

NUMERICAL ANALYSIS ON THE BUCKLING CHARACTERISTICS OF A HYBRID STAINLESS STEEL PLATE GIRDER

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Abstract - A plate girder is a built-up I-beam section, used for carrying heavy loads which cannot be carried economically by rolled I-sections. To mitigate corrosion damage and minimize fabrication expenses, a hybrid stainless steel girder is introduced in bridge construction. In this current the hybrid girder combines lean duplex stainless steel (LDSS) for the web and duplex stainless steel (DSS) for the flanges, aiming to enhance corrosion resistance and reduce fabrication costs. LDSS, a specific category of stainless steel, has gained popularity as a structural member because of its enhanced corrosion resistance and durability compared to traditional steel. Plate girders feature web holes that serve the purpose of accommodating service, inspection, and maintenance requirements. However, the introduction of openings in the web affects the distribution of stress within the structural member and impacts its collapse behavior.

This study focuses on utilizing a finite element model within the ABAQUS which enables the prediction of buckling behavior, stress-strain relationship, and force-displacement characteristics of plate girders with various web openings. The study also involves comparing analytical outcomes related to ultimate load values and load deflection relationships for different web openings providing valuable insights into the performance of plate girders with different web configurations, aiding in their structural design and evaluation.

Key Words: Plate Girder, Hybrid Stainless Steel, ABAQUS, Buckling, Web opening.

1. INTRODUCTION

Stainless steel is included to the family of corrosion-resistant steel alloys primarily composed of iron (Fe), with at least 10.5% chromium (Cr) by mass. The addition of chromium is what gives stainless steel its remarkable corrosion resistance. Other elements like nickel (Ni), molybdenum (Mo), and manganese (Mn) are often added to enhance specific properties such as strength, durability, hardness, resistance to extreme temperatures and an attractive appearance. Stainless steel is renowned for its versatility and widespread application, owing to its well-established properties, making it essential in various industries and applications.

It comes in a range of grades and can be broadly classified into four types: duplex, ferritic, martensitic, and austenitic. In addition, compared to carbon steel, stainless steel exhibits special mechanical qualities such as notable strain hardening, a high strength to weight ratio, remarkable ductility, low maintenance costs, excellent impact and fire resistance, etc. Because of these special qualities, it presents a desirable alternative to conventional carbon steel in the construction industry. However, because of its increased nickel content (8–11% by mass), it has a very high starting cost, which stands in the way of its widespread application as a structural element. Other more affordable stainless-steel types have therefore appeared, like Duplex Stainless Steel (DSS) and Lean Duplex Stainless Steel (LDSS), which have lower nickel contents.

Compared to austenitic stainless steel, DSS is stronger and more resistant to corrosion and wear. DSS is a desirable primary structural material since it has a stronger grade of stainless steel than other grades. In contrast to DSS, LDSS is a more recent variety of stainless-steel alloy that is distinguished by a lower nickel content and strong mechanical properties, which improves its use's economic viability. Compared to the austenitic type, LDSS has superior fracture toughness, acceptable weldability, greater temperature characteristics, and improved corrosion resistance.

Modern hybrid carbon steel sections are currently being investigated in research and construction as an affordable alternative to homogeneous steel plate girders.

A plate girder is basically an I-beam built up from three different plates i.e. a central web and two outer flanges, constructed through riveting or welding. It serves as a deep flexural member suitable in situations involving heavy and expansive spans, where traditional rolled sections are economically impractical. One advantage of plate girder is that it provides the flexibility (within defined limits) to select the web and flanges dimensions. Among all rolled sections, plate girders have the highest moment bearing capacity.

A hybrid steel plate girder is formed by incorporating steel flanges with higher strength and a steel web with lower strength, potentially saving up to 15% in costs in contrast to a homogeneous girder.

1.1 Plate girder with opening for a web

The role of a structural engineer extends beyond ensuring safety and serviceability in structure design. It also encompasses considering operational needs specific to the structure's intended use. In structures like power stations or multi-storey buildings, traditional structural steel structure consists of ropes with solid nets that can impede the installation of necessary ducts and air conditioning pipes. This can lead to service engineers having to adjust these components postconstruction, incurring extra costs and inefficiencies. To mitigate this, it has become common practice to incorporate web openings into the structural design, eliminating the need for service engineers to make holes in the wrong places.

The shape of these web openings is typically a matter of the designer's preference and the intended purpose of the opening. There aren't any strict rules dictating their shapes. Designers often opt for standard shapes like ovals or rectangles for simplicity. However, it's essential to note that introducing openings in the web can reduce the stiffness of the beams, resulting in more significant variations compared to solid webs. Proper consideration of plastic deformations caused by both moments and cuts in the openings is crucial to maintain the structural integrity of beams with openings. The realized strength will depend on the interaction between the moment and shear. When an opening is present, the moment capacity of the perforated web diminishes due to the reduced contribution of the web to the moment capacity. However, this decrease is usually negligible since the web's contribution to the moment capacity is minimal. Conversely, the reduction in shear capacity at the opening can be considerable. Therefore, the ultimate capacity under the action of moment and shear at the cross-section where there is an opening will be less as opposed to the normal cross-section without opening i.e. some strength is lost.

To restore this lost strength, reinforcement can be added along the edges of the openings. As a general guideline, it is advisable to avoid placing the openings in high shear regions and also to make sure that they are not closely spaced.

2. OBJECTIVES

- 1) To investigate the buckling behavior of hybrid stainless steel plate girders with varying web openings.
- 2) To analyze the stress-strain relationships and force-displacement characteristics of plate girders with different web configurations.
- 3) To compare the ultimate load values and load-deflection relationships of plate girders with various web opening designs.
- 4) To assess the influence of web openings on the collapse behavior and structural effectiveness of hybrid stainless steel plate girders.

3. VALIDATION

By contrasting the FE models' output with the findings of actual experiments, the models' accuracy was evaluated. Validation is done using ABAQUS 2020. Values given are Young's modulus = 224600 MPa, Poisson's ratio = 0.225, vertical displacement load of 5 mm is applied at the midpoint. The dimensions were taken from reference journal [1].

Plate Girder	V-2205-500ad1
Material Grade	1.4462
Effective span, L	1198.3 mm
Distance b/w stiffener, a	499 mm
Edge distance, e	100.2 mm
Height of girder, h _w	498.4 mm
Breadth, b	150.2 mm
Thickness of web, t _w	3.9 mm
Thickness of flange or stiffener, t _f and t _s	12.9 mm

Table -1: Dimensions of plate girder for Validation

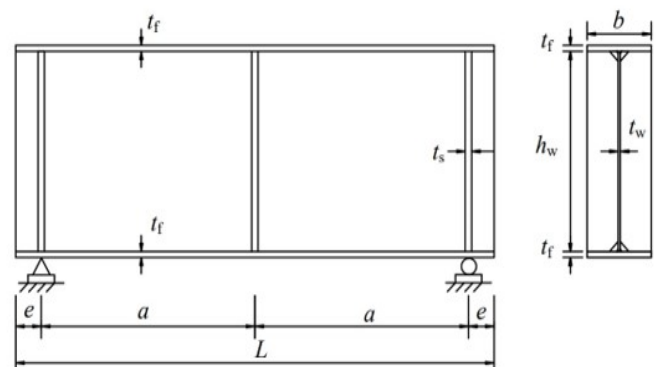


Fig -1: 2-D Geometry

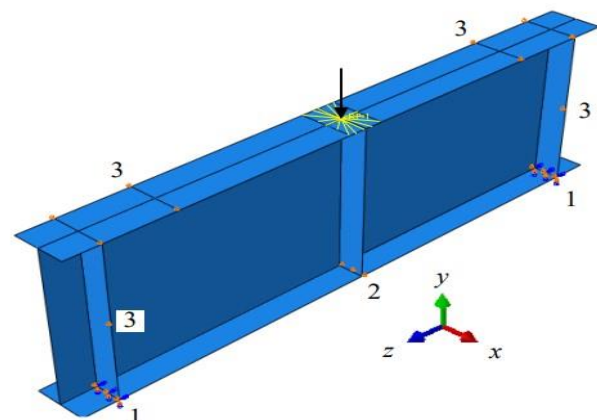


Fig -2: 3-D Geometry

Locations	u_x	u_y	u_z	θ_x	θ_y	θ_z	
1	1	1	0	0	1	1	0=free
2	0	0	1	0	0	0	1=restrained
3	1	0	0	0	0	0	

Fig -3: Boundary condition

3.1 Results of Validation

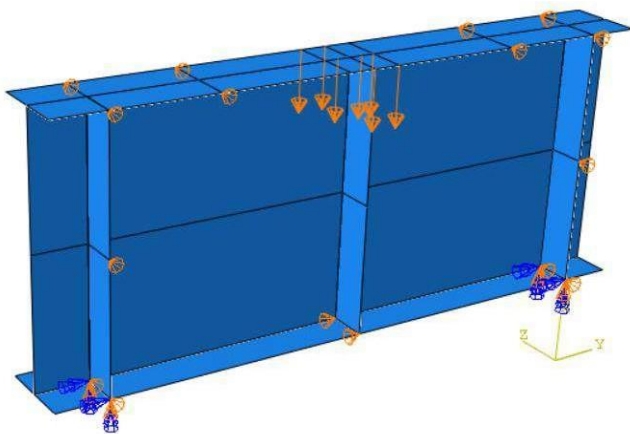


Fig -4: Model of plate girder with loads

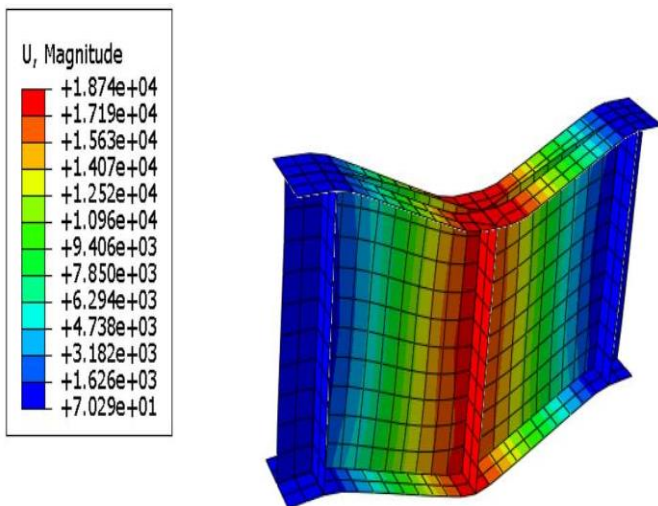


Fig -5: Deformed shape of plate girder

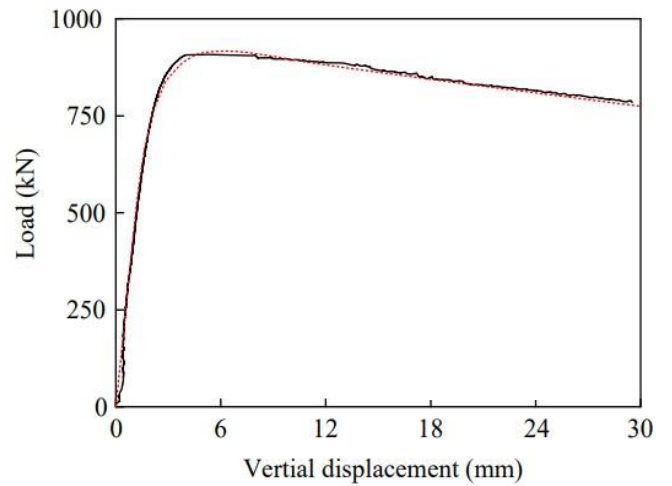


Chart -1: Load vs Displacement from the reference study

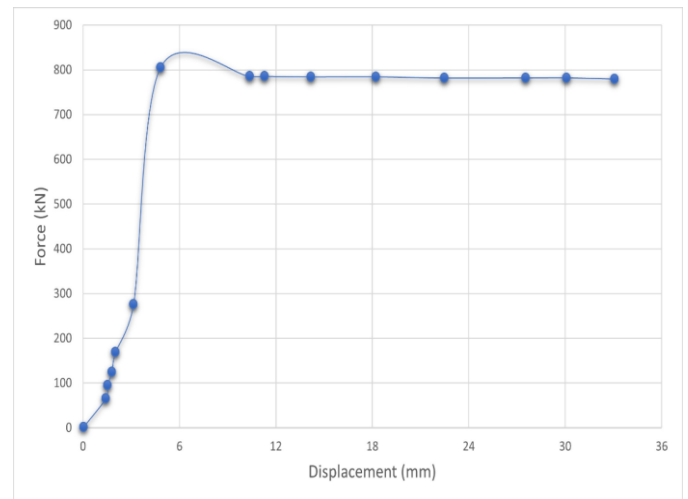


Chart -2: Load vs Displacement from Validation

Model	Target Displacement					
	Values from the reference study		Values from the Validation study		Percentage Error	
	X-axis (mm)	Y-axis (kN)	X-axis (mm)	Y-axis (kN)	X-axis	Y-axis
V-2205-500ad1	4	860	4	806.68	0	6.2 %

Table -2: Percentage error from Validation

3.2 Conclusion

The output of Analytical, FEA and Experimental analysis are in quite good argument with each other. The difference in their value is within 10% limit and is acceptable.

4. NUMERICAL ANALYSIS OF HYBRID STAINLESS STEEL PLATE GIRDER WITH OPENINGS

In this analysis, we focus on modelling and studying plate girders that incorporate web openings in various shapes, namely circular, square and rectangular. These plate girders exhibit a hybrid construction, featuring a web portion made of Duplex Stainless Steel and flange portion constructed from Lean Duplex Stainless Steel. The structural analysis involves applying a midpoint load as a displacement of 5 mm, and appropriate boundary conditions are also applied. Material property of the web and flange is given in Table 3.

Table -3: Material properties of hybrid plate girder

Model	Modulus of Elasticity (MPa)	Poisson's ratio	Yield Stress (N/mm ²)
Duplex Stainless Steel	208800	0.2	854
Lean Duplex Stainless Steel	203000	0.2	727.5

4.1 Modelling and Results

Table -4: Designation of models analysed

Designation	Model
Model 1	Circular web opening with small diameter
Model 2	Circular web opening with large diameter
Model 3	Square web opening with small area
Model 4	Square web opening with large area
Model 5	Rectangle web opening with small area
Model 6	Rectangle web opening with large area

Table -5: Dimensions of plate girder

Plate Girder	V-2205-500ad1
Material Grade	1.4462
Effective span, L	1198.3 mm
Distance b/w stiffener, a	499 mm
Edge distance, e	100.2 mm
Height of girder, hw	498.4 mm
Breadth, b	150.2 mm
Thickness of web, tw	3.9 mm
Thickness of flange or stiffener, tf and ts	12.9 mm

4.1.1 Model 1

The model 1 is a hybrid plate girder with circular web opening of smaller diameter. Load is applied at the midpoint as a displacement load of 5 mm and boundary condition is also applied.

For this model the diameter provided is

$$\frac{\text{height}}{6} = \frac{498.4}{6} = 83.06 \text{ mm}$$

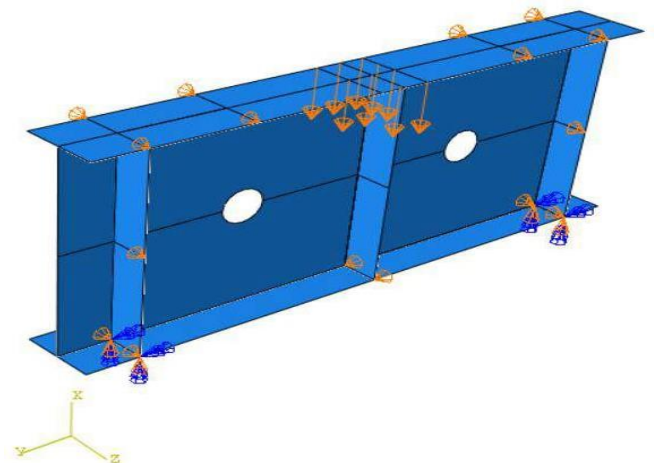


Fig -6: Model of hybrid plate girder with circular web hole

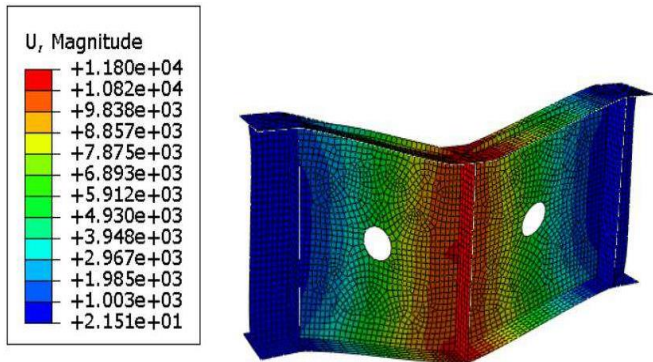


Fig -7: Deformed shape of hybrid plate girder with circular web hole

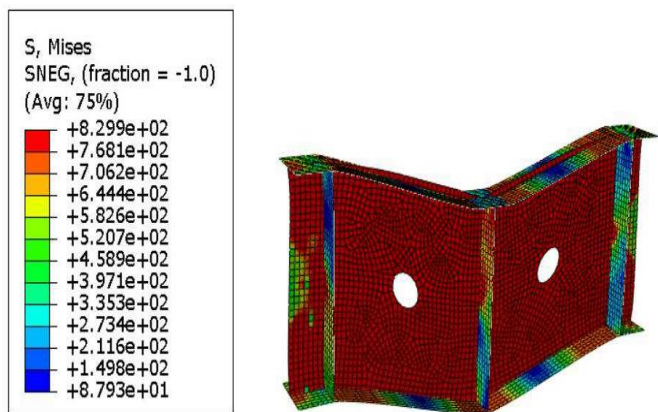


Fig -8: Von-Mises stress of Model-1

According to the Von Mises yield criterion, a material will undergo yielding if its Von mises stress under loading matches or is above the material’s yield limit under simple tension.

The red colour denotes the maximum stress portions and the blue colour denotes less stress areas. In this case, the maximum Von Mises stress noted is recorded as 8.299e+02.

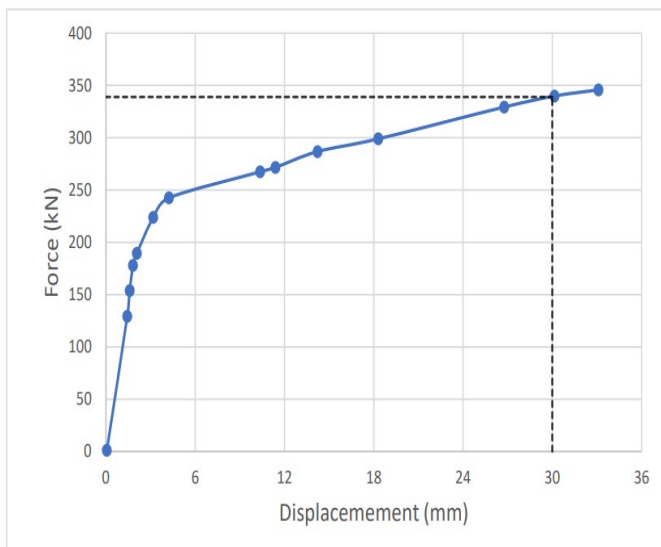


Chart -3: Force vs Displacement of Model-1

From the above chart it has been noted that the maximum load obtained is 339.9326 kN at a displacement of 30 mm respectively.

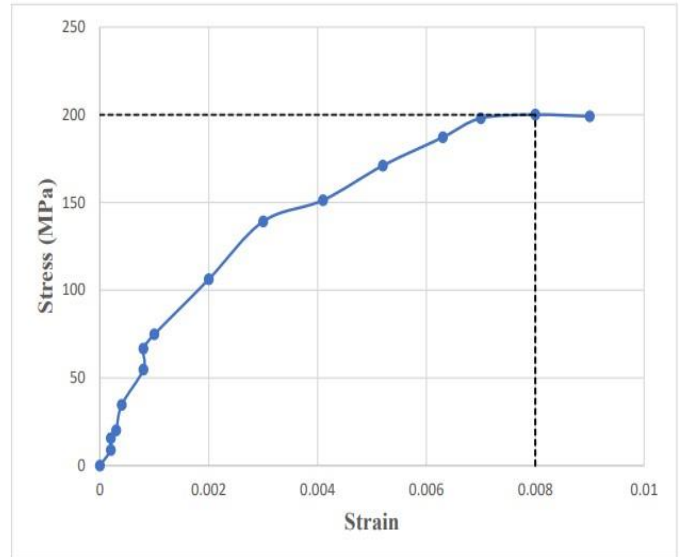


Chart -4: Stress vs Strain of Model-1

The maximum value of stress is approximately 200 MPa at a strain of 0.008.

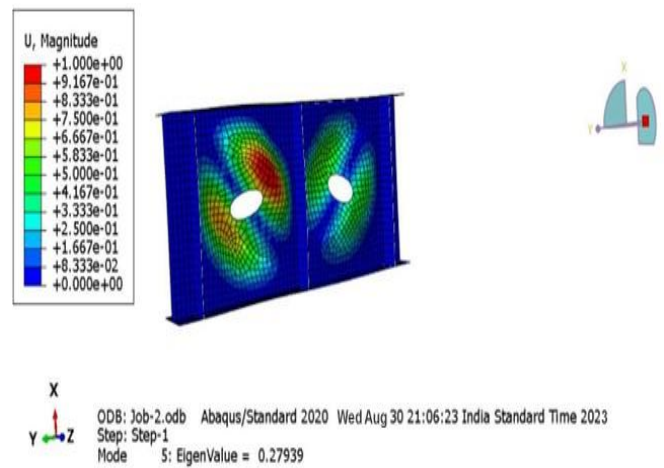


Fig -9: Buckled shape of Model-1

Buckling load is the load under which a structural member distorts under compression.

The buckling load is the product of eigen value and the load. Here the load is given as a displacement of 5 mm respectively and the eigen value is taken from Fig. 9.

$$\text{Buckling load} = \text{Eigen value} \times \text{Force} = 0.27939 \times 5 = 1.395 \text{ kN}$$

4.1.2 Model 2

The model 2 is a hybrid plate girder with circular web opening of larger diameter. Load is applied at the midpoint as a displacement load of 5 mm and boundary condition is also applied.

For this model the diameter provided is

$$\frac{\text{height}}{3} = \frac{498.4}{3} = 166.13 \text{ mm}$$

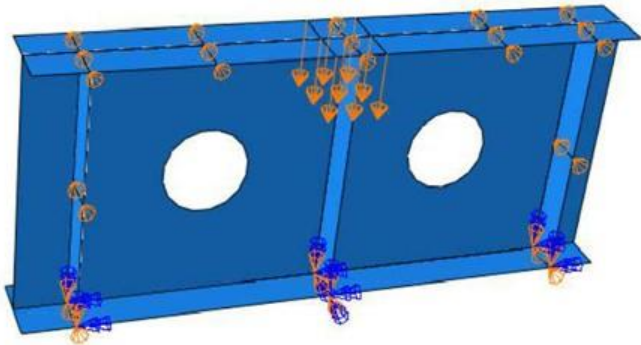


Fig -10: Model of hybrid plate girder with circular web hole

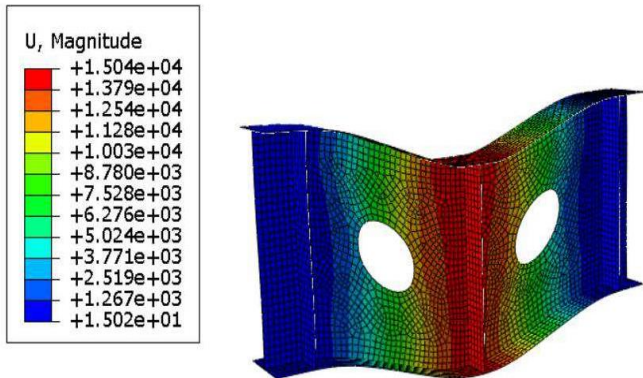


Fig -11: Deformed shape of hybrid plate girder with circular web hole

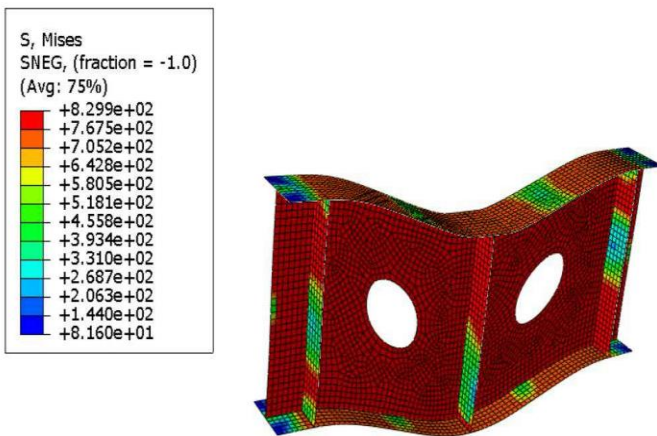


Fig -12: Von-Mises stress of Model-2

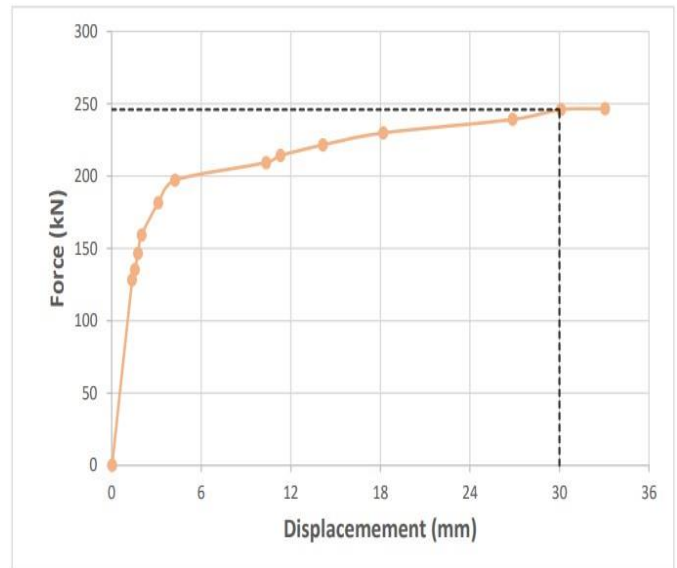


Chart -5: Force vs Displacement of Model-2

From the above chart it has been noted that the maximum load obtained is 246.0370 kN at a displacement of 30 mm respectively.

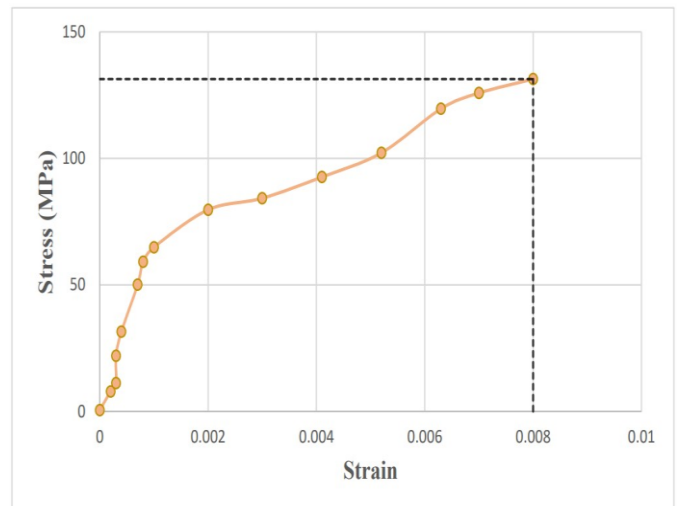


Chart -6: Stress vs Strain of Model-2

The maximum value of stress is approximately 131.352 MPa at a strain of 0.008.

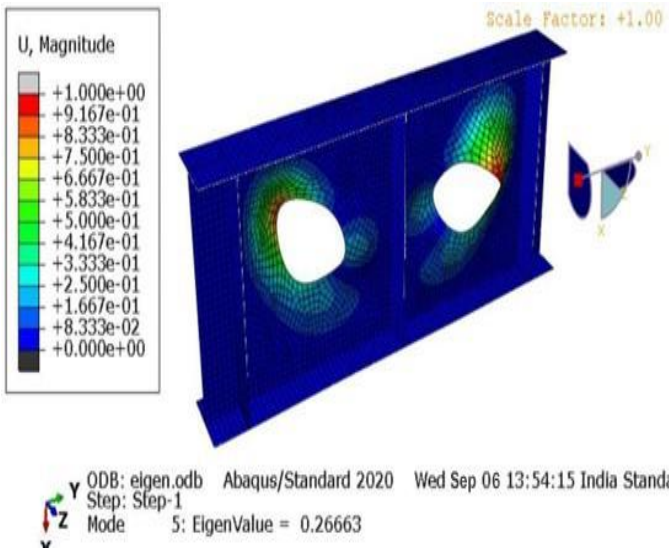


Fig -13: Buckled shape of Model-2

Buckling load = Eigen value × Force = 0.26663 × 5 = 1.333 kN

4.1.3 Model 3

The model 3 is a hybrid plate girder with square web opening of smaller area. Load is applied at the midpoint as a displacement load of 5 mm and boundary condition is also applied.

$$\begin{aligned} \text{Area of square (A)} &= \text{Area of circle} = \pi \times r^2 = \pi \times (41.53)^2 \\ &= 5418.43 \text{ mm}^2 \end{aligned}$$

$$\text{Therefore, side of square} = \sqrt{A} = \sqrt{5418.43} = 73.16 \text{ mm}$$

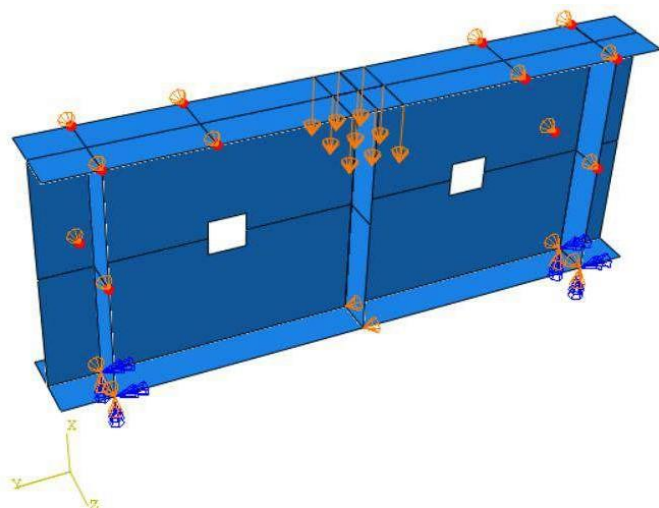


Fig -14: Model of hybrid plate girder with square web hole

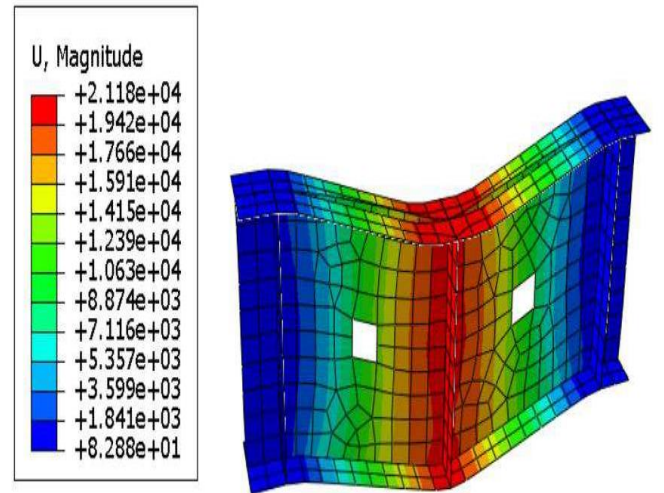


Fig -15: Deformed shape of hybrid plate girder with square web hole

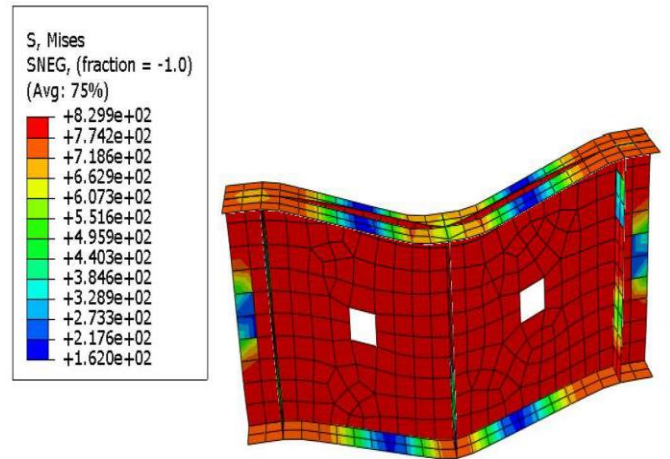


Fig -16: Von-Mises stress of Model-3

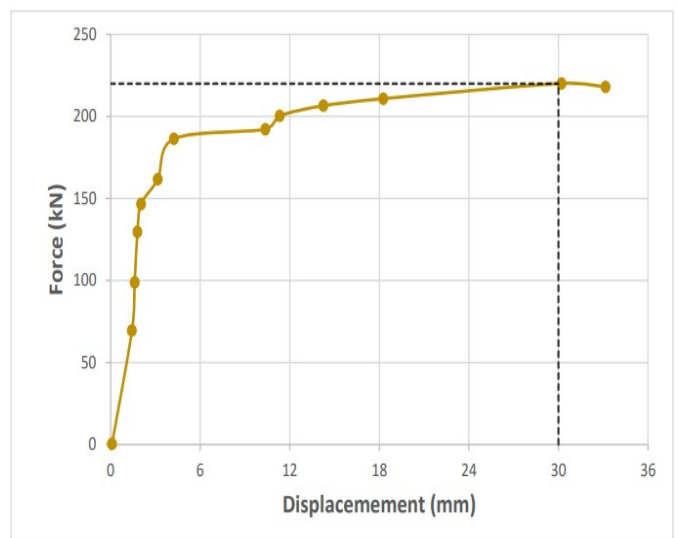


Chart -7: Force vs Displacement of Model-3

From the above chart it has been noted that the maximum load obtained is 220.1444 kN at a displacement of 30 mm respectively.

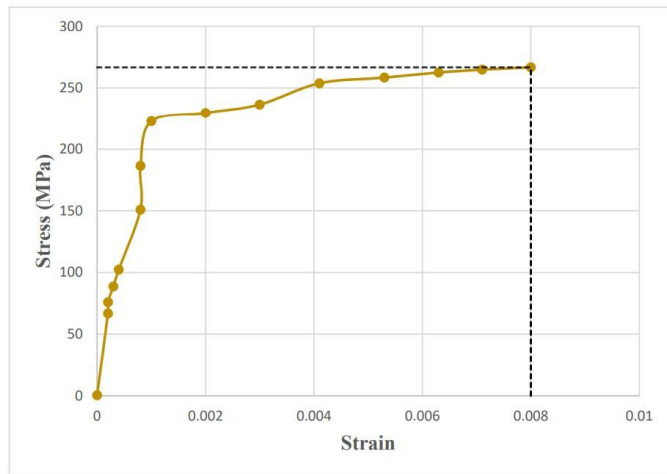


Chart -8: Stress vs Strain of Model-3

The maximum value of stress is approximately 266.7278 MPa at a strain of 0.008.

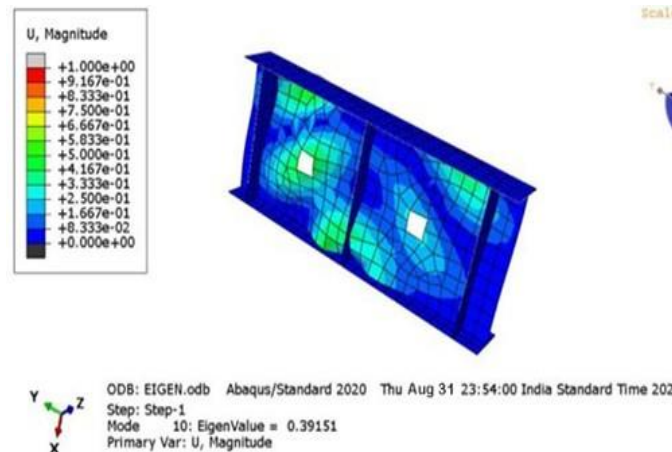


Fig -17: Buckled shape of Model-3

Buckling load = Eigen value \times Force = $0.39151 \times 5 = 1.965$ kN

4.1.4 Model 4

The model 4 is a hybrid plate girder with square web opening of larger area. Load is applied at the midpoint as a displacement load of 5 mm and boundary condition is also applied.

$$\begin{aligned} \text{Area of square (A)} &= \text{Area of circle} = \pi \times r^2 = \pi \times (83.06)^2 \\ &= 21673.73 \text{ mm}^2 \end{aligned}$$

Therefore, side of square = $\sqrt{A} = \sqrt{21673.73} = 147.22$ mm

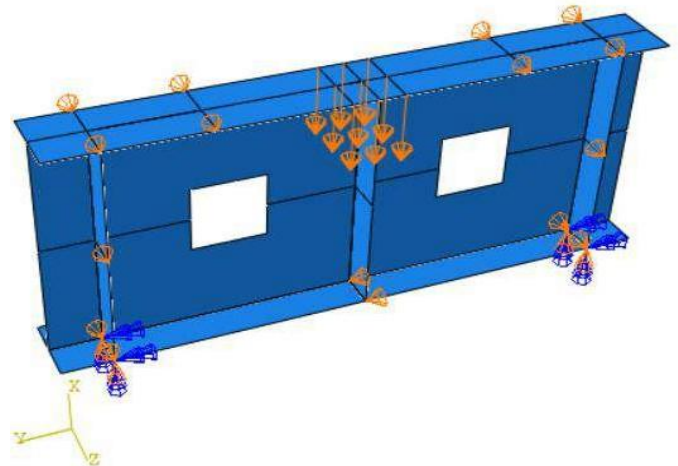


Fig -18: Model of hybrid plate girder with square web hole

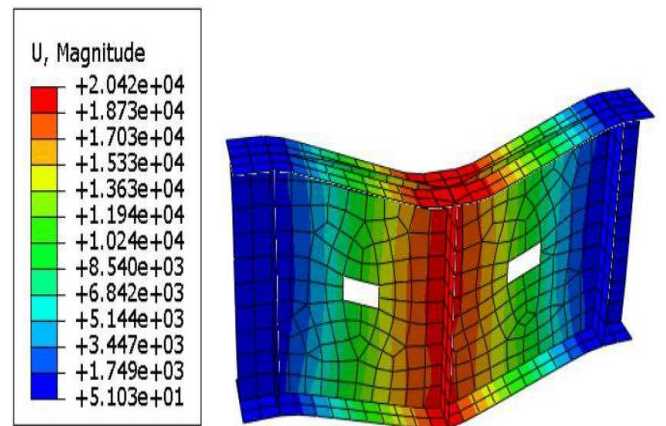


Fig -19: Deformed shape of hybrid plate girder with square web hole

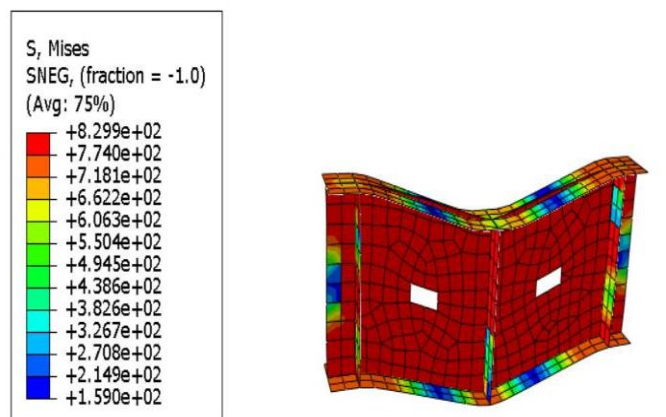


Fig -20: Von-Mises stress of Model-4

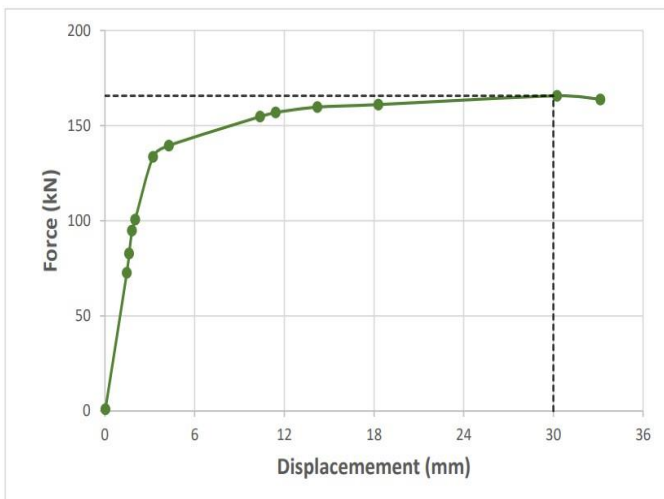


Chart -9: Force vs Displacement of Model-4

From the above chart it has been noted that the maximum load obtained is 165.6970 kN at a displacement of 30 mm respectively.

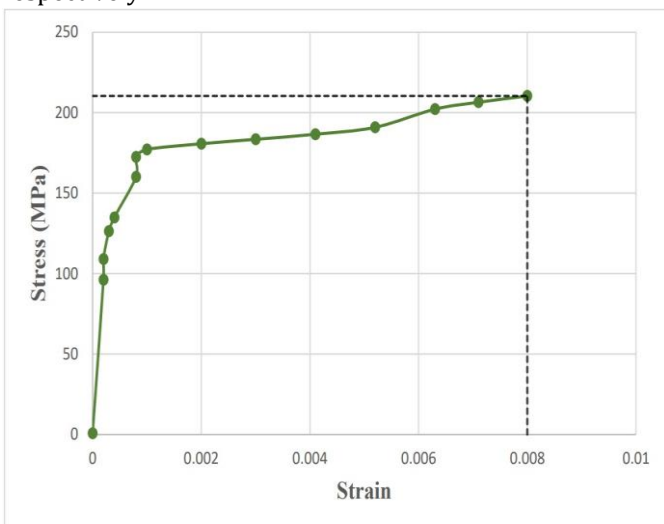


Chart -10: Stress vs Strain of Model-4

The maximum value of stress is approximately 210.3992 MPa at a strain of 0.008.

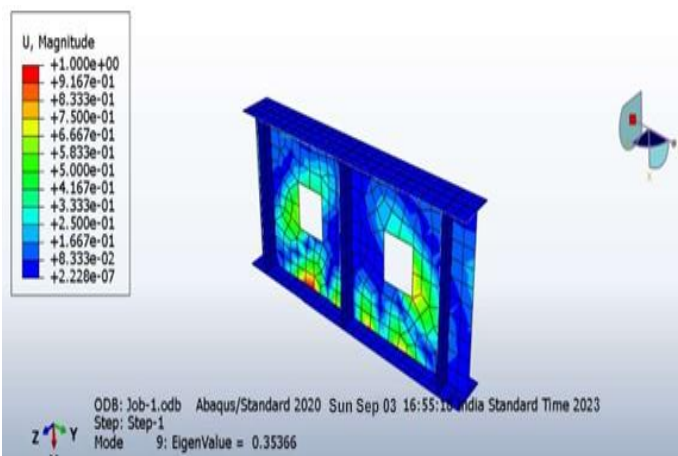


Fig -21: Buckled shape of Model-4

$$\text{Buckling load} = \text{Eigen value} \times \text{Force} = 0.35366 \times 5 = 1.765 \text{ kN}$$

4.1.5 Model 5

The model 5 is a hybrid plate girder with rectangular web opening of smaller area. Load is applied at the midpoint as a displacement load of 5 mm and boundary condition is also applied.

$$\text{Area of rectangle (A)} = \text{Area of circle} = \pi \times r^2 = \pi \times (41.53)^2 = 5418.43 \text{ mm}^2$$

$$(L = 2 \times B) \text{ Length of rectangle} = 104.1 \text{ mm}$$

$$\text{Breadth of rectangle} = 52.05 \text{ mm}$$

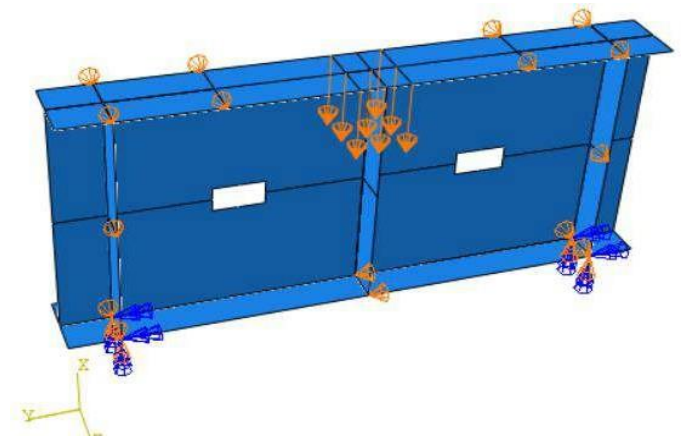


Fig -22: Model of hybrid plate girder with rectangular web hole

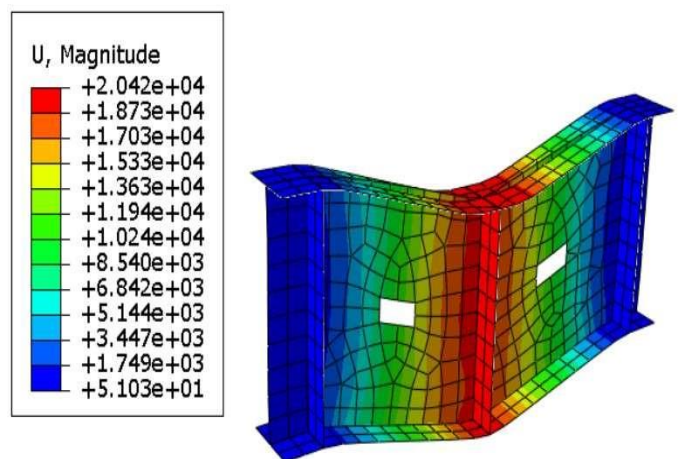


Fig -23: Deformed shape of hybrid plate girder with rectangular web hole

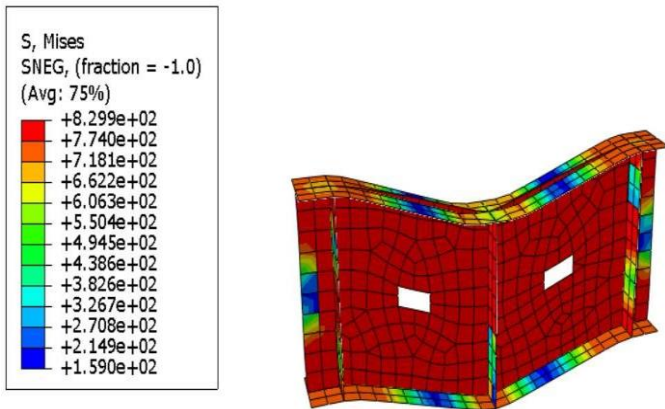


Fig -24: Von-Mises stress of Model-5

The maximum value of stress is approximately 369.5749 MPa at a strain of 0.008.

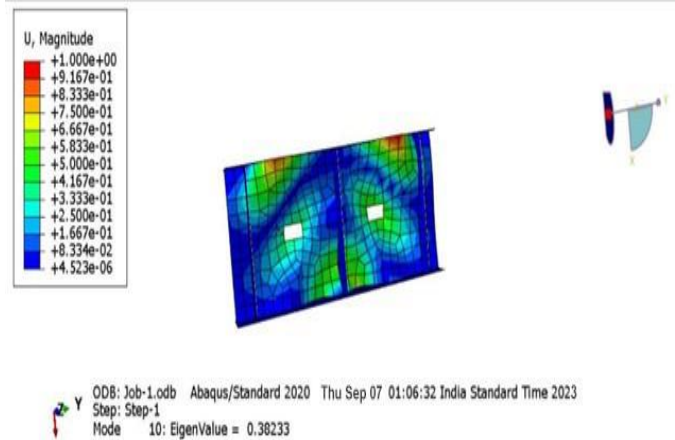


Fig -25: Buckled shape of Model-5

Buckling load = Eigen value × Force = 0.38233 × 5 = 1.911 kN

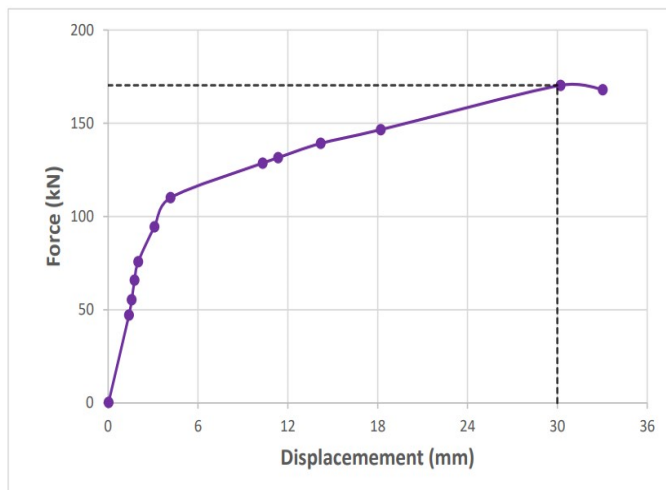


Chart -11: Force vs Displacement of Model-5

From the above chart it has been noted that the maximum load obtained is 170.3625 kN at a displacement of 30 mm respectively.

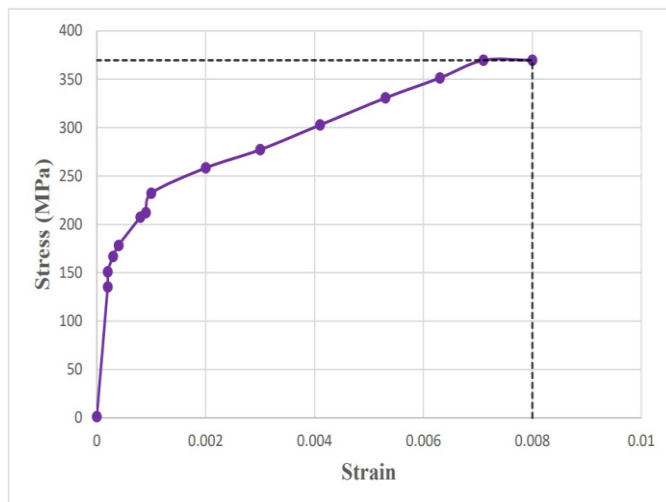


Chart -12: Stress vs Strain of Model-5

4.1.6 Model 6

The model 6 is a hybrid plate girder with rectangular web opening of larger area. Load is applied at the midpoint as a displacement load of 5 mm and boundary condition is also applied.

$$\text{Area of rectangle (A)} = \text{Area of circle} = \pi \times r^2 = \pi \times (83.06)^2 = 21673.73 \text{ mm}^2$$

$$(L = 2 \times B) \text{ Length of rectangle} = 208.2 \text{ mm}$$

$$\text{Breadth of rectangle} = 104.1 \text{ mm}$$

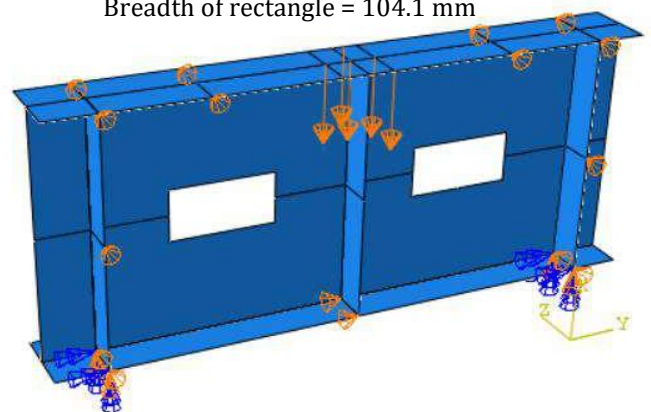


Fig -26: Model of hybrid plate girder with rectangular web hole

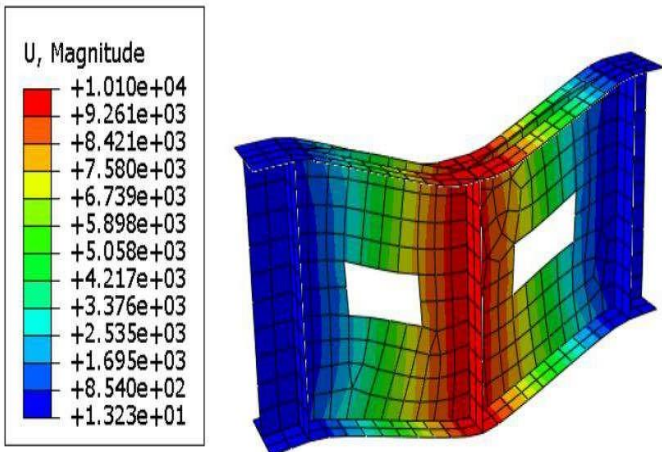


Fig -27: Deformed shape of hybrid plate girder with rectangular web hole

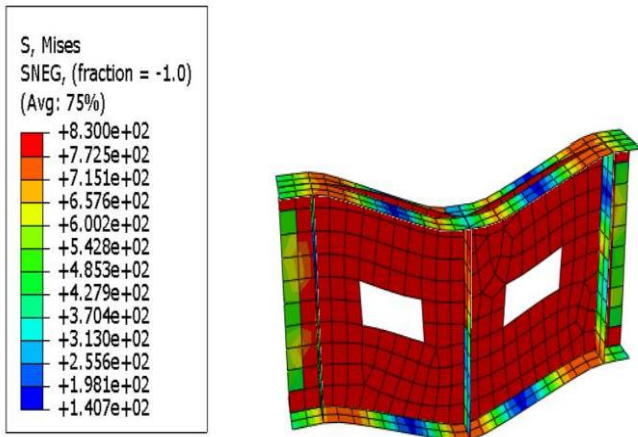


Fig -28: Von-Mises stress of Model-6

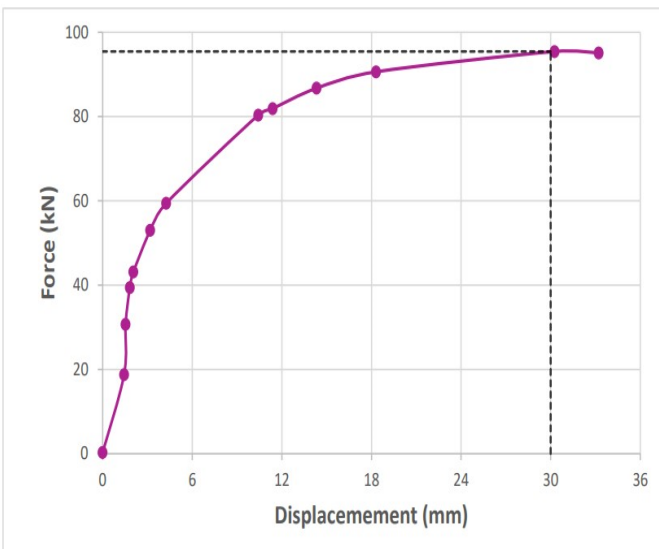


Chart -13: Force vs Displacement of Model-6

From the above chart it has been noted that the maximum load obtained is 95.4432 kN at a displacement of 30 mm respectively.

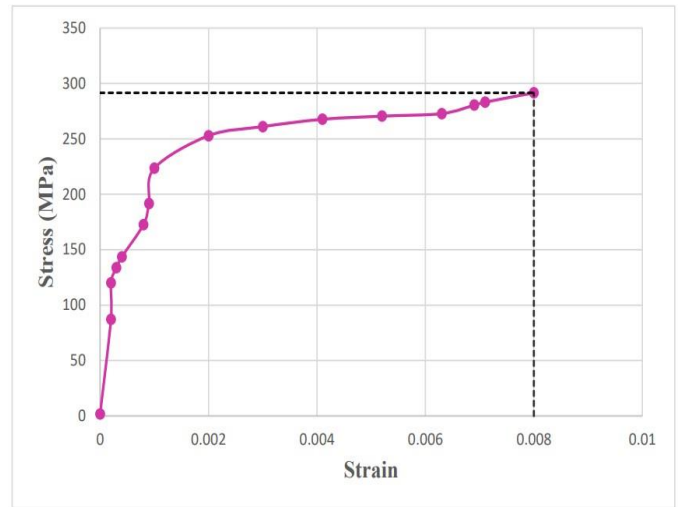


Chart -14: Stress vs Strain of Model-6

The maximum value of stress is approximately 291.5235 MPa at a strain of 0.008.

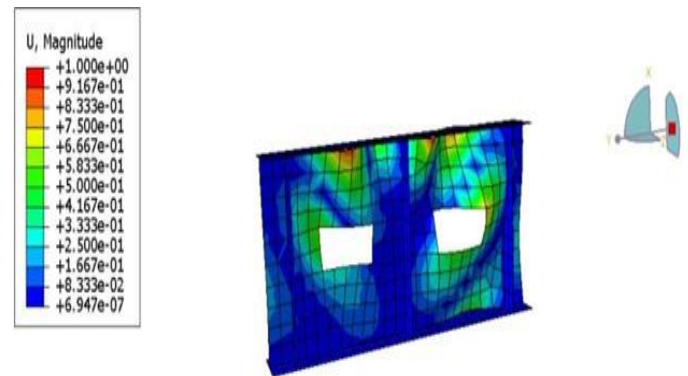


Fig -29: Buckled shape of Model-6

Buckling load = Eigen value \times Force = 0.34451 \times 5 = 1.722 kN

5. RESULTS AND DISCUSSIONS

5.1 Comparison graph of Load- Displacement

The load displacement graph of model-1, model-3, model-5 were compared as in Chart-15, since the area of opening was same for the following models.

From Chart-15 it is clear that Model-1 (Circular web opening with small diameter) can take maximum load and Model-5 (Rectangular web opening with small area) can take the minimum load.

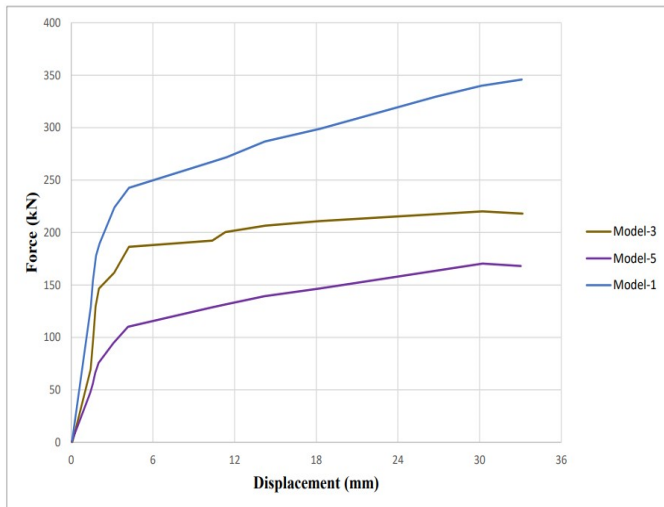


Chart -15: Comparison graph of load displacement for Model 1,3,5

Similarly, the load displacement graph of model-2, model-4, model-6 were compared as in Chart-16, since the area of opening was same for the following models.

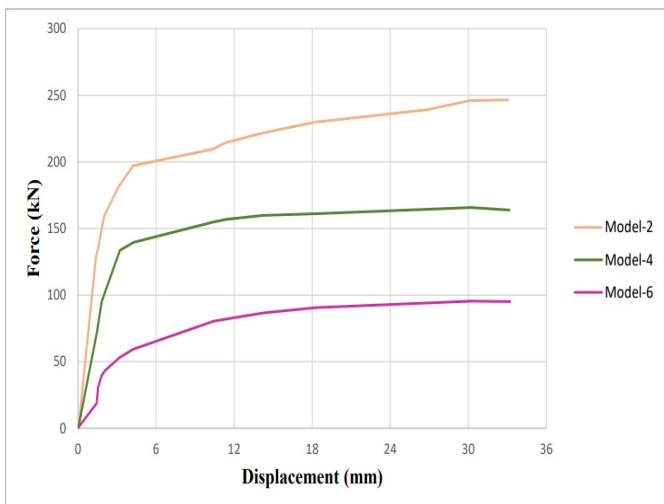


Chart -16: Comparison graph of load displacement for Model 2,4,6

From Chart-16 it is clear that Model-2 (Circular web opening with large diameter) can take maximum load and Model-6 (Rectangular web opening with large area) can take the maximum load.

In comparisons of Chart-15 and Chart-16 it can be said that circular web openings can carry the highest loads before experiencing significant displacement.

5.2 Comparison graph of Stress- Strain

The stress strain graph of model-1, model-3, model-5 were compared as in Chart-17, since the area of opening was same for the following models

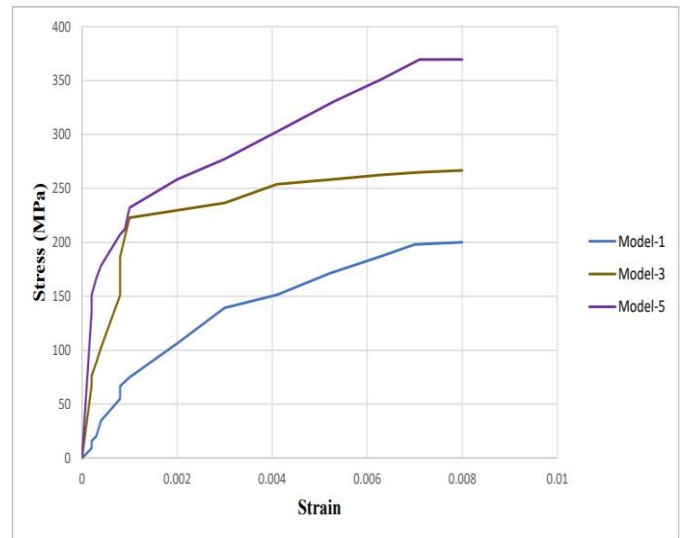


Chart -17: Comparison graph of stress strain for Model 1,3,5

From Chart-17 it is clear that Model-5 (Rectangular web opening with small area) is subjected to maximum stress and Model-1 (Circular web opening with small diameter) is subjected to minimum stress

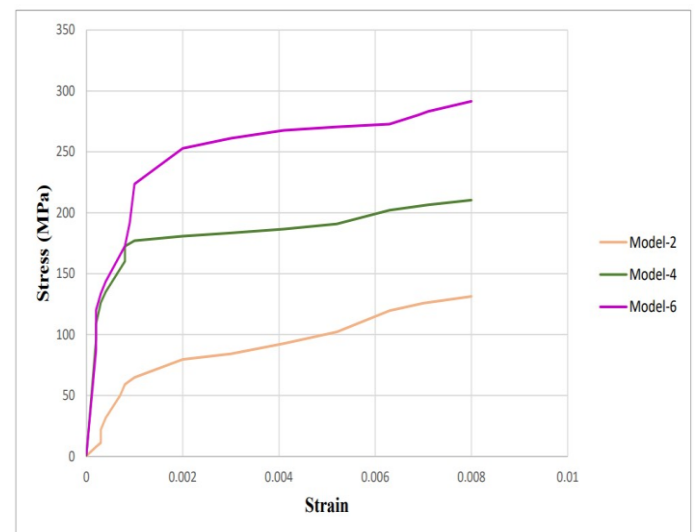


Chart -18: Comparison graph of stress strain for Model 2,4,6

Similarly, the stress strain graph of model-2, model-4, model-6 were compared as in Chart-17, since the area of opening was same for the following models.

From Chart-18 it is clear that Model-2 (Circular web opening with large diameter) is subjected to maximum stress and Model-6 (Rectangular web opening with large area) is subjected to minimum stress.

In comparisons of Chart-17 and Chart-18 it can be said that as the area of web opening increases, the stress on the girder increases. Thus, circular web openings experience lower stress compared to other models.

5.3 Comparison graph of Buckling load

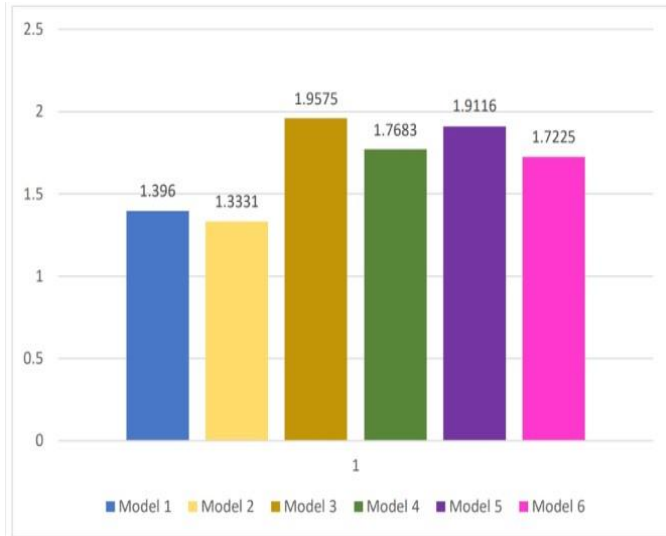


Chart -19: Comparison graph of Buckling loads

From Chart-19 it is clear that Model-1 (Circular web opening with small diameter) and Model-2 (Circular web opening with large diameter) has less buckling load when compared to other models.

The presence of a circular web opening in a plate girder can indeed reduce its buckling load capacity and it is essential that one has to carefully analyze and design such girders to maintain structural integrity and safety.

6. CONCLUSIONS

- 1) From the analysis it is evident that Hybrid plate girders with circular web openings contribute better in load carrying capacity and structural stiffness.
- 2) It appears that Hybrid plate girder with circular web opening experience lower stress compared to other models and have more favorable stress distribution. (As the area of the web opening increases, the stress on the girder increases)
- 3) Hybrid Plate girder with rectangular web opening is subjected to maximum stress.
- 4) Hybrid Plate girder with circular web openings have lower buckling load when compared to other models.
- 5) For design consideration
 - Circular openings can enhance load capacity but may require additional measures to address buckling concerns.
 - Rectangular & square openings might be favored in applications where the stress concentration can be managed effectively.

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