



## Numerical investigation of stress concentration and deformation behavior of steel I-beams with web openings using the finite element method

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### ABSTRACT

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Steel I-beams with web openings are widely used in modern steel structures to accommodate mechanical and electrical services and improve construction efficiency. However, web openings alter the internal force transfer mechanism of the beam, leading to stress concentration and increased deformation, which may affect structural safety and serviceability. This study presents a numerical investigation of the stress distribution and deformation behavior of steel I-beams with web openings using the Finite Element Method (FEM). Three-dimensional finite element models of IPE steel beams are developed in ANSYS, incorporating elastic-plastic material behavior and geometric nonlinearity. Beams with different web configurations, including solid webs, circular openings, and square openings with equivalent areas, are analyzed under four-point bending. The effects of opening geometry on stress concentration, mid-span deflection, and overall structural response are examined. The numerical results show that the presence of web openings significantly increases stress concentration and reduces beam stiffness compared to solid web beams. Circular openings produce a more uniform stress distribution with lower peak stresses, while square openings lead to higher stress concentration at the corners due to pronounced Vierendeel action. Comparison with analytical solutions for solid beams demonstrates good agreement, confirming the validity of the numerical modeling approach. The findings provide useful insights for the design and assessment of perforated steel beams in practical engineering applications.

**Contribution/Originality:** This study is original in that it presents a unified three-dimensional nonlinear finite element comparison of steel I-beams with circular and square web openings of equivalent area under identical four-point bending conditions, focusing on stress concentration and serviceability behavior rather than ultimate strength.

### 1. INTRODUCTION

Steel structures have been extensively used in civil and industrial construction due to their high strength-to-weight ratio, ease of fabrication, and rapid construction. Among various structural members, steel I-beams play a critical role as primary load-bearing elements in floors, roofs, and frames. In modern buildings, the demand for large unobstructed spaces and efficient integration of mechanical, electrical, and plumbing (MEP) systems has increased significantly. To meet these requirements, web openings are often introduced into steel beams, allowing service ducts and pipes to pass through the beam depth without increasing floor height [1-4].

Despite their functional advantages, web openings can significantly affect the structural behavior of steel I-beams. The removal of material from the web reduces the shear capacity and stiffness of the beam and causes stress concentration around the opening edges. In particular, when openings are located in regions of high shear or bending

moment, the beam's structural safety may be compromised. Therefore, a detailed understanding of the stress distribution and deformation characteristics of steel I-beams with web openings is essential for safe design and assessment [5-9].

Traditional analytical methods often rely on simplified assumptions and empirical formulas, which may not accurately capture the complex stress states around web openings. With the advancement of computational mechanics and numerical methods, the Finite Element Method (FEM) has become a powerful tool for analyzing complex structural problems. FEM allows detailed modeling of geometry, material nonlinearity, and boundary conditions, making it suitable for investigating the behavior of steel beams with web openings [10-14].

In this study, finite element analysis using ANSYS investigates the stress and deformation behavior of steel I-beams with web openings. The focus is on comparing different opening shapes and their effects on stress concentration and deflection. The results support the assessment and design of steel I-beams with web openings, especially for existing structures such as workshop buildings and training facilities [15-19].

In recent decades, the application of steel beams with web openings has become increasingly common in modern building construction, particularly in commercial and industrial facilities where the integration of mechanical, electrical, and plumbing (MEP) systems is essential. The use of web openings allows service ducts to pass through the beam depth, thereby reducing floor-to-floor height and improving architectural flexibility. This design approach is widely adopted in steel-framed buildings, workshops, and training facilities, where efficient space utilization is a primary concern [20-24].

However, introducing openings in the web inevitably modifies the internal force transfer mechanism of the beam. Unlike solid-web beams, perforated beams exhibit localized stress redistribution, increased deformation, and potential reductions in shear and bending capacity. Several parameters, including opening size, shape, location, spacing, and proximity to supports, influence the structural behavior of such beams. Improperly designed web openings may lead to premature yielding, excessive deflection, or even local buckling and failure [23, 25].

Current design standards, such as AISC 360 and Eurocode 3, provide simplified guidelines and empirical recommendations for web openings. These provisions are often conservative and limited in scope, especially when dealing with nonstandard opening shapes or configurations. Moreover, analytical solutions based on classical beam theory are generally insufficient to capture the complex three-dimensional stress state that develops around web openings, particularly under combined bending and shear loading [26].

In this context, numerical simulation techniques, particularly the Finite Element Method (FEM), offer a powerful alternative for investigating the structural behavior of beams with web openings. FEM enables accurate representation of geometry, material behavior, boundary conditions, and load application, allowing detailed insight into stress concentration, deformation patterns, and nonlinear response. Previous studies have demonstrated the effectiveness of FEM in analyzing steel beams with circular and rectangular openings; however, systematic comparisons between different opening shapes under identical conditions remain limited.

Furthermore, most existing studies focus primarily on ultimate strength or buckling behavior, while relatively fewer investigations address the detailed stress and deformation response under service-level loading conditions. For practical engineering applications, especially in existing structures, understanding stress concentration and deflection behavior is equally important for assessing safety, durability, and serviceability.

Therefore, the present study aims to provide a comprehensive finite element investigation of steel I-beams with various web opening shapes using ANSYS. By comparing solid beams with beams containing circular and square openings of equivalent area, this research seeks to clarify the influence of opening geometry on stress distribution, deformation characteristics, and overall structural performance. The results contribute to a deeper understanding of the mechanical behavior of perforated steel beams and offer valuable references for engineers involved in the design, assessment, and strengthening of steel structures.

## 2. LITERATURE REVIEW

The structural behavior of steel beams with web openings has been extensively researched over the past decades. Early investigations were mainly experimental, focusing on ultimate strength and failure modes. Researchers observed that web openings significantly influence shear capacity and induce local bending effects, commonly described as the Vierendeel mechanism. These studies laid the foundation for understanding the critical role of opening geometry and placement.

Shanmugam and Dhanaraj [1] investigated steel beams with circular and rectangular web openings, revealing that rectangular openings caused higher stress concentrations and earlier failure due to sharp corners. Erdal and Saka [2] conducted numerical and experimental studies on the ultimate load-carrying capacity of beams with web openings, emphasizing the importance of opening size and location relative to shear force distribution. Their findings showed that openings near mid-span generally have less adverse effects than those near supports.

With the advancement of computational tools, numerical approaches based on FEM have become dominant in this research area. Cook, et al. [3] emphasized that FEM provides superior accuracy in modeling stress gradients and local effects compared to analytical methods. Abbas and Hussein [27] conducted a numerical study on steel IPE beams strengthened with CFRP plates and showed that appropriate reinforcement could partially restore the loss of stiffness caused by web openings.

Several studies have focused specifically on stress concentration factors around openings. Pilkey and Pilkey [4] provided extensive stress concentration factor formulations for various geometries, which are often used for preliminary design. However, these formulations are typically derived for simplified geometries and loading conditions and may not be directly applicable to real structural beams with complex boundary conditions.

Recent studies have extended the analysis to include nonlinear material behavior and large deformation effects. Advanced finite element formulations, such as the Extended Finite Element Method (XFEM), have been employed to model arbitrary openings and discontinuities without mesh conformity. Sukumar, et al. [5] demonstrated the effectiveness of XFEM in modeling holes and inclusions, while Nguyen and Huang [23] and Nguyen and Huang [24] applied XFEM to functionally graded material plates with circular holes, achieving accurate stress concentration predictions.

Despite these advancements, a gap remains in the literature regarding systematic comparisons of different opening shapes under consistent modeling assumptions and loading scenarios. Many studies consider only one type of opening or focus primarily on ultimate strength rather than serviceability behavior. Additionally, most available research emphasizes plate or shell structures, while detailed three-dimensional beam models are less frequently reported.

Therefore, the present study addresses these gaps by conducting a unified finite element investigation of steel I-beams with different web opening shapes under bending loads. By maintaining consistent geometry, material properties, and boundary conditions, the influence of opening shape on stress and deformation behavior can be clearly identified and quantified.

## 3. THEORETICAL BACKGROUND

### 3.1. Mechanical Behavior of Steel I-Beams

Steel I-beams resist bending mainly through their flanges, while the web primarily carries shear forces. Under bending loads, normal stresses develop in the flanges, reaching maximum values at the extreme fibers, whereas shear stresses are concentrated in the web. When a web opening is introduced, the load transfer mechanism is disturbed, leading to a redistribution of stresses and localized stress concentrations.

Under pure bending, the normal stress distribution across the beam depth can be expressed as:

$$\sigma = M \cdot y / I \quad (1)$$

Where  $M$  is the bending moment,  $y$  is the distance from the neutral axis, and  $I$  is the second moment of area of the cross-section.

The average shear stress in the web can be estimated by:

$$\tau = V \cdot Q / (I \cdot t_w) \quad (2)$$

Where  $V$  is the shear force,  $Q$  is the first moment of area, and  $t_w$  is the web thickness.

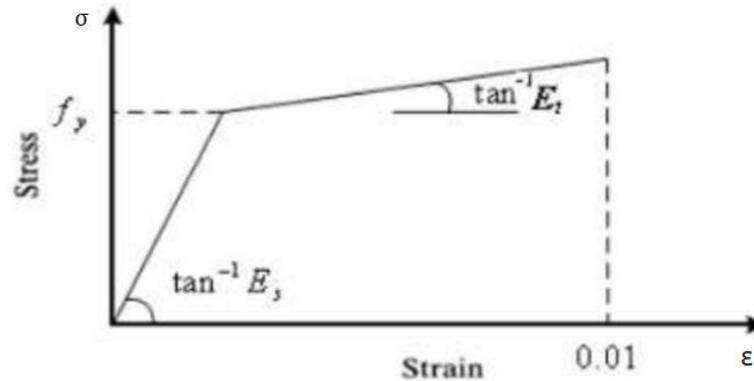


Figure 1. Typical stress distribution in an I-beam under bending.

Figure 1 illustrates the typical stress distribution in a steel I-beam subjected to bending shows normal stresses concentrated in the flanges, while shear stresses are primarily carried by the web.

### 3.2. Stress Concentration Around Web Openings

Web openings interrupt the continuity of the web and induce local bending and shear effects, commonly referred to as the Vierendeel mechanism. This mechanism generates additional bending moments around the opening corners, resulting in high stress concentration. The magnitude of stress concentration depends on the opening shape, size, location, and the applied loading conditions.

When a web opening exists, the beam segment around the opening behaves like a Vierendeel panel. The additional bending moment around the opening edges can be approximated as:

$$M_v = V \cdot e \quad (3)$$

Where  $V$  is the shear force, and  $e$  is the eccentricity between the centroidal axes of the upper and lower tee sections.

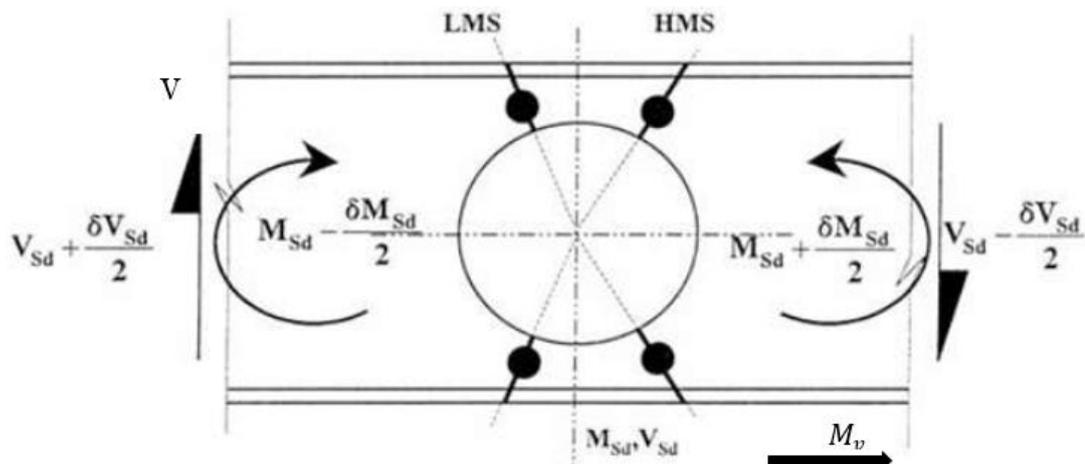


Figure 2. Illustration of the Vierendeel mechanism around a web opening, showing local bending moments and shear forces.

Figure 2 illustrates the Vierendeel mechanism around a web opening, showing the development of local bending moments and shear forces in the beam segments above and below the opening.

### 3.3. Finite Element Method

The Finite Element Method is a numerical technique for solving boundary value problems in engineering. In structural analysis, the domain is discretized into finite elements interconnected at nodes. The governing equations are formulated based on equilibrium, compatibility, and constitutive relationships. In this study, shell elements are used to model the steel I-beam, allowing accurate representation of bending, shear, and membrane actions.

The general equilibrium equation in FEM is given by:

$$[K]\{u\} = \{F\} \quad (4)$$

Where  $[K]$  is the global stiffness matrix,  $\{u\}$  is the nodal displacement vector, and  $\{F\}$  is the external force vector.

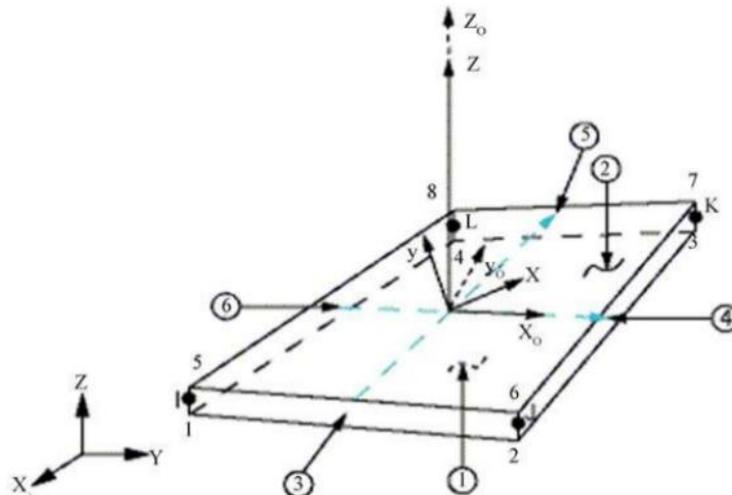


Figure 3. Discretization of a beam into finite elements and nodal degrees of freedom.

Figure 3 illustrates the finite element discretization of the steel I-beam, showing the element mesh, nodal degrees of freedom, and the overall modeling framework used in the numerical analysis.

## 4. FINITE ELEMENT MODELING

### 4.1. Geometry and Beam Configuration

The investigated beam is a steel I-beam with an IPE-type cross-section. The total beam length is 2200 mm, with a clear span of 2000 mm between supports. Web openings are introduced at the mid-span region. Four beam configurations are analyzed: (Figure 4a,b).

- Solid web beam (reference model).
- Beam with a circular web opening.
- Beam with a square web opening.

All openings have comparable areas to ensure a fair comparison of their effects.

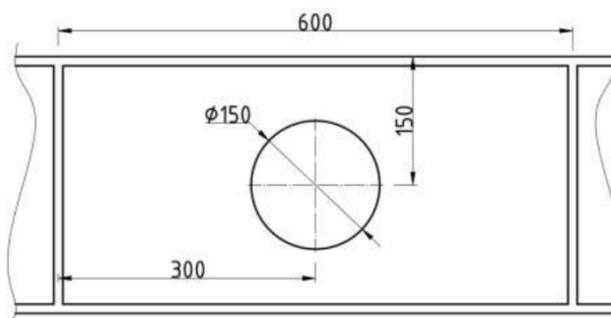


Figure 4a. Dimensioned geometry (beam with a circular web opening).

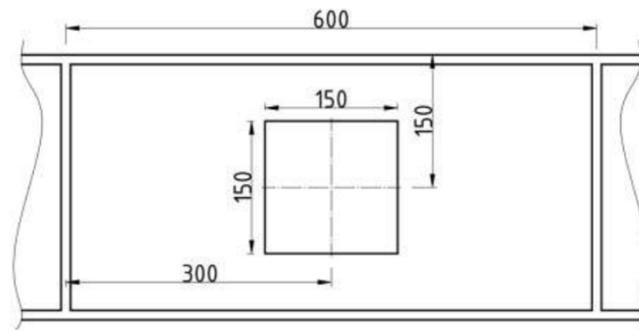


Figure 4b. Dimensioned geometry (Beam with a square web opening).

#### 4.2. Material Properties

The steel material is modeled as an elastic–plastic material with a bilinear stress–strain relationship. The Young’s modulus is 200 GPa, Poisson’s ratio is 0.3, and the yield strength is 253 MPa. Isotropic hardening is assumed to simulate post-yield behavior (Figure 5).

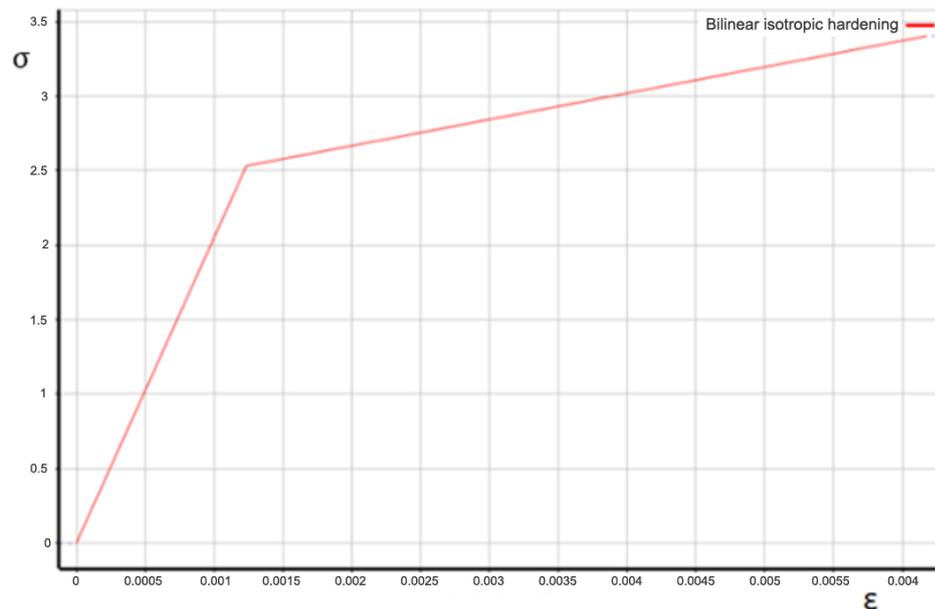


Figure 5. Bilinear stress-strain curve of steel in ANSYS.

#### 4.3. Element Type and Mesh

Shell elements (SHELL181) in ANSYS model beams effectively, suitable for thin to moderately thick shell structures, accurately capturing bending and membrane behavior. Mesh refinement around web opening regions helps to accurately capture stress concentration effects (Figure 6a,b).

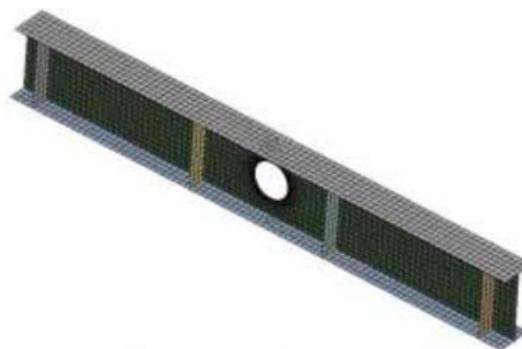


Figure 6a. Element mesh (Beam with a circular web opening).

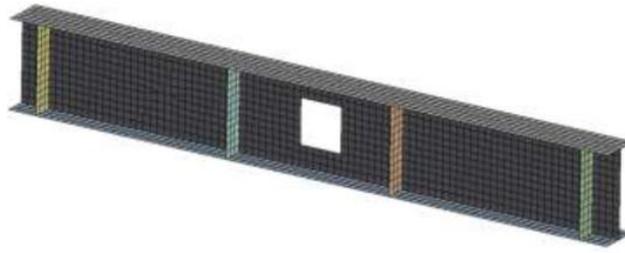


Figure 6b. Element mesh (Beam with a square web opening).

#### 4.4. Boundary Conditions and Loading

The beam is simply supported at both ends. Vertical displacement is restrained at the supports, while rotation is allowed. A four-point bending configuration is applied by imposing two equal concentrated loads symmetrically about the mid-span. The load is increased incrementally to capture the nonlinear response.

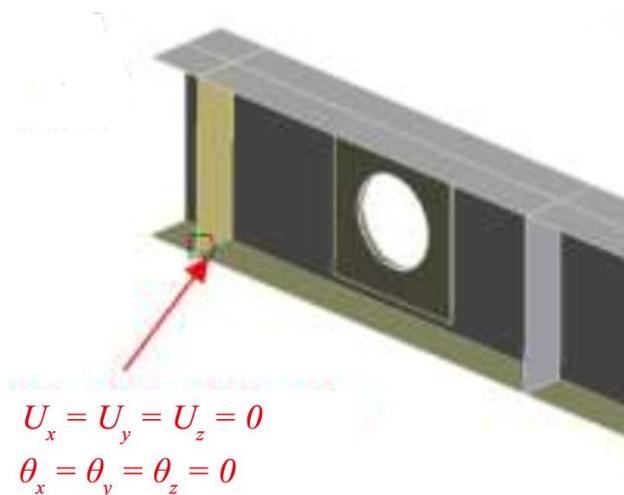


Figure 7. The boundary conditions of a fixed clamp at one end.

Figure 7 illustrates the boundary conditions and loading configuration applied to the steel I-beam in the finite element model, including support restraints and the four-point bending load arrangement.

#### 4.5. Numerical Convergence and Model Verification

To ensure the reliability of the finite element results, a mesh convergence study was conducted. Several mesh densities were examined, particularly near the web openings where high stress gradients are expected. The results indicate that further mesh refinement beyond the selected configuration causes negligible changes in maximum stress and displacement, confirming the numerical stability of the model.

Additionally, the solid web beam model was validated against classical beam theory predictions for mid-span deflection under four-point bending. The numerical results showed good agreement with analytical solutions, with an error of approximately 4.1%, which is acceptable for structural finite element analysis. This validation provides confidence in the accuracy of the modeling approach and supports its application to beams with web openings.

## 5. RESULTS AND DISCUSSION

### 5.1. Stress Distribution

The finite element results show that the solid web beam exhibits a relatively uniform stress distribution, with maximum stresses occurring in the flanges. In contrast, beams with web openings develop significant stress concentration around the opening edges. Circular openings produce smoother stress contours, while square openings exhibit sharp stress peaks at the corners.

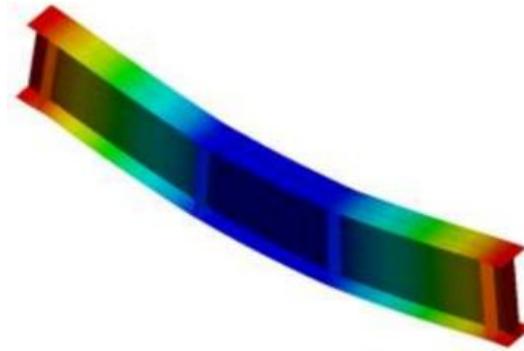


Figure 8. Deflection field of an unperforated steel beam.

Figure 8 illustrates the deflection distribution of the solid (unperforated) steel I-beam under four-point bending, showing the maximum displacement occurring at the mid-span.

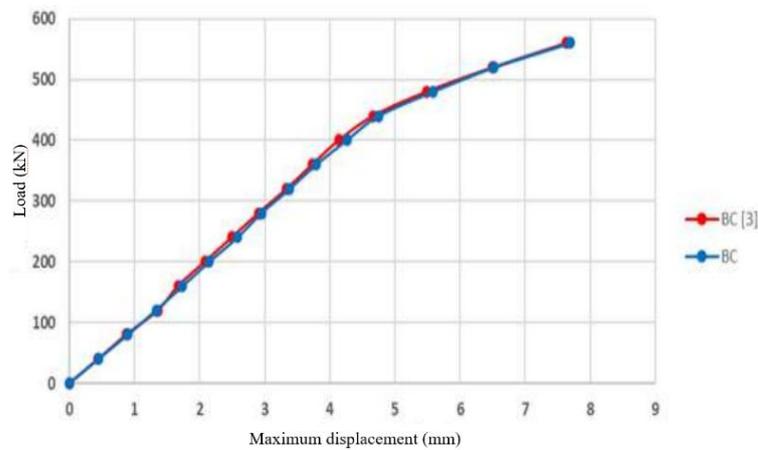


Figure 9. Relationship between load and maximum deflection of an unperforated beam.

The result shows Figures 8, 9, and an error of approximately 4.1%. The error is relatively low, so the solution method will continue to be implemented in the following sections.

### 5.2. Deformation Behavior

The presence of web openings increases the mid-span deflection of the beam due to reduced stiffness. Among the studied cases, the beam with a square opening shows the largest deflection, followed by the circular opening, while the circular opening results in the smallest increase in deflection compared to the solid beam.

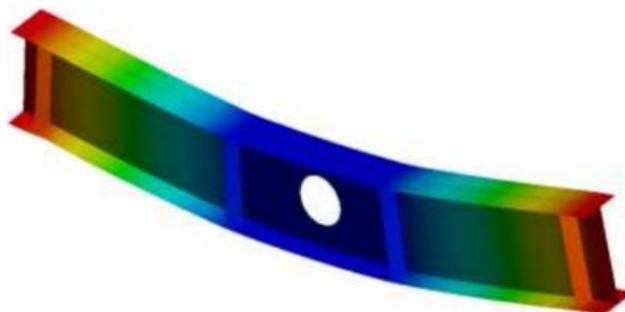


Figure 10. Deflection field of a steel beam containing a circular hole.

Figure 10 illustrates the deflection distribution of the steel I-beam with a circular web opening under applied loading, highlighting the deformation pattern and maximum displacement at mid-span.

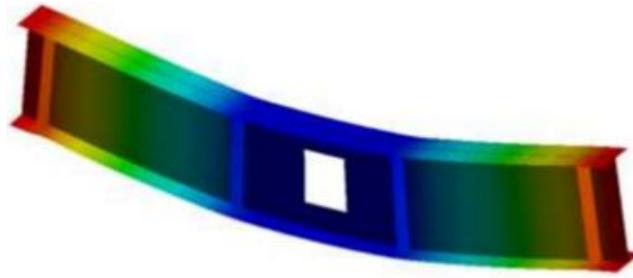


Figure 11. Deflection field of a steel beam containing a square hole.

The results of the total displacement distribution of the steel beam containing holes under a load of 40kN are shown in Figures 10,11.

Figure 11 illustrates the deflection distribution of the steel I-beam with a square web opening under applied loading, showing higher deformation levels compared to the circular opening case.

### 5.3. Influence of Opening Shape

A comparative analysis indicates that the opening shape plays a crucial role in structural performance. Circular openings are the most efficient in minimizing stress concentration and deformation. Square openings are the least favorable due to pronounced Vierendeel action and stress concentration at sharp corners.

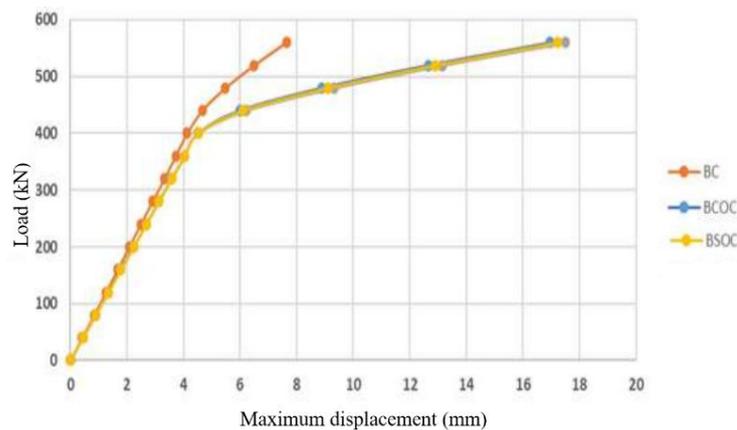


Figure 12. Relationship between applied load and maximum displacement at the middle of the beam of beams containing holes.

Figure 12 illustrates the effect of the hole shape when positioned at the mid-span of a beam. Simulation results show that placing the hole at the center of the beam web significantly increases the total mid-span displacement compared to a beam without a hole. This indicates that the overall stiffness of the beam is reduced due to the presence of the opening.

### 5.4. Engineering Implications

The findings of this study have important implications for the design and assessment of steel beams with web openings. The results confirm that opening shape significantly affects stress concentration and deformation behavior, even when the opening area is kept constant. From a practical design perspective, circular openings are preferable due to their smoother stress distribution and lower stress concentration.

In existing structures, where web openings are introduced during retrofitting or service installation, finite element analysis can serve as an effective tool for safety assessment. The methodology presented in this study can be applied to evaluate whether additional strengthening measures, such as stiffeners or reinforcement plates, are required.

Moreover, the results highlight the limitations of relying solely on simplified design formulas when dealing with nonstandard opening geometries. For critical structures or heavily loaded beams, numerical simulation should be considered as part of the design verification process to ensure structural safety and serviceability.

## 6. CONCLUSIONS AND FUTURE WORK

This study provides a comprehensive finite element analysis of stress distribution and deformation in steel I-beams with web openings using ANSYS. It compares solid beams with those containing circular and square openings of equal area, systematically evaluating how opening geometry affects structural performance.

The numerical results demonstrate that web openings significantly modify the internal force transfer mechanism of steel beams, leading to localized stress concentration and increased deflection. Circular openings provide the most favorable structural response due to reduced stress concentration and smoother load redistribution. In contrast, square openings induce pronounced Vierendeel action and sharp stress peaks at the corners, which may lead to premature yielding.

The study confirms that finite element analysis is a reliable and effective tool for assessing the behavior of perforated steel beams. The good agreement between numerical results and analytical solutions for the solid beam case validates the adopted modeling approach.

Future research may extend the present work by considering additional parameters such as opening size, multiple openings, and different opening locations along the beam length. Experimental validation and the investigation of strengthening techniques, such as web stiffeners or composite reinforcement, are also recommended to further enhance the applicability of the findings to real engineering practice.

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**Competing Interests:** The author declares that there are no conflicts of interests regarding the publication of this paper.

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