# Buckling Analysis of Perforated Hot Rolled Steel Sections

**Sagar Dubey**
Civil Engineering Department
SSIPMT
Raipur, India
sagardubey1712@gmail.com

**Pradeep Kumar Ghosh**
Director,
UTD, CSVTU, Bhilai
pradeepkghosh8@gmail.com

**Barkha Verma**
Civil Engineering Department
SSIPMT
Raipur, India
barkha.verma@ssipmt.com

**Anurag Wahane**
Civil Engineering Department
SSIPMT
Raipur, India
anurag.wahane@ssipmt.com

**Ravi Kumar Khandel**
Civil Engineering Department
SSIPMT
Raipur, India
Khandelravi7@gmail.com

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**Abstract**: — Perforated steel plates are frequently used in the construction industry because they are inexpensive, simple to fabricate, have a good strength by weight ratio, and are suitable for a variety of applications. The research present about the effect due to perforation on the buckling resistance of perforated ISMB 400 & ISMB 600 section members are analyzed. The paper deals with three categories i.e., the first case is analyzing the ISMB 400 & 600 section without perforation, the second is analyzing the ISMB 400 section with perforation having equal and unequal spacing and the third case is analyzing ISMB 600 perforated section with equal and unequal spacing. The results show that the deformation increases due to increase in load application the in case of members without perforation and in perforated members' deformation increase with an increase in the diameter of perforation when they are placed equidistant while the deformation reduces with an increase in diameter of perforation when they are not placed at equidistant.

**Keywords**— Hot rolled sections, ISMB 400, ISMB 600, Buckling Analysis, Ansys etc.

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## 1. Introduction

Structural steel comes in two varieties i.e., hot-rolled, and cold-formed section and its classification is based on the manufacturing process. As per the report, India is the second-largest producer of steel having applications in various sectors. Hot-rolled steel is best used in applications where precise, complex geometries and heavy load-carrying members are needed such as Bridges & Infrastructure Builds, and also used in Automotive Engines & Parts, Water Transmission pipes, etc. The commonly used sections are Channel, Z, I sections, angles, and T-section, although I-section steel is among the most popular section in India and the ISMB section is the most widely used. Also, the emergence of the perforated sections is the development in steel structure which leads to saving of the steel while serving the desired load-carrying capacity, stress & strain distribution, and resisting the buckling which safeguards the failure of the structure. In the research paper, the study of the buckling behavior of the different ISMB, I-section has been done in order to derive up to which floor height ISMB sections with perforation of varying diameter and spacing are suitable and how much steel can be saved without a buckling mechanism having one end fixed and another end hinged.

## 2. Literature Review

Various research and studies have been done in the past to demonstrate the suitability of Hot as well as Cold Formed Steel with hollow or perforated sections analyzed & experimented to determine the buckling capacity & various other components. (Brando & Matteis, 2013) Determines the impact of perforation on the ability of a perforated hot-rolled steel angle member to resist buckling under compression under both the critical and collapse loads. The findings demonstrate that the existence of perforation does not significantly affect the critical load or the load-bearing capacity of members with middle-low slenderness. (Singh & Chan, 2020) The buckling performance of perforated cold and hot-rolled steel module columns is quantified using finite element (FE) by taking into account the effects of geometric characteristics including eccentricity, forms, diameters, and depth/height of perforation. According to the investigation, the biggest drop in column capacity occurs when the perforation is situated at the middle of the column. As the perforation size ratio (perforation size/width) rises, it is discovered that the critical buckling capacity of the perforated module column linearly decreases. According to the results, perforation eccentricity has a negligible impact on critical buckling, however perforation size (perforation width or diameter) has a significant impact. Perforation depth and height have no discernible impact on critical buckling capacity. (Meena & Patil, 2021) Author studied the behavior of steel moment resistant frame through response spectrum analysis (elastic analysis) and pushover analysis (non-linear static analysis) to determine the reserve capacities of the moment-resistant steel frames for heights ranging from G+3 to G+15.(Srinivas Suresh Kogilgeri, Beryl Shanthapriya, 2015) Analysis of the outrigger system's static and dynamic behaviour while decreasing the outrigger's depth. Software, ETABS v2013 is used to model 5X5 bay 40 story steel constructions. (Ratheesh & Chacko, 2019) In order to determine the maximum load behaviour and additional deflection caused by single and multiple openings, a study was undertaken on the utilisation of steel beams with web openings (SBWOs) for structures including industrial buildings and high-rise buildings. Think about the tension concentration in the web openings as well. (Chen et al., 2017) A new type of design with beam-to-beam bolted connections that allow for simple access without being impacted by the structural components, an experimental study on internal connections in modular steel buildings is conducted. For skeletal curves, joint stiffness degradation patterns, energy dissipation capability, and ductile performance, finite element analysis and experiments were conducted. The outcome demonstrates how the two-unit joints have an impact on the deformation patterns and distribution of bending loads at the joints. (Lacey, Chen, Hao, & Bi, 2019) The paper outlines the inter-module connections in modular steel constructions that are bolted together and their stiffness properties. Theoretical models were assessed by taking into account particular connections in order to comprehend structural behaviour and enable the construction of suitable theoretical models. According to the findings, it was unable to estimate the inter-connection shear stiffness accurately, especially the initial slip stiffness.(Lacey, Chen, Hao, Bi, et al., 2019) Investigated the initial shear load-slip behaviour and proposed a new post-tensioned vertical inter-module connection for modular steel constructions. The suggested connection's initial load-slip behaviour is described by a novel exponential model that is better suited to inter-module connections with higher initial shear stiffness. in light of the obtained result, which demonstrates that the slip load can be effectively controlled by varying the bolt preload & faying surface slip factor.(Shanmugam et al., 1999) Perforated plates exposed to uniaxial or biaxial compression had their post-buckling behaviour and maximum load capacities examined. The ultimate load capacity of perforated plates was predicted using a design formula after comprehensive studies were conducted utilising criteria such plate slenderness, opening size, boundary conditions, and the type of loading. Plates were evaluated using the finite element method (FEM). According to the analysis's findings, perforated plates' ultimate strength significantly decreases as hole size and slenderness ratio rise. Additionally, compared to plates with clamped edges, perforated plates with merely supported edges have lesser strength. (Cheng et al., 2013) A self-balanced loading system was used to examine the compression behaviour of perforated (single-row or double-row elliptical hole) plates in the steel tower anchoring zones of cable-stayed bridges using experimental and computational approaches. The findings demonstrate that continuous elliptical perforations have detrimental effects on the mechanical behaviour of compressed plates. For example, all plates' compression strength decreases linearly as hole width increases, larger hole spacing always increases the load-carrying capacity of perforated plates, and continuous elliptical holes had no effect on the plates' failure pattern. (Garbatov & Soares, 2016) Using a uni-axial compressive load, the ultimate strength of steel plates with large centre circular openings was experimentally determined. The effects of perforation (opening size) on the ultimate strength were also examined. The obtained results demonstrate that the specimen behaves as a plate for small opening sizes, a column for larger opening sizes, and a decline in load-carrying capability for larger opening sizes. (El-sawy et al., 2004) Square and rectangular plates with circular cut-outs were evaluated using the FEM approach for elasto-plastic buckling under compression. According to the findings, buckling failures with tiny holes remain elastic, while elasto-plastic failures occur as hole sizes grow. ( C. J. Brown, 1990) Analysed the elastic buckling of perforated plates under concentrated loads and came to the conclusion that the placement of the perforation causes the plates' elastic stability properties to be disrupted. (R. Narayanan, F.Y. Chow, 1984) Provided a method for approximating the projection of the ultimate load-carrying capacity and the post-buckling behaviour of perforated plates with square and circular apertures when the plates are compressed. The calculations yield the result for Ultimate Load Capacity and post-buckling behaviour, and graphs are drawn to show this. (Yu & Lee, 2012) The impact of perforation at various sites on the ultimate strength of a simply supported plate under uniaxial compression was examined using FEM analysis with ABAQUS. ( C.M. Madasamy, V. Kalyanaraman, 1994) Two cases, a plane shear wall with a very big hole and a plane shear wall supported on two piers, were used to demonstrate how to analyse plate and plane stress problems with cut-outs using the spline finite strip method. The outcome demonstrated that the degree of freedom for the Spline Finite Strip Method is lower than for the Finite Element Method. ( R. Jwalamalini, R. Sundaravadivelu, C.P. Vendhan & C. Ganapathy, 1992) Using the Finite Element programme BUCSAP (Buckling Structural Analysis Program), the stability of a simply supported square plate with square apertures under in-plane loading is examined. The outcome showed that when the opening size grows, the buckling coefficient, k, decreases. ( Christopher J. Brown and Alan L. Yettram, 1986) The conjugate load-displacement approach is used in this study to offer solutions for the elastic stability of plates with perforations. It was also shown how the elastic buckling load is affected by the size of the centre square hole in a square plate. The experimental analysis shown that the conjugate load/displacement method of instability analysis can be used to analyse perforated plates that are subjected to non-symmetric systems of loads and a range of boundary conditions..(Roberts & Azizian,

1984) Under uniaxial compression, biaxial compression, and pure shear, finite element solutions for the buckling and geometrically nonlinear elastoplastic collapse of perforated plates were reported and discovered that as the hole size increases, the ultimate or collapse load of plate reduces. ( Wei-wen Yu, 1971) The structural behaviour of cold-form compression and flexural members with perforated stiffening components has been investigated analytically and experimentally. The inference made is that perforation might lessen the buckling load of the stiffened compression parts.

## 3. Research Work

The objective of the analytical investigation is to evaluate the buckling capacity of the different sections with and without perforations having equal and unequal spacing with one end fixed and another end hinged. The study involves fourteen different cases have been considered for analytical investigation. ISMB sections were analyzed due to their wide application in India. As per studies considered in the literature review, ISMB 600 section can be considered when the storey height is more than G+15 and is generally placed on the storey ranging from 1st up to 6th storeys (i.e., on the lower storeys), while ISMB 400 sections are used when the storey height is more than G+15 and is generally placed on the top storeys i.e., storeys ranging from 20-30 storeys on a building of 40 storey. The First two case considered is the ISMB 400 & ISMB 600 section without any perforation. From the 3rd to 8th cases considered is the ISMB 400 sections having an equal and unequal spacing of perforation with varying perforated diameter and from the 9th to 14th cases ISMB 600 sections having an equal and unequal spacing of perforation with varying perforated diameter to determine the buckling capacity. Fig.1 & Fig.2 shows the geometric representation of the cases considered under analysis and all the models of the ISMB 400 section have been subjected to a load application of 300.11 KN while ISMB 600 section section have been subjected to a load application of 974.454 KN which was calculated by the compressive strength equation mentioned below having one end fixed and another end hinged (k=1.2) . The buckling, stress & strain component has been observed very carefully. The standard model arrangement that shows the position of the perforation and its spacing are shown below:

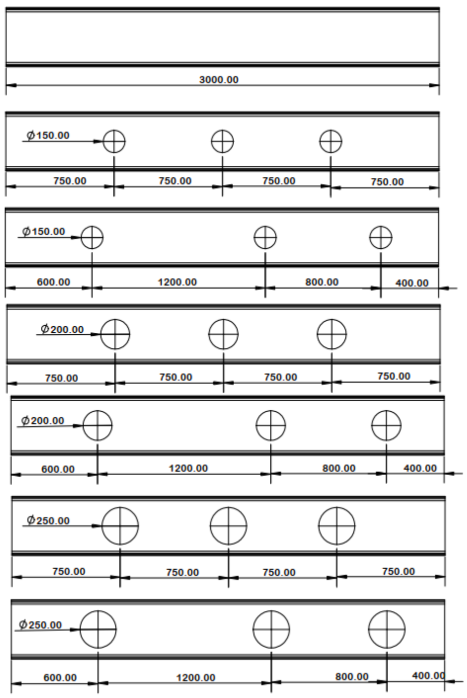



**Fig. 1 Longitudinal Sectional view of ISMB 400**

Commonly, flexural buckling is the cause of failure for hot-rolled and built-up steel members employed to carry axial compression. The residual stresses, initial bow, and random eccentricity of the load all have an impact on the buckling strength of these parts. The strength of parts subjected to axial compression is characterised by a, b, and c buckling classes in order to take into consideration all of these elements.

Design Compressive Strength,

$P_d = A \times f_{cd}$ ……………………….(1)

(As per IS 800, 2007, Considering Buckling Class-C)

Safe Load = $P_d/1.5$ ……………………….(2)

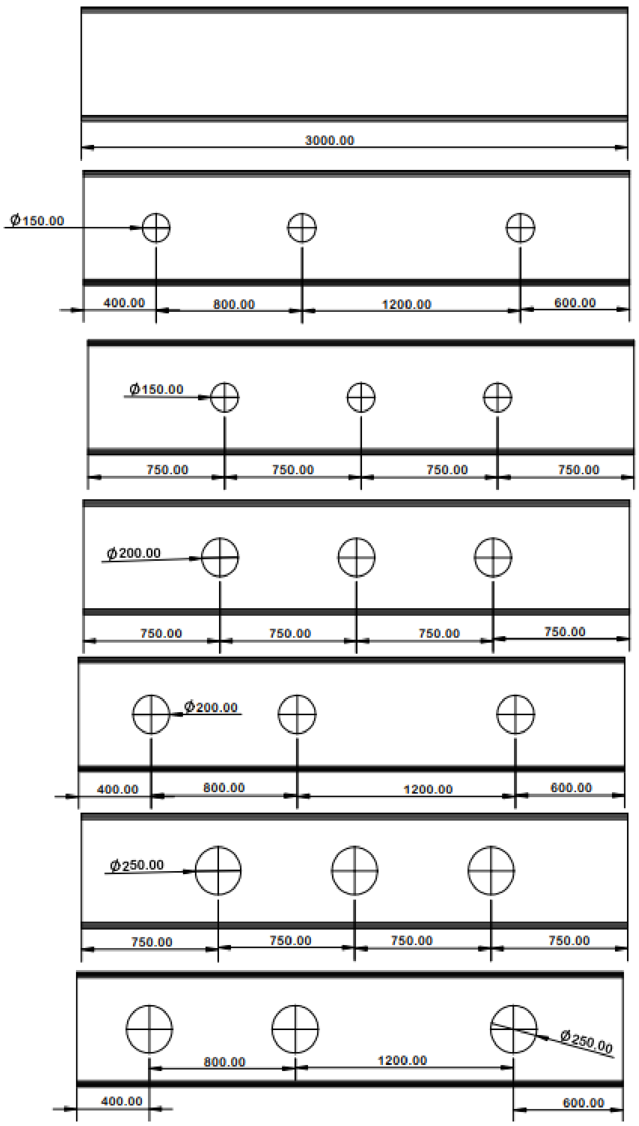



**Fig. 2 Longitudinal Sectional view of ISMB 600**

## I. Analytical Investigation

In order to investigate the buckling response of different
ISMB sections under varying perforation and spacing. An actual ISMB 400 & 600 section is developed by taking all the specifications from the steel table. The detailed specification of ISMB 400 & 600 are as follows:

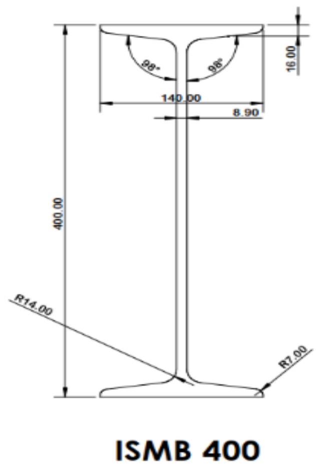



**Fig. 3 Transverse sectional view of ISMB 400**

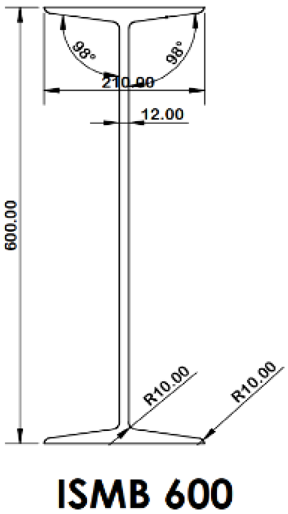



**Fig. 4 Transverse sectional view of ISMB 600**

**Table No. 1 Specification of ISMB 400 & ISMB600**

| Description | ISMB 400 | ISMB 600 |
|---|---|---|
| Mass (M) | 61.5 kg/m | 123 kg/m |
| Cross Sectional Area (A) | 78.4 $cm^2$ | 156 $cm^2$ |
| Total Depth (D) | 40 cm | 60 cm |
| Flange Width (B) | 14 cm | 21 cm |
| Thickness of Web (t) | .89 cm | 1.2 cm |

| | | |
|---|---|---|
| Thickness of Flange (T) | 1.6 cm | 2.03 cm |
| Radius at Root ($R_1$) | 14 mm | 20 mm |
| Radius at Root ($R_2$) | 7 mm | 10 mm |
| Moment of Inertia ($I_X$) | 20500 $cm^4$ | 91800 $cm^4$ |
| Moment of Inertia ($I_Y$) | 622 $cm^4$ | 2650 $cm^4$ |
| Radius of Gyration ($r_x$) | 16.2 cm | 24.2 cm |
| Radius of Gyration ($r_y$) | 2.82 cm | 4.12 cm |
| Modulus of Section ($Z_X$) | 1020 $cm^3$ | 3060 $cm^3$ |
| Modulus of Section ($Z_Y$) | 88.9 $cm^3$ | 252 $cm^3$ |

In the investigation, the calculation of load applications is described below:
End Condition considered
One end is fixed (TOP)
Another end hinged (BOTTOM)
Effective Length = KL (K=1.2)
For ISMB 400:
The Design Compressive Strength of ISMB 400
Section, from equation (1)
$P_d$= 600.219 KN
Safe load considered by taking the factor of safety i.e., 1.5
Therefore,
The Safe Load= 600.219/1.5= 400.146 KN

Considering only 75% of load
75% Of Safe Load: 75% x 400.146 KN: 300.11 KN ………………………(3)

For ISMB 600:

The Design Compressive Strength of ISMB 600
Section, from equation (1)
$P_d$= 1948.908 KN
Safe load considered by taking the factor of safety i.e., 1.5
Therefore,
The Safe Load= 1948.908 /1.5= 1299.272 KN

Considering only 75% of load
75% Of Ultimate Load Carrying Capacity: 75% x 1299.272 KN: 974.545 KN ………………………(4)
During the analysis in ANSYS, load was applied in ISMB 400 and ISMB 600 sections considered the buckling was observed at certain load multiplier. The load multiplier is the extent of load application at which the first buckling will occur i.e., some multiplier times the load applied. In our investigation two load multipliers are considered for each case and buckling was observed.
The detailed observation of ISMB sections with their respective load multiplier and the deformation observed in all the sections are mentioned below in the table:

| Description | Notation | Length (mm) | Perforation | Spacing |
|---|---|---|---|---|
| ISMB 400 Section | I4 | 3000 | No Perforation | - |
| ISMB 600 Section | I6 | 3000 | No Perforation | - |
| Cases Consider for the building having storeys Upto 15 Floors. | | | | |
| ISMB 400 section with circular opening at equal spacing | I4E15 | 3000 | 3-150 mmØ | 750 mm |
| ISMB 400 section with circular opening at unequal spacing | I4U15 | 3000 | 3-150 mmØ | 400, 800, 1200 mm |
| ISMB 400 section with circular opening at equal spacing | I4E20 | 3000 | 3 -200 mmØ | 750 mm |
| ISMB 400 section with circular opening at unequal spacing | I4U20 | 3000 | 3 -200 mmØ | 400, 800, 1200 mm |
| ISMB 400 section with circular opening at equal spacing | I4E25 | 3000 | 3-250 mmØ | 750 mm |
| ISMB 400 section with circular opening at unequal spacing | I4U25 | 3000 | 3-250 mmØ | 400, 800, 1200 mm |
| Cases Consider for the building having storeys >15 but < 40 floors. | | | | |
| ISMB 600 section with circular opening at equal spacing | I6E15 | 3000 | 3-150 mmØ | 750 mm |
| ISMB 600 section with circular opening at unequal spacing | I6U15 | 3000 | 3-150 mmØ | 400, 800, 1200 mm |
| ISMB 600 section with circular opening at equal spacing | I6E20 | 3000 | 3 -200 mmØ | 750 mm |
| ISMB 600 section with circular opening at unequal spacing | I6U20 | 3000 | 3 -200 mmØ | 400, 800, 1200 mm |
| ISMB 600 section with circular opening at equal spacing | I6E25 | 3000 | 3-250 mmØ | 750 mm |
| ISMB 600 section with circular opening at unequal spacing | I6U25 | 3000 | 3-250 mmØ | 400, 800, 1200 mm |

**Table 2: Description of the cases considered for the analysis**

Note: Notations mentioned in the above table are described below:

I: I Section

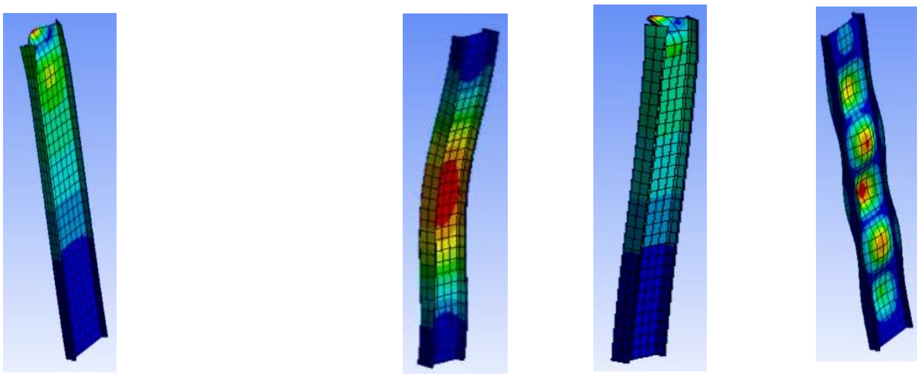
4: ISMB 400 section considered

6: ISMB 600 section considered
L: Length of a section taken
3000: length of section considered in mm i.e., 3000mm
E: Equal Spacing
U: Unequal spacing
15: 150 mm diameter of perforation
20: 200 mm diameter of perforation
25: 250 mm diameter of perforation

## 4. Results

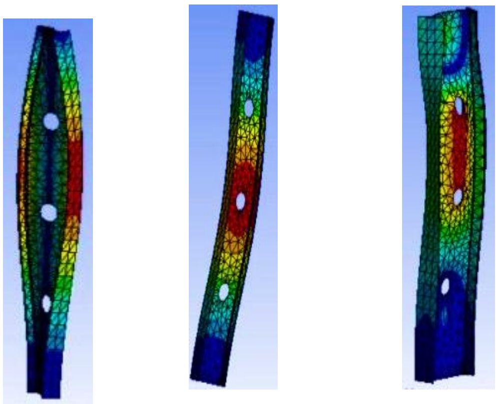
The result of the applied load, von mises stress & strain, and maximum principal stress on the different sections with and without perforation are compared, results of different sections considered are given below in the table 3, Total deformation of section.

**Deformation -** The deformations of sections with applied load 300.11 KN in ISMB 400 & 974.545 KN in ISMB 600 with & without perforation are observed and shown below:

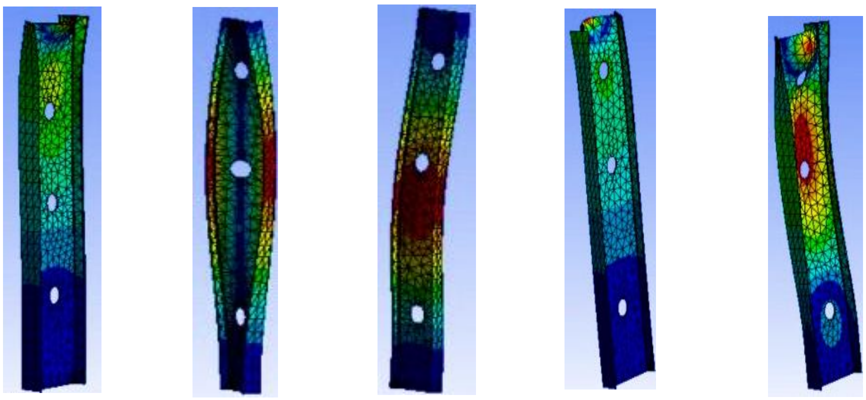


Section I4 under deformation
Section I6 under deformation

**Fig. 5 Deformation in sections without perforation**



Section I4E15 Section I6E15



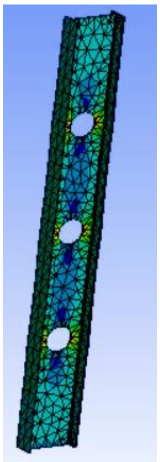
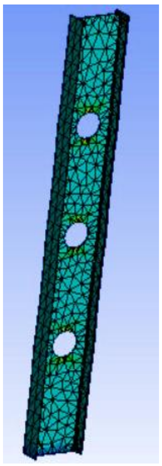
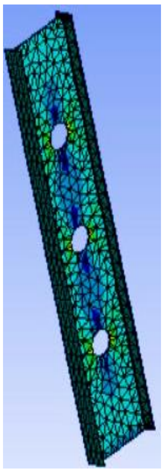
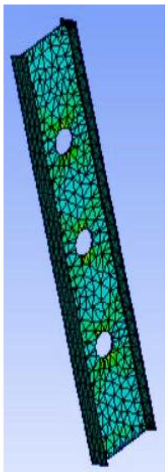
Section I4U15 Section I6U15

**Fig. 6 Deformations of section with perforation having equal spacing**

**Stress & Strain -** The stress component developed in the section having load 300.11 KN & 974.545 KN in ISMB 400 & 600 respectively are shown in table 4, and stresses in section I4E15 & I6E15 are shown below:

| Notation | Applied Load (KN) | Load Multiplier (LM) | | Actual Load (AL) (KN) {Applied Load x LM} | | Total Deformation (TD) (mm) *Average* | |
|---|---|---|---|---|---|---|---|
| | | **LM1** | **LM2** | **AL1** | **AL2** | **TD1** | **TD2** |
| **I4** | 300.11 | 9.078 | 12.51 | 2724.399 | 3754.376 | 0.21 | 0.43274 |
| **I6** | 974.545 | 3.5753 | 6.2989 | 3484.291 | 6138.562 | 0.2342 | 0.1634 |
| **I4E15** | 300.11 | 12.612 | 12.973 | 3784.987 | 3893.327 | 0.41956 | 0.45096 |
| **I4U15** | 300.11 | 12.47 | 12.939 | 3742.372 | 3883.123 | 0.4177 | 0.43912 |
| **I4E20** | 300.11 | 12.167 | 13.069 | 3651.438 | 3922.138 | 0.42143 | 0.45317 |
| **I4U20** | 300.11 | 12.191 | 13.157 | 3658.641 | 3948.547 | 0.4339 | 0.4668 |
| **I4E25** | 300.11 | 11.499 | 13.182 | 3450.965 | 3956.05 | 0.42731 | 0.46559 |
| **I4U25** | 300.11 | 9.4553 | 10.743 | 2837.63 | 3224.082 | 0.2297 | 0.43078 |
| **I6E15** | 974.545 | 7.1346 | 11.016 | 6952.989 | 10735.59 | 0.26613 | 0.3174 |
| **I6U15** | 974.545 | 4.3603 | 10.499 | 4249.309 | 10231.75 | 0.22311 | 0.35013 |
| **I6E20** | 974.545 | 6.9173 | 11.462 | 6741.22 | 11170.23 | 0.25579 | 0.33463 |
| **I6U20** | 974.545 | 4.2582 | 11.03 | 4149.808 | 10749.23 | 0.21711 | 0.29173 |
| **I6E25** | 974.545 | 5.8434 | 11.479 | 5694.656 | 11186.8 | 0.23809 | 0.37118 |
| **I6U25** | 974.545 | 4.2933 | 11.773 | 4184.014 | 11473.32 | 0.22117 | 0.28641 |

**Table 4: Equivalent Stress, Strain and Maximum Principal Stress of sections**

**Equivalent Stresses (Von-mises stress), 46.794 MPa**

**Maximum Principal Stress, 1.7502 MPa**

**Equivalent Stresses (Von-mises stress), 75.65 MPa**

**Fig. 7 Section I4E15 with circular opening at equal spacing**

**Fig. 8 Section I6E15 section with circular opening at equal spacing**

**Fig. 7 Deformation of section with perforation having unequal spacing**

**Table 4: Equivalent Stress, Strain and Maximum Principal Stress of sections**

| Notation | Equivalent Stress (MPa) | Equivalent Strain (e-004 mm/mm) | Maximum Principal Stress (MPa) |
|---|---|---|---|
| **I4L3** | 43.045 | 2.1539 | [illegible]03 |
| **I6L3** | 76.859 | 3.8456 | [illegible].4 |
| **I4E15** | 44.708 | 2.2524 | [illegible] |
| **I4U15** | 44.695 | 2.2523 | 1.1506 |
| **I4E20** | 46.794 | 2.3608 | 1.7502 |
| **I4U20** | 48.93 | 2.4717 | 1.4353 |
| **I4E25** | 49.628 | 2.5103 | 2.0724 |
| **I4U25** | 49.799 | 2.5194 | 2.4555 |
| **I6E15** | 75.592 | 3.8028 | 0.62986 |
| **I6U15** | 75.432 | 3.7943 | 0.72535 |
| **I6E20** | 75.65 | 3.8109 | 1.0711 |
| **I6U20** | 76.068 | 3.8303 | 1.3768 |
| **I6E25** | 76.323 | 3.8462 | 2.3359 |
| **I6U25** | 77.532 | 3.9077 | 2.9422 |

**Maximum Principal**

## 5. Conclusion

Following are the few conclusions that have been listed from the analysis carried out in the paper:

- For Unperforated ISMB 400 section, deformation increases with an increase in the load.
- For Unperforated ISMB 600 section, deformation decreases with an increase in the load.
- For perforated sections(ISMB 400 & 600) having equal distance, deformation increases when place equidistant with increasing diameter.
- For perforated sections ISMB 400 & 600) having equal distance, with the increase in diameter of the perforation, deformation increases.
- For perforated sections (ISMB 400 & 600) having equal distance, maximum Principal stress, Von-mises stress & strain increases with increase in diameter of the perforation.
- For perforated sections (ISMB 400 & 600), deformation reduces when perforations are not at equidistance with increasing diameter.
- For perforated sections (ISMB 400 & 600) having unequal distance, with increase in diameter of the perforation, deformation decreases.

For perforated sections having unequal distance, maximum Principal stress, Von-mises stress & strain increases with increase in diameter of the perforation

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