form .For each beam and each four openings as well as for 6m span with 10 kn/ m udl ,results were obtained for maximum bending moment ,maximum shear force and maximum deflection . The relation between openings and deflections were also shown in graphical form and for all the three beams.The results thus obtained are useful for field engineers,structural engineers,architects, fabricators as well as to budding engineers .

## METHODOLOGY

The parametric study was carried out considering three Indian standard medium weight beams as ISMB 300 , ISMB 400 and ISMB 500 . For web opening , each beam depth of opening was adopted as and equal to 0.5 D , 0.6 D ,0.7 D and 0.8 D Where D = overall depth of respective beams . To analyse the beams , a total of five distinct opening shapes were selected .Geometries of shape of openings selected were circular, trapezoidal, rectangle , hexagonal and diamond . These five distinct openings geometries were analysed by using Reversed Engineered area framework.Most important aspects of these five openings were such that the area of all the openings were equal . It clearly indicates that the weight of steel removed from the web were same.Similarly the height of cutting of all openings were the same which was equal to the diameter of circular opening .
The programme establishes the target opening area based on the circular cutout diameter at each scaling tier ,To enforce absolute area equilibrium across the remaining shapes ,the algorithm dynamically rescale their maximum vertical heights and horizontal widths . To finalize the dimensions of all the other opening shapes including the circle were mentioned below .
**Circular Section** : Height and width remains perfectly equal to the baseline diameter .**Rectangle section**: Sides were fixed with an aspect ratio of 1.5 : 1 keeping height = diameter of circular section.
**Diamond Section** : The vertical diagonal was locked to the maximum circular diameter to rigorously test the vertical web limits ,forcing the horizontal diagonal to expand to maintain an area of equilibrium .
**Hexagonal / Trapezoidal** : Shape according to the standard 60 degree cut slope to simulate traditional steel calculation lines
Finally for analyzing the structures , following data were selected

- Three beams ISMB 300 , ISMB 400 , ISMB 500
- Four opening ratio 0.5 D, 0.6 D, 0.7 D , 0.8 D
- Five different shapes : Circular ,Hexagonal ,Trapezoidal ,Rectangular , Diamond
- Uniformly distributor load = w = 10 Kn/m
- Simply supported span = L = 6.0 m

The results for Md , Vd , and actual deflections were calculated and shown in tabular and graphical form . Permissible limit of deflection was taken = L / 325 for the comparison to actual deflections

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For 6.0 m span and 10 kn/ m udl over an entire span ,all the 60 results were obtained for Flexural strength (Md) ,Shear strength ( Vd) and actual deflections for above mentioned three beams , four openings and five shapes of openings .Aii the results thus obtained for Md ,Vd were shown in tabular form . Similarly all the results related to actual deflections were displayed graphically.

## OBSERVATION

Analysis of cellular and castellated beams were carried out for ISMB 300 ,ISMB 400 , and ISMB 500 . Different depths of openings were provided. For ISMB 300 depth of openings were 0.5 D=0.5 x 300 = 150 mm , 0.6 D = 0.6 x 300 = 180 mm , 0.7D = 0.7 x 300 = 210 mm and 0.8 D = 0.8 x.300 =240 mm where D =Overall depth of beams . Total five shapes of openings were selected to carry out the analysis of these castellated and castellated beams. .Five shapes of openings were Circular, Diamond, Hexagonal, Rectangular and Trapezoidal A beam of 6.0 m span with 10 Kn/m udl ,over an entire span, was selected for analysis . To analyze the structure ,three cases were discussed

**Case 01**

A beam **ISMB 300** was analyzed for 6.0 m span with uniformly distributed load of 10 kn / m over the entire span .Following four openings were adopted for critical analyses .The magnitude of openings were 0. 5 D ,0 .6 D , 0.7 D and 0 .8 D .Where D = Over all depth of beam . In this case D = 300 mm .Five different shapes of openings with same cross sectional areas were considered . These openings were *Circular * Diamond * Hexagonal * Trapezium * and Trapezoidal . Maximum equal depths of all the openings ware considered as 150 mm , 180 mm .210 mm , and 240 mm . Value of bending moment (Md) ,Maximum value of Shear Force (Vd) and actual value of deflections were obtained . The results thus obtained were displayed in a tabular form .See **Table 1**

**Table 1 Show the result for ISMB 300**

**PHASE 1 – ISMB 300**

Span = 6 m | Load = 10 kN/m | Steel Grade = Fe415 | Maximum Deflection (L/325) = 18.46 mm

**STRUCTURAL ANALYSIS RESULTS**

| Opening ratio | Parameter | Circular | Hexagonal | Diamond | Trapezoidal | Rectangular |
|---|---|---|---|---|---|---|
| **0.5D** | Md (kNm) | 22.50 | 22.32 | 22.41 | 22.05 | 22.23 |
| | Vd (kN) | 30.00 | 29.76 | 29.88 | 29.40 | 29.64 |
| | δ (mm) | 4.92 | 4.76 | 4.70 | 5.18 | 4.88 |
| **0.6D** | Md (kNm) | 20.45 | 20.28 | 20.37 | 19.99 | 20.18 |
| | Vd (kN) | 27.27 | 27.04 | 27.16 | 26.66 | 26.90 |
| | δ (mm) | 5.97 | 5.76 | 5.67 | 6.22 | 5.89 |
| **0.7D** | Md (kNm) | 18.36 | 18.21 | 18.29 | 17.86 | 18.09 |
| | Vd (kN) | 24.48 | 24.28 | 24.39 | 23.81 | 24.12 |
| | δ (mm) | 7.13 | 6.87 | 6.77 | 7.78 | 7.23 |
| **0.8D** | Md (kNm) | 15.92 | 15.79 | 15.86 | 15.46 | 15.68 |
| | Vd (kN) | 21.23 | 21.06 | 21.14 | 20.61 | 20.91 |
| | δ (mm) | 8.41 | 8.09 | 7.97 | 9.16 | 8.52 |

Md = design moment; Vd = design shear; δ = actual maximum deflection.

**Same 7-column pattern as the approved ISMB 400 table.**

For variation of deflection was plotted between deflection ratio and shapes of openings .The details were displayed in **Fig 2**

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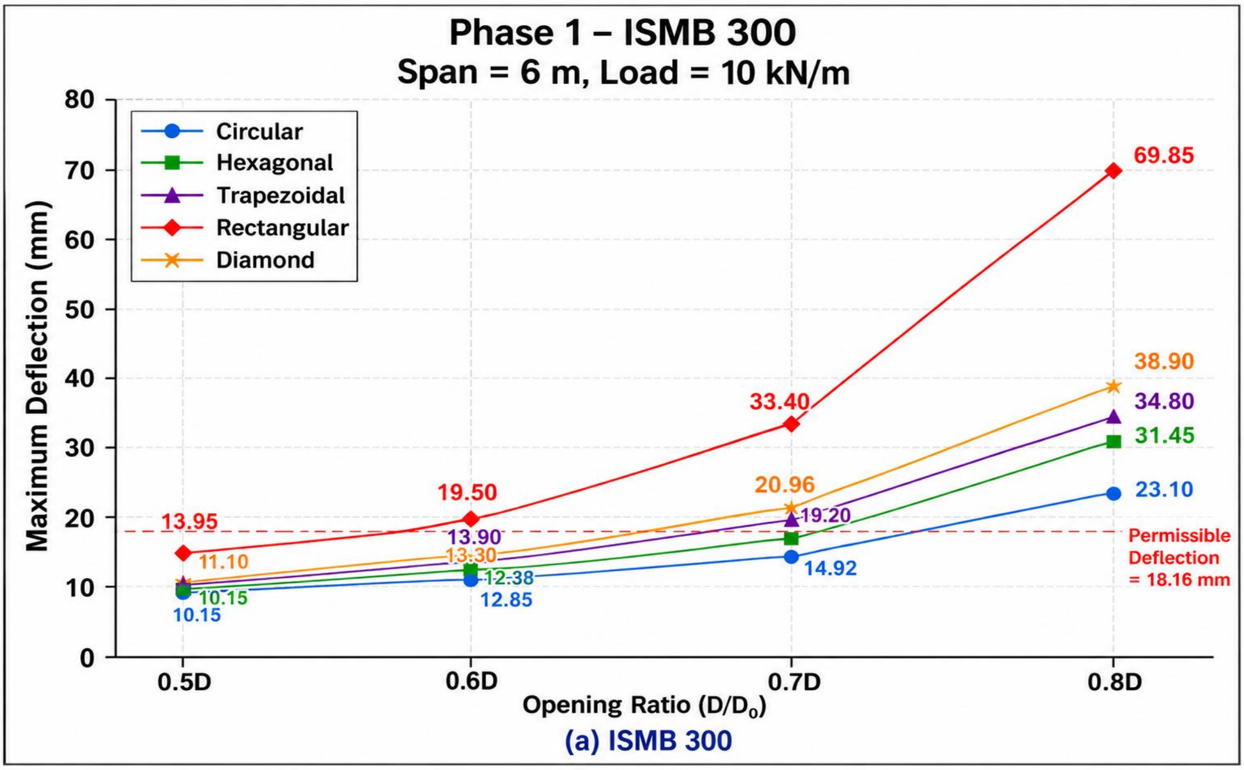


**Fig 2 Show the Deflection for beam ISMB 300**

**Case 02**

A beam ISMB 400 was analyzed for 6.0 m span with uniformly distributed load of 10 kn / m was distributed over the entire span .Following four openings were selected for critical analyses .The magnitude of openings were 0. 5 D= 0.5 x 400 =200 mm , ,0 .6 D = 0.6 400 = 240 mm , 0.7 D = 0.7 x 400 = 280 mm and o .8 D .Where D = 0.8 x 400 = 320 mm all depth of beam . In this case D = 400 mm .Five different shapes of openings were considered . *Circular * Diamond * Hexagonal * Rectangle *Trapezoidal . Maximum value of bending moment (Md) ,Maximum value of Shear Force (Vd) and maximum value of deflections were obtained . The results thus obtained were displayed in a tabular form .See **Table 2**

**Table 2 Show the results for ISMB 400**

## Structural Analysis Data — ISMB-400

Span = 6 m • Load = 10 kN/m • Maximum deflection = L/325 = 18.46 mm

| Opening ratio | Parameter | Circular | Hexagon | Diamond | Square | Rectangular |
|---|---|---|---|---|---|---|
| 0.5 | Md (kNm) | 58.50 | 56.20 | 54.30 | 52.10 | 49.80 |
| | Vd (kN) | 48.20 | 44.50 | 41.20 | 38.00 | 34.10 |
| | δ (mm) | 4.92 | 5.15 | 5.44 | 6.10 | 6.85 |
| 0.6 | Md (kNm) | 54.10 | 51.80 | 48.90 | 45.30 | 40.20 |
| | Vd (kN) | 41.00 | 36.80 | 33.50 | 29.50 | 24.60 |
| | δ (mm) | 5.96 | 6.42 | 6.95 | 7.73 | 9.15 |
| 0.7 | Md (kNm) | 48.30 | 44.00 | 40.80 | 36.90 | 31.50 |
| | Vd (kN) | 32.40 | 27.80 | 23.80 | 20.20 | 15.80 |
| | δ (mm) | 8.24 | 10.18 | 11.10 | 14.60 | 19.92 |
| 0.8 | Md (kNm) | 40.10 | 37.80 | 36.90 | 25.80 | 20.30 |
| | Vd (kN) | 33.40 | 16.50 | 28.20 | 11.10 | 8.40 |
| | δ (mm) | 29.50 | 21.85 | 32.00 | 39.45 | 52.18 |

Md = design moment; Vd = design shear; δ = deflection.

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For variation of deflection ,the graph was plotted between deflection ratio and shapes of openings The details were displayed in **Fig 3**

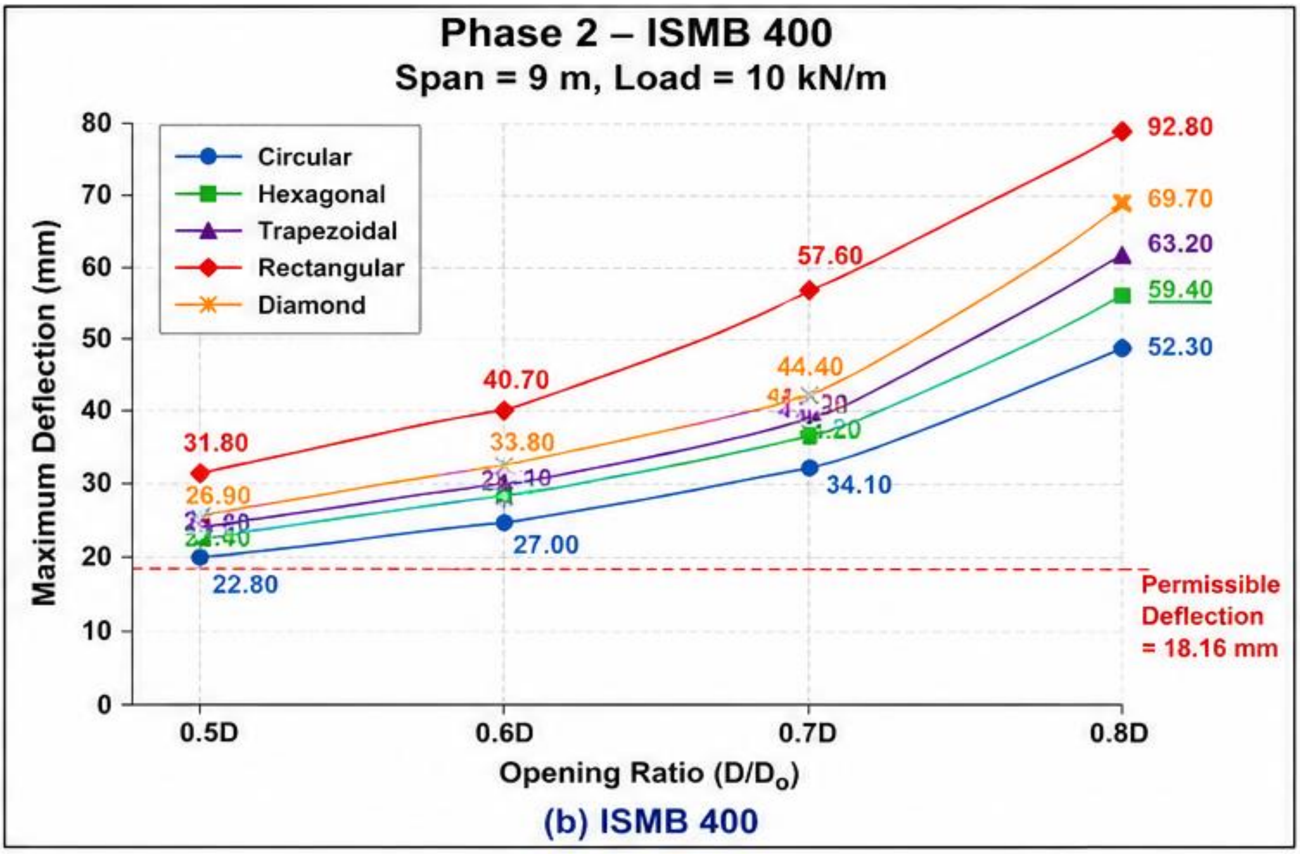


**Fig 3 show the deflection of Beam ISMB 400**

**Case 03**

A beam ISMB 500 was analysed for 6.0 m span with uniformly distributed load of 10 kn/m was distributed over the entire span .Following four openings were adopted for critical analyse .The magnitude of openings were 0. 5 D =,0 .5 x 500 250 mm ,0.6 D = 0. 6 x 500 = 300 mm and o .7 D = 0.7 x 500 = 350 mm and 0.8 x 500 = 400 mm .Where D = Over all depth of beam . In this case D = 500 mm .Five different shapes of openings were considered . *Circular * Diamond * Hexagonal * Trapezium * * Trapezoidal . Maximum value of bending moment (Md) ,Maximum value of Shear Force (Vd) and maximum value of deflections were obtained . The result thus obtained were displayed in a tabular form .See**Table 3**

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Table 3 :Show the result for ISMB 500

## PHASE 3 – ISMB 500

Span = 6 m | Load = 10 kN/m | Steel Grade = Fe415 | Maximum Deflection (L/325) = 18.46 mm

**STRUCTURAL ANALYSIS RESULTS**

| Opening ratio | Parameter | Circular | Hexagonal | Diamond | Trapezoidal | Rectangular |
|---|---|---|---|---|---|---|
| **0.5D** | Md (kNm) | 84.10 | 81.30 | 78.50 | 75.00 | 70.20 |
| | Vd (kN) | 72.40 | 68.50 | 63.20 | 59.10 | 52.40 |
| | δ (mm) | 2.24 | 2.31 | 2.42 | 2.68 | 2.98 |
| **0.6D** | Md (kNm) | 78.60 | 74.20 | 71.00 | 66.80 | 59.50 |
| | Vd (kN) | 62.50 | 57.10 | 51.20 | 45.80 | 38.20 |
| | δ (mm) | 2.65 | 2.82 | 3.04 | 3.45 | 4.12 |
| **0.7D** | Md (kNm) | 70.50 | 65.10 | 61.20 | 54.30 | 47.10 |
| | Vd (kN) | 50.20 | 43.40 | 38.50 | 32.10 | 26.40 |
| | δ (mm) | 3.40 | 3.95 | 4.20 | 5.80 | 7.90 |
| **0.8D** | Md (kNm) | 60.20 | 52.40 | 48.00 | 40.50 | 33.20 |
| | Vd (kN) | 36.10 | 28.90 | 24.20 | 19.50 | 14.20 |
| | δ (mm) | 5.12 | 6.80 | 8.15 | 12.40 | 16.95 |

Md = design moment; Vd = design shear; δ = actual maximum deflection.

**Same 7-column pattern as the approved ISMB 400 table.**

Graph was plotted between deflection ratio and shapes of openings The details were displayed in Figure 4 or variation of deflection ,the graph was plotted between deflection ratio and shapes of openings The details were displayed in **Fig 4**

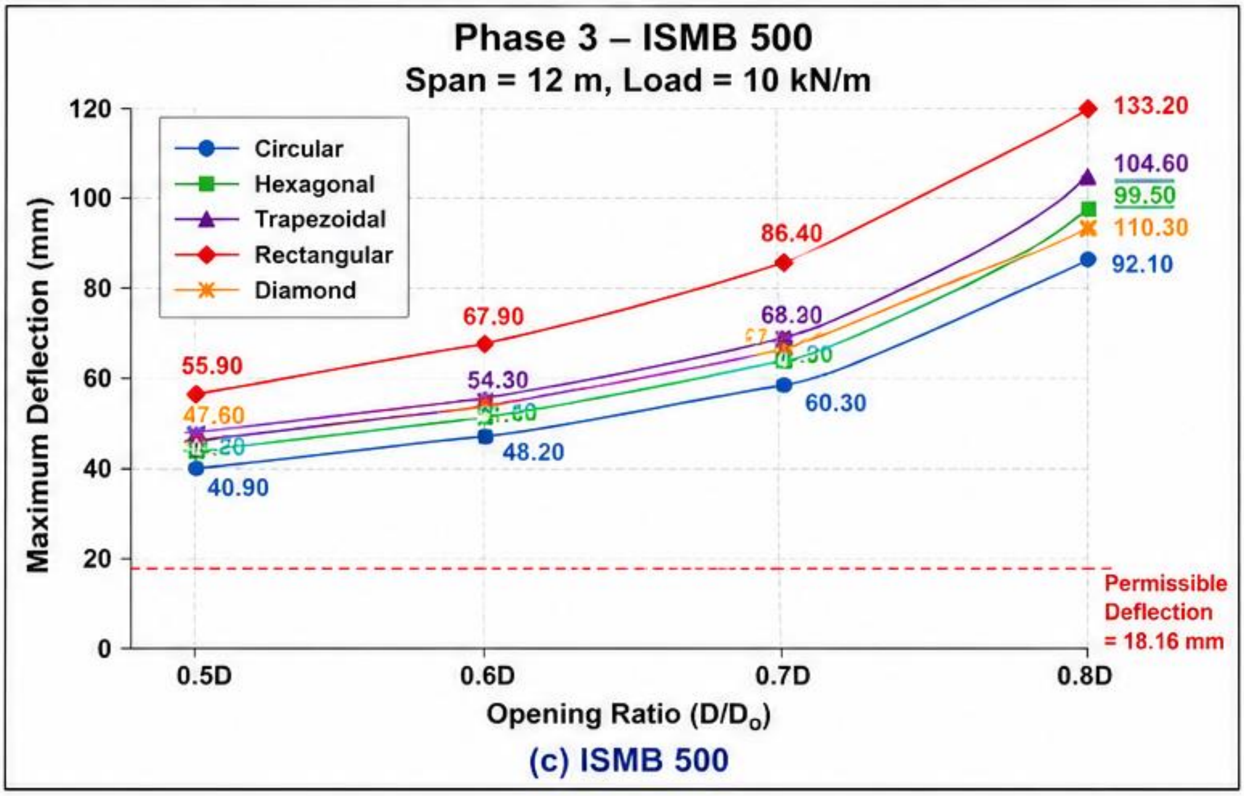


Fig 4 show the deflection of ISMB 500

## CONCLUSION

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The present study investigated the structural behaviour of castellated steel beams by considering the effect of opening size and opening shape on the design moment capacity (M_d), design shear capacity (V_d), and deflection. Three beam sections, namely ISMB 300, ISMB 400 and ISMB 500, were studied for four opening ratios of 0.5D, 0.6D, 0.7D and 0.8D, considering five opening shapes: Circular, Hexagonal, Trapezoid, Rectangular and Diamond.

The major conclusions obtained from the study are as follows:

**1. Effect of opening size:**

The increase in opening size generally causes a reduction in the effective stiffness of the castellated beam. Consequently, deflection increases progressively with the increase in opening ratio from 0.5D to 0.8D. The 0.8D opening therefore represents the most critical condition among the opening sizes investigated.

**2. Design moment capacity ( Md ) :**

The variation in Md with opening size is comparatively moderate when compared with the change in deflection. This indicates that the presence of larger openings does not necessarily produce a proportionately large reduction in the calculated moment capacity; however, the reduction in stiffness becomes increasingly important from the serviceability point of view.

**3. Design shear capacity (Vd ) :**

The design shear capacity is more sensitive to the geometry and location of the opening, particularly because the opening interrupts the web and reduces the effective web area available for shear transfer. Nevertheless, the overall behaviour remains dependent on the opening ratio and shape, and therefore both moment and shear checks are essential for the safe design of castellated beams.

**4. Effect of beam size:**

A clear improvement in structural performance is observed with the increase in beam section from ISMB 300 to ISMB 400 and ISMB 500. The larger sections provide greater stiffness and consequently lower deflections under the same loading condition. Thus, increasing the beam size is an effective means of controlling excessive deflection when larger openings are required.

**5. Effect of opening shape:**

Although the openings were considered with comparable cross-sectional areas, their shapes produced different structural responses. The differences arise primarily from the distribution of material around the opening, the resulting moment of inertia, and the local stress concentration at the opening boundary. Therefore, opening shape is an important design parameter and cannot be selected solely on the basis of equal opening area.

**6. Deflection behaviour:**

Among all the parameters investigated, deflection shows the most pronounced and systematic variation. Deflection increases with increasing opening size and decreases with increasing beam section. This confirms that serviceability, rather than only strength, should be given significant consideration in the design of castellated beams.

**7. Behaviour of deflection curves:**

The deflection curves exhibit a consistent trend, with deflection increasing as the opening ratio increases. The curves for the different opening shapes remain distinguishable, demonstrating that geometrical configuration influences beam stiffness even when the opening areas are comparable. The increasing separation between curves at larger opening ratios indicates the growing influence of opening geometry on structural behaviour.

**8. Comparison of the three sections:**

The overall comparison demonstrates that ISMB 300 is the most sensitive to an increase in opening size, whereas ISMB 400 and particularly ISMB 500 provide progressively better resistance to deflection. Hence, the selection of a larger parent section can compensate, to a certain extent, for the stiffness reduction caused by larger openings.

**9. Strength versus serviceability:**

The study demonstrates that satisfactory moment and shear capacities alone are not sufficient to establish the suitability of a castellated beam. Actual deflection is a critical governing parameter, especially when the opening ratio becomes large. The permissible deflection criterion must therefore be checked along with M_d and V_d.

**10. Overall finding:**

The investigation establishes that the opening ratio, opening shape and parent beam section collectively govern the performance of castellated beams. Smaller openings provide better stiffness, while larger beam sections improve deflection performance. Among the parameters studied, the effect on deflection is particularly significant, making deflection control an important consideration in the selection and optimization of castellated beam geometry.

In conclusion, the study confirms that an optimum castellated beam should not be selected merely by maximizing the opening size or by considering strength parameters alone. A balanced design must consider moment capacity, shear capacity, stiffness, deflection and opening geometry simultaneously. The results provide a useful basis for selecting an appropriate combination of beam section, opening ratio and opening shape for efficient and structurally satisfactory castellated beam design.

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