SSRG International Journal of Industrial Engineering
ISSN: 2349 – 9362 / https://doi.org/10.14445/23499362/IJIE-V13I1P101
Volume 13 Issue 1, 1-15, Jan-Apr 2026

Original Article

Assessing The Configuration and Structural Behavior of Web-Opening Steel Beams: A Comprehensive Review

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Received: 02 December 2025 Revised: 03 January 2026 Accepted: 18 January 2026 Published: 05 February 2026

Abstract *- This paper comprehensively reviews the various configurations of web-opening steel beams and their impact on load-bearing capacity, safety, economy, and failure modes. This review encompasses the seismic performance, fire resistance, the role of stiffeners, and the composite behavior of web-opening beams. The findings show that circular openings often display lower stress concentrations than rectangular ones. In contrast, in terms of load-carrying capacity, hexagonal openings perform better than both circular and rectangular openings. Additionally, Sinusoidal openings in castellated beams perform better than hexagonal openings, and diamond-shaped openings offer more strength than circular ones. Furthermore, the study indicates that the main failure modes, such as web post buckling, lateral torsional buckling, and Vierendeel, negatively influence the load-bearing capacity, but integrating stiffeners and using composite beams helps control these failure modes. The findings suggest that while more common opening shapes have been widely investigated, studying and utilizing innovative and unconventional shapes offers new opportunities for advancement. Additionally, the behavior and the performance of composite open-web steel beams with shallow depths in masonry and traditional mud structures remain unexplored, highlighting an opportunity for further research.*

Keywords *- Web-Opening Steel Beam, Failure Modes, Stiffeners, Composite Behavior, Cellular Beam.*

1. Introduction

Innovation, lightweight design, high strength, economy, and serviceability are all key criteria in today's modern construction. Additionally, the primary goal of structural steel design is to determine the optimal shape and amount of steel required to carry a specific applied load. which web-openings steel beams are an effective solution for meeting these demands due to their structural advantages. Similarly, in a fast-paced construction environment, where projects must be completed efficiently and economically, open web beams have become increasingly popular due to the integration of building utilities such as HVAC systems inside constrained ceiling spaces and economic and aesthetic advantages.

ArcelorMittal [1] and NSC [2] have highlighted that these perforated web beams offer lightweight and flexible solutions that improve structural performance while lowering overall weight by providing efficient routes for pipes and ducts. Longer spans and column-free spaces are made possible by lightweight design, which makes them appropriate for a variety of uses, including parking buildings, power plants, oil and gas, and petrochemicals. Web openings in beams are regularly spaced along the length, although they can vary in shape and spacing to satisfy specific design requirements [3].

Fig. 1 Passing Pipes Through a Beam With an Opening Web [3].

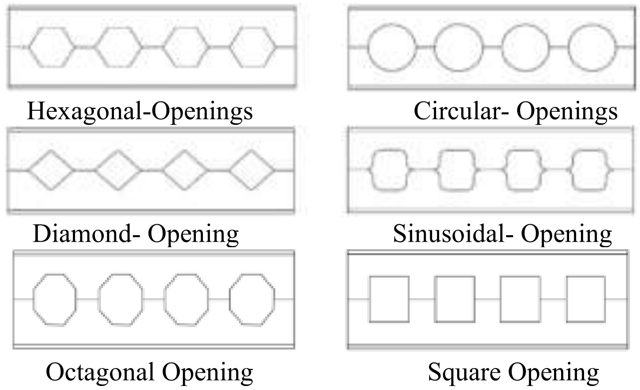


Fig. 2 Types of Castellated Beam [4]

To produce these open web beams, the webs are cut in a zigzag pattern, and after that, these cut pieces are placed opposite each other and then are welded together. A comparative and parametric review of web-opening effects conducted by S. H. Patil and R. R. Kurlapkar [4] showed that the shapes of the openings in the web sections of Castellated Steel Beams (CSBs) define their classification, which has a substantial impact on both structural performance and aesthetics.

O. Victor [5] studied composite beams with web openings identifying three primary methods: hot-rolled I sections with individually cut openings, hot-rolled I sections cut along the web profile and re-welded for deeper beams, and fabricated sections made from three plates with openings cut in the web plate either before or after the I section is formed are the three primary methods of fabrication.

Although significant results and achievements have been reported, several openings, particularly curvilinear, L-shaped, and C-shaped openings, have not yet been thoroughly investigated.

Furthermore, it is still unknown how diamond-shaped and circular openings perform differently, which is an important issue that needs more research.

Moreover, research on new kinds of shear studs in comp osite beams is essential, and the behavior and performance of open web steel beams with shallow depths in masonry and conventional mud buildings are still poorly understood. This offers another chance for in-depth research.

The primary objective of the study is to provide a thorough overview of the behavior and structural performance of web-opening steel beams in modern construction. This research aims to:

1. Investigate the opening configurations:
2. Compare cellular and castellated beams:
3. Examine failure modes:
4. Assess seismic performance and fire resistance:
5. Investigate the role of Stiffeners:
6. Examine composite behavior:

Despite many achievements regarding the open web steel beam, there is currently no thorough evaluation that integrates all these parameters in a unified document, so this study compiles all these parameters.

2. Literature Review

Open web steel beams are widely used in bridges and building construction due to their high strength-to-weight ratio, versatility, and several other advantages. As the structural behavior of the beam can be significantly impacted by adding openings, open-web steel beams have been the subject of several experimental and numerical studies. Therefore, opening shape, size, location, and spacing are various factors that must be carefully taken into account during the design and analysis of these beams.

An extensive study by A. S. Shaikh and H. R. Aher [6] reported that web openings are helpful in allowing pipes, ducting, and electrical conduits to pass through and be installed without raising the floor-to-floor height, particularly in beam elements, as shown in Figure 3.

Fig. 3 Cellular Beams Can be Used to Build Different Components of a Structural System [6]

As has been discovered by Prof. R. R. Jichkar [7], the web openings can reduce the buckling stress of steel beams while increasing the beam's deflection. Moreover, increasing the opening area often reduces ultimate load capacity and stiffness [5], and the middle two-thirds of the span is usually the best location for openings [8]. However, R. M. Lawson [3] found that additional bending moments in web posts are caused by asymmetry in the cross-section.

2.1. Configuration of Openings

The web opening's shape has a significant impact on how the structure works. A series of recent studies has indicated that circular openings often perform better and have lower stress concentrations than rectangular openings, which results in reduced deflection and increased load capacity [9-10]. Not only that, S. G. Morkhade et al. [11] found that rectangular openings can lead to higher deformations and increased stress concentrations. To further continue this discussion, K. Sriman et al. [12] and I. Barkiah et al. [13] explored that hexagonal openings frequently perform better than both rectangular and circular openings due to their superior load-carrying, deformation capabilities, and [10] less deflection.

S. Poul et al. [14] revealed that castellated beams with sinusoidal openings have a large shear transfer area and a uniform stress distribution because of their curved edges, which decreases stress concentration close to the corners. Equally, castellated beams with sinusoidal web openings have a higher load-carrying capacity than those with hexagonal, rectangular, or square openings [15]. This similarity results from the fact that failure is primarily caused by shear concentration.

Moreover, the diamond-shaped openings may provide more strength than circular openings, with particular ideal sizes found to be 0.67 and 0.73 times the total depth [16].

In most cases, the use of different materials also has its own effect in building construction, and weight, which, with regard to this issue, F. C. A. [17] concluded in a comparative study that Trapezoidal Sections use less material than rectangular sections.

Regarding the use of the new shape, Ayat Ihsan et al. [18] and K. D. Tsavdaridis et al. [19] emphasized the manufacturing of innovative shapes over conventional cellular beams, such as double castellated and zigzag castellated beams.

Many researchers discussed the size of openings, which has a tremendous and direct effect on the load-bearing capacity, structural behavior, and deflection of a steel beam. H. Zheng et al. [20] suggested that increasing the opening diameter and edge distance of openings, while decreasing the spacing between them, ensures the structural load-carrying capability, especially when it is more advantageous for catenary action. Many authors proposed that openings should not be placed any closer to the support than 10% of the span or twice the beam depth, whichever is greater [21].

Some studies show that bigger openings result in earlier deformation and failure because they reduce the ultimate load capacity and stiffness [8], [9]. More on that, S. G. Morkhade and L. M. Gupta [11] further experimentally and parametrically studied that greater deflection and stress concentrations result from larger openings, particularly in the vicinity of the corners. Equally, F. De'nan and M. Mustar [22] demonstrated that larger web openings can increase the beam's vulnerability to Lateral-Torsional Buckling (LTB). On the other hand, A. C. Manoharan and R. K. Tripathi [23] found that there is no significant change in deflection for openings close to supports as compared to solid beams.

Strength capacity is decreased by an opening ratio of more than 0.75, while a ratio less than 0.5 has little effect. Similarly, up to an opening ratio of 1.5, deflection decreases, but after that, it increases [24]. Figure 4 compares beams with the same diameter and number of openings but different opening shapes—circular, rectangular, and hexagonal.

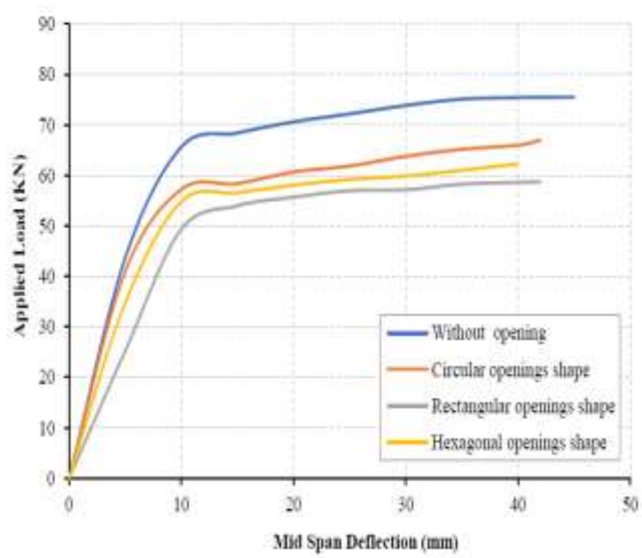


Fig. 4 The Load Against Mid-Span Deflection for Steel Beams with Various Opening Shapes and an Aspect Ratio of 1.71 [22]

A study [21] concluded that unstiffened openings should not be longer than 1.5D or deeper than 0.6D, whereas stiffened openings should not be longer than 2D or deeper than 0.7D.

In the context of circular holes in the web of steel I-beams, [25] stated that the optimal diameter for a circular hole in the web of a steel I-beam, when no stiffeners are present, should not exceed half of the height of the steel I-beam (0.5 H). However, for practical reasons, there has been an increasing trend in recent years to use larger openings up to 75% of the entire section's height with various opening shapes [26].

About Castellated Beams, beams with diamond-shaped openings, which are sized at 0.67 times the entire depth, perform better than those with circular openings, which are sized at 0.73 times the overall depth [16]. As a result, castellated beams with diamond openings may support more loads than those with circular and hexagonal openings.

However, although much research has been done on the shapes of openings, sizes and location of openings, and spacing between them, several questions remain unanswered, such as the study of curvilinear, L-shaped, and C-shaped openings, which is a notable area for further investigation.

2.2. Comparison of Cellular and Castellated Beams

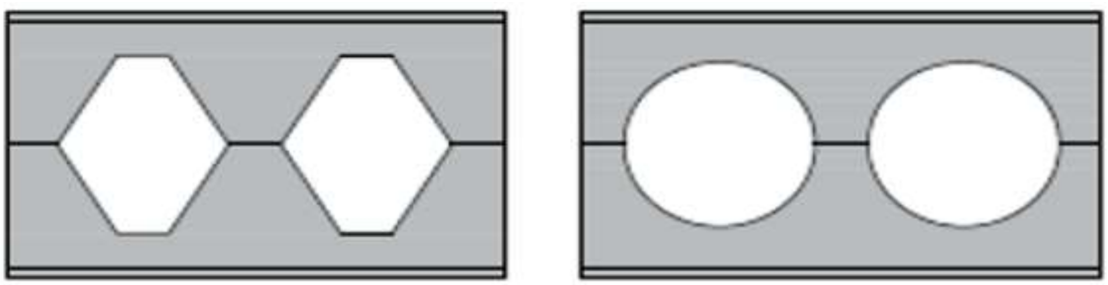
The more common types of open web steel beams are cellular and castellated ones, each with distinct construction techniques and performance traits. A cellular beam is distinguished by its circular or elliptical web arrangements. In contrast, a castellated beam is created by cutting the web into a succession of hexagonal or rectangular openings, as shown in Figure 5. In comparison to the solid web beam, both cellular and castellated open web beams increase the beam's load-bearing capacity.

Benchmark fabricated steel [28] states that Castellated Beams with hexagonal openings increase depth, which in turn increases strength, but they also create stress concentrations that may cause failure under dynamic loadings. However, on the other side, this study adds that cellular beams with circular perforations provide a more even distribution of stress, enhancing fatigue resistance and stability, particularly in dynamic situations.

An important benefit of cellular beams resides in their versatility, offering more usable surface, which makes them appropriate for particular loading, aesthetic, and cost-effective requirements [29]. Conversely, research by A. S. Shaikh and H. R. Aher [6] demonstrated that Castellated Beams boost strength without adding weight by increasing depth.

Research shows that cellular beams must be at least 30 times their gyration radius to outperform original beams, but castellated beams can be optimized for both short and long spans [30]. Furthermore, cellular beams usually require fewer infill plates, which lowers costs and makes it easier to integrate mechanical systems [29].

In conclusion, both castellated and cellular steel beams have advantages of their own, and the decision between the two is influenced by a variety of parameters, including span, loading conditions, structural use, and so on.



A. Castellated beam **B. Cellular beam**

Fig. 5 Steel Beams with Continuous Web Openings [27]

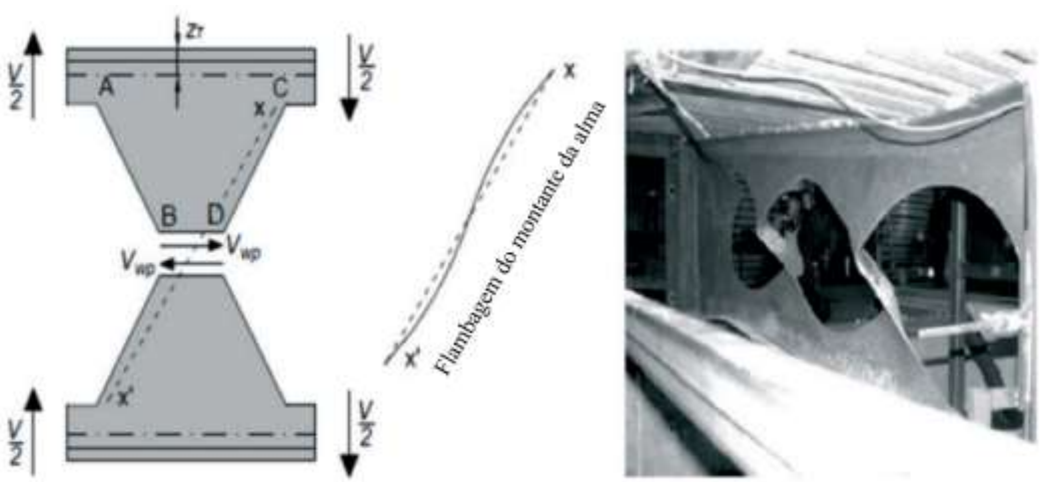


Fig. 6 Shear-Induced Web Post Buckling [27]

2.3. Failure Modes

Open-web beam's structural behavior is thought to be crucial for the structure's reliability, economy, serviceability, and safety. Therefore, to achieve the above demands and have a successful design, it is essential to obtain sufficient information about failure modes and reduce their effects. Several studies have investigated the most critical failure modes, including Web Post Buckling (WPB), Lateral-Torsional Buckling (LTB), Web Distortional Buckling (WDB), and Vierendeel Mechanisms (VM). These failure modes and overall structural performance are influenced by many factors, such as opening parameters, loading conditions, type of structure, type of opening, width, dimensions of the beam, stiffeners, and so on [31-32].

2.3.1. Web Post Failures

Web post buckling is caused by the horizontal shear force passing through the web post. Consequently, the web-post will twist throughout its height due to the buckling, as shown in Figure 6.

The Geometry and Thickness (slenderness) of the web post usually determine the specific failure mode. So, in connection with this matter, M. Ranisavljević et al. [32] highlighted three main reasons why web posts fail: (i) flexural failure driven by the formation of a plastic hinge in the web post; (ii) buckling failure of the web post; or (iii) rupture of the welded joint. In this case, the view of other authors suggests that a sudden decrease of strength and stiffness under load might result from web post buckling [33].

The previous works [31], [34], [35] indicate that the interaction between web openings, local web post buckling, and web distortional buckling is especially important because it can have a substantial impact on the beams' overall load-bearing capacity. More importantly, Different non-standard web opening shapes showed improved perforated beams' structural performance, especially when the web post buckling failure mode is present [36]; however, T. C. H. Liu et al. [26] found that shear failure and flexural failure are other examples of standard failure modes.

Innovation has its own features and complexities, which, in this case, a study by [18] indicates that due to improved force distribution and geometric-continuity curves, the Double Castellated Beams (DCB) and Zigzag Castellated Beam (ZCB) beams delayed the moment of web-post buckling.

S. S. Elaiwi [37], following on the work of D. Sonck [38] and C. Müller et al [39], conducted a more comprehensive analysis and design of castellated beams concerning the compression buckling of web posts. They found that to mitigate the impact of bearing and buckling, stiffeners should be employed at the reaction points and areas of concentrated load, which can be directly applied to the web post of Castellated Beams. She further stated that by increasing the web post width, the bending failure of the web post can be prevented.

A comparative study carried out by E. V. Santos et al [40] showed that steel-concrete composite beams with bigger web-post dimensions and end-post widths are less likely to have higher resistance than those with smaller web-posts. They highlighted that Web-post buckling is more likely to occur in perforated beams with large elliptically based web openings than in Vierendeel bending failure modes.

Lateral Torsional Buckling

A lateral displacement and a cross-sectional rotation are the characteristics of Lateral Torsional Buckling, and all types of Steel Beams are prone to lateral buckling, particularly in unbraced spans. When it comes to lateral buckling, both cellular beams and solid web beams behave similarly; however, the centerline of the openings should be used to determine the geometric characteristics of cellular beams [41], [27].

LTB deformation and the typical finite element mesh are shown in Figure 7.

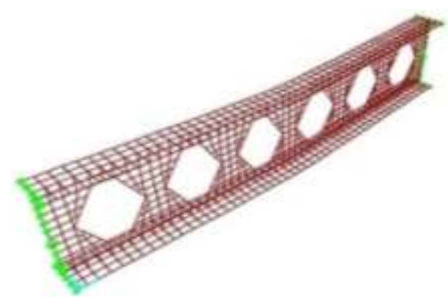


Fig. 7 LTB Deformation and a Typical Finite Element Mesh in FEA [42]

Amilton Rodrigues et al. [43] and [35] highlighted that the load-bearing capacity of hollow-core steel beams with both hexagonal and elliptical openings is greatly affected by Lateral-Torsional Buckling (LTB) and Web Post Buckling (WPB) collapse modes. Similarly, Danny Gunawn et al. [42] utilized FEA to study the Lateral-Torsional Buckling (LTB) of honeycomb beams subjected to concentrated and uniformly distributed loads. They revealed that the ANSI/AISC 360-10 methods can be modified by introducing a reduction factor dependent on unbraced length and loading conditions.

Moreover, J. Nseir et al [44] suggest new design guidelines that allow for material savings while significantly increasing accuracy and safety.

T. Zirakian and H. Showkati [45] explored distortional buckling of castellated beams, stating that this phenomenon occurs in restrained mid-length sections and is a significant concern in Castellated Beams, where eccentricity can reduce load capacity [46-47].

Vierendeel Failure Mode: Vierendeel failure is considered one of the major concerns and challenges in the analysis and design of open web beams**,** characterized by high shear forces that can cause the formation of plastic hinges at web openings and deformation of the tee-sections above them. Both the primary moment (Conventional Bending Moment) and the secondary moment (Vierendeel Moment) that originate from shear along the web opening must be supported by the tee-sections for this failure to occur [36], [18].

Tsadaridis et al. [36] and [47] stated that perforated beams can collapse via either Vierendeel action from hinges formed in high shear zones or plastic stress blocks in the tee-sections. Among these, the creation of plastic hinges by Vierendeel bending at the aperture is the most notable failure mechanism brought about by the openings (Figure 8).

Fig. 8 The Mechanism of Vierendeel [48]

Studies also add that in the most desired section at the opening, where these solicitations cause the formation of a plastic hinge, the "Vierendeel" mechanism is always critical. It is worth noting that beam types differ in their deflection behavior, with the maximum deflection usually occurring at the load application point (L/2). It has been noticed that when compared to beams with circular cuts, solid web beams exhibit less vertical displacement, which may result in reduced rigidity and loading capacity [49]. The elastic buckling load can be significantly increased, and the peak load can be slightly increased by increasing the web thickness. However, in some cases [50], the local buckling of the web is not significantly impacted by an increase in web thickness.

According to A.I. Naji and M. Al-Shamaa [18], the Double-Castellated Beam (DCB) performed better because of more ductile failure mechanisms and better load distribution, with a gradual development of Vierendeel Mechanisms being especially noticeable.

It is necessary to conduct thorough studies that methodically assess how well beams with different web opening geometries function under various loading scenarios.

2.3. Seismic Performance

Open web Steel beams exhibit better structural performance in terms of seismic events, because they increase energy dissipation, ductility, and light-weight.

S. H. Patil and R. R. Kurlapkar [4] found that the seismic response of open-web beams is greatly influenced by the size, shape, and spacing of web openings. In order to prevent brittle failure, steel constructions with cellular beams can have a good energy absorption capacity and form plastic hinges away from beam-to-column joints [51]. Moreover, S. Erfani et al [52] reported that the implementation of web openings prevents inelastic flexural deformations and has a negligible effect on global stiffness and strength.

Despite the abundance of studies on the seismic resistance of open web beams, there is insufficient extensive comparative research on castellated versus conventional beams and castellated versus cellular opening beams under seismic forces. This indicates the need for further research and innovation.

2.4. Fire Resistance

Another important consideration for open web steel beams is fire resistance. In the event of a fire, the properties of the steel beam change and undergo a process called Thermal Expansion. During this process, its color changes, and if exposed to high temperatures, its overall structure and integrity may be compromised.

Research shows that under high temperatures, Cellular Steel Beams (CSBs) can undergo substantial deformation and display the Vierendeel Mechanism. Even with intumescent coatings that improve fire resistance, web-post buckling still happens [53]. Similarly, P. Wang et al. [54] conducted a computer simulation that showed CSBs undergo catenary motion at lower temperatures and endure lower compression forces than solid beams due to their regulated thermal elongation. Notably, this catenary activity is not significantly impacted by the number or shape of web openings. Furthermore, E. Zhu et al. [55] examined the steel-concrete cellular composite beams, showing that local buckling and torsion during fire can cause instability. They further expanded the research and found that hinged beams have a 90-minute fire resistance limit, whereas inflexible beams have a 75-minute limit. Significantly, inflexible beams also showed more complex crack patterns after being exposed to fire. Similarly, the findings of M. Yahyai [56] indicate that castellated composite beams are unable to endure temperatures over 800 degrees Celsius.

2.5. The Influence of Stiffeners

Stiffeners are steel plates that are welded to the webs of beams to prevent failure of the beam and increase its structural capacity. As the web of the beam is responsible for transferring the shear force, openings in the web of steel beams cause the web to fail more easily. To prevent this, the thickness of the beam web can be increased, but this is certainly not cost-effective and dramatically increases the weight of the section. Therefore, several stiffeners are used at certain intervals in the web of the beam [50]. Most scholars [50,59,60] suggested various techniques to add these stiffeners, but the vertical, horizontal, and diagonal stiffeners are the most popular. These studies further suggest that the use of stiffeners can significantly improve the strength and structural performance of open-web steel beams and can help prevent or mitigate failure modes such as Lateral-Torsional Buckling and Web Post Buckling.

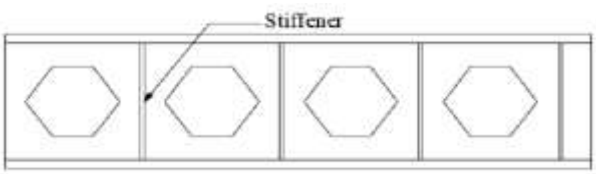
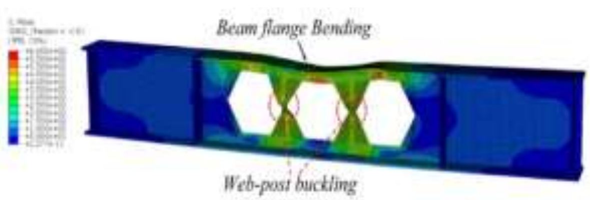


Fig. 9 Hexagonal Castellated Beam with Transverse Stiffeners [30].

Moreover, the direction of stiffeners has significant effects; for instance, Y. Yang and E. M. Lui [59] examined that the inclined stiffeners significantly increase Lateral-Torsional Buckling Capacity, while longitudinal stiffeners improve bending and shear strength.

According to Miss Pooja P. Rugge et al.'s [60] review, adding stiffeners to a Castellated Beam's web section reduces deflection and increases strength. The stiffeners also assist in preventing web buckling between large openings during pure bending. In relation to this issue, L. Jia et al [50] demonstrated in Figure 10 that the beam flange's bending range reduces when the stiffeners increase the flange's peak bearing capacity.



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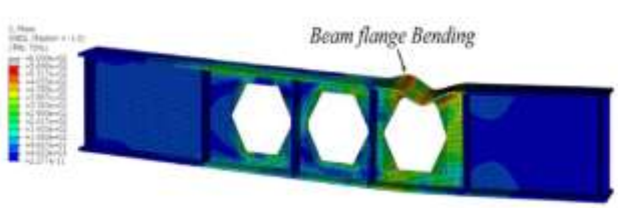


B

Fig. 10 Failure Modes [50]

Recent developments indicate that Carbon Fiber-Reinforced Polymer (CFRP) may be able to replace steel stiffeners. To reinforce the castellated beam, P. Ponsorn and K. Phuvoravan [30] recommend investigating the use of CFRP strips as stiffeners, and compared to conventional I-beams, Fiber-Reinforced Polymer (FRP) stiffeners have been demonstrated to increase strength by 44% while reducing weight.

Studies conducted by K. M. Pawar et al [58] and H. W. A. Al-Thabhawee et al [61] show that circular ring stiffeners functioned better than octagonal ones and minimize deflection and maximize ultimate strength around castellated beam web openings.

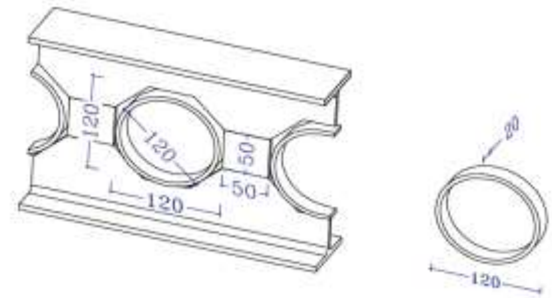


Fig. 11 Stiffeners Made of Ring Steel for Octagonal Castellated Beams [61]

On the other hand, H. S. Dhaidan and I. S. I. Harba [62] indicate that welding around openings raised capacity by 25.6% to 26.5%, while strengthening beams with square steel bars boosted load capacity by 64.5%.

N. Kumaragurubaran et al [63] examined the impact of different stiffener configurations—including those with one, two, and three stiffeners on the open web beam. For each case, they found that cyclic loading caused deflections of 65%, 45%, and 77%. Significantly, deflection increased in case III but decreased in case II, suggesting that stiffeners positioned at two end holes outperform those at three end holes.

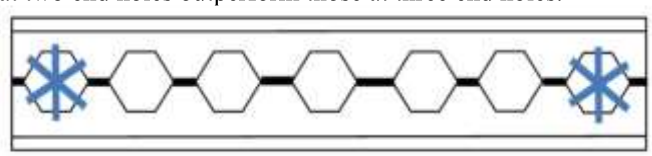


Fig. 12 Each End of the Beam Chassis Specimen has a Stiffener in a Single Web Opening.

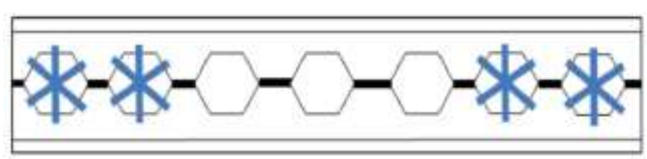


Fig. 13 The Beam Chassis Specimen Contains a Stiffener in Two Nearby Web Openings at Each End.

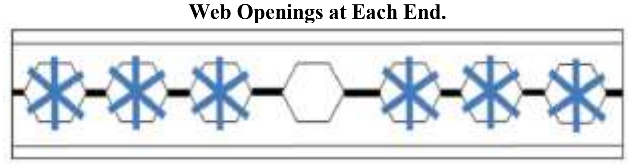


Fig. 14 Stiffeners in Three Successive Web Openings at the Beam Chassis Specimen

Findings indicate that compared to castellated beams having hexagonal openings (without spacer plates), those having octagonal openings (with spacer plates) have produced more satisfying ultimate strength [61].

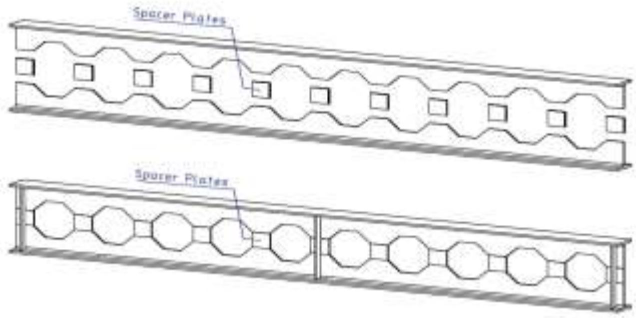


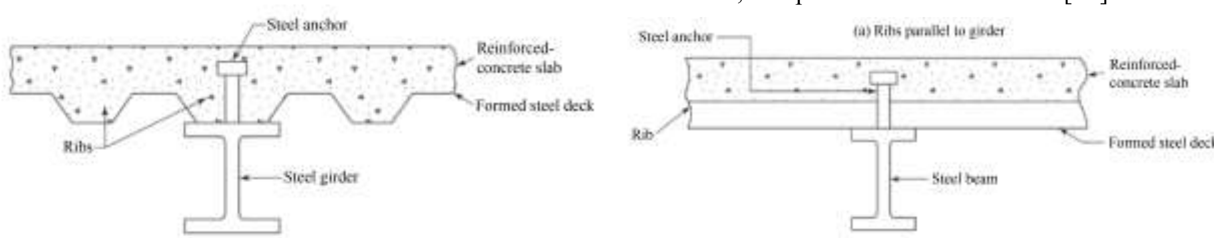
Fig. 15 A Castellated Steel Beam That Has Been Rejoined With an Increment Plate (Octagonal Opening) [61].

Despite these developments, there is still a significant knowledge gap about the relative performance of various stiffener materials (such as mild steel against CFRP) under different loading conditions.

In order to optimize load-carrying capacity while decreasing weight, future research should concentrate on optimizing stiffener design.

2.6. Composite Beams

The composite beam is defined as a combination of two or more materials having differing stress-strain relationships that work together as a single unit [62]. In modern construction, as shown in Figure 16, a steel beam and concrete slab are connected by shear connectors, typically steel-headed shear studs, which are welded to the beam top flange at prescribed intervals. Once the concrete is poured and hardened, composite action is achieved [63].



(a) Composite beam with metal deck **(b) Composite beam without metal deck**

Fig. 16 Composite Section [66]

The efficient use of materials, greater stiffness, improved structural performance, improved bending resistance, reduced floor depths, lower weight, and fireproofing cost are the advantages of the composite beam. Additionally, composite beams are beneficial for creating open areas in structures like parking garages, warehouses, and hospitals [64].

The influence of concrete topping above the steel beam on the overall behavior of the steel beam was extensively investigated by various researchers. O. Vassart [67] highlighted that the honeycomb steel beams and their interaction with the concrete slab have an impact on the mechanical performance of honeycomb composite beams.

While web openings in steel beams enable service integration, they introduce some failure modes such as Web Post Buckling (WPB) and the Vierendeel Mechanism (VM) for the steel beam, as well as leading to cracks and crushing for concrete [68], [69]. These failure modes, such as web post buckling and the Vierendeel Mechanism of open web composite beams, happen after steel yield [69].

Recent studies conducted by V. M. de Oliveira et al [70] and F. P. V. Ferreira et al [76] investigated the Steel-Ultra-High-Performance Concrete (UHPC) composite beams, which show that WPB and MV are the primary failure modes, even though UHPC slabs offer better stiffness and loading than ordinary concrete.

Different web-opening sizes and shapes have a significant impact on composite beams' behavior. For instance, cellular beams with hexagonal and circular openings are more capable of withstanding shear than rectangular ones [71]. On the other hand, a Castellated Composite Beam shows improved carrying capacities under negative moments [72-73]. The shear strength is increased by a smaller diameter or a smaller opening height. However, when the opening rate surpasses 0.3, the ultimate shear strength dramatically drops [72], [74].

Recent studies show that at a specific displacement under stress, steel yielding started close to the openings; however, the concrete slab had not been impacted by the localized damage, suggesting that it could sustain additional load even if the steel profile failed [75], [76],[77].

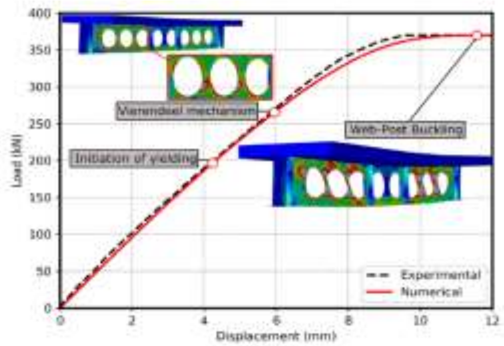


Fig. 17 Load-Displacement Curves: Evaluation of Instability and Behavior [75]

H. Wu et al [77] suggest that a steel-bamboo composite beam with web openings dramatically decreases stiffness and shear capacity. This study further highlighted that Bamboo Tearing and Cold-Formed Thin-Walled Steel (CFTWS) buckling indicate that failure takes place in the vicinity of the opening.

Despite the potential advantages of composite beams, there are still research gaps, especially when it comes to using innovative shear studs. Filling in these gaps may result in safer and more effective design techniques.

3. Research Methodology

To have a comprehensive and structured review of web opening steel beams, a systematic approach was taken. According to G. C. Uzoaru et al [78], as cited in S. H. Asar et al. [79], the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) standards, which provide a structured framework for conducting and reporting systematic reviews, are followed in this study.

Establishing eligibility criteria, choosing a database, developing a search strategy, and conducting study screening are all steps in the technique. The PRISMA flow diagram of this study is shown below.

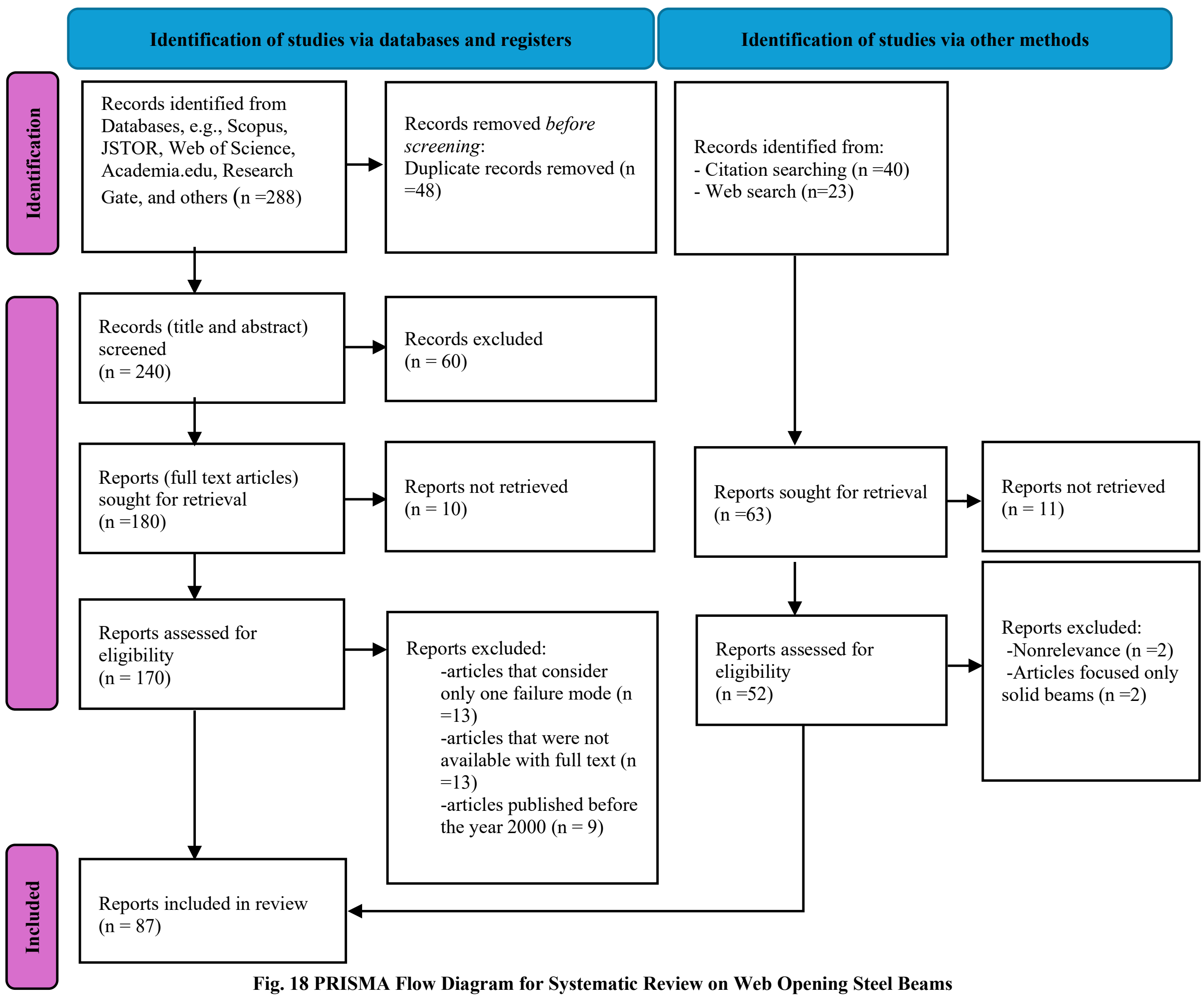


Fig. 18 PRISMA Flow Diagram for Systematic Review on Web Opening Steel Beams

4. Discussions

A comprehensive review was conducted to synthesize findings from previous studies and assess how web openings impact the structural integrity of steel beams. The results suggest that, in addition to providing a conducive environment for accommodating mechanical services, web-openings beams also have several other advantages.

Studies show that the shape of the opening, such as circular, rectangular, hexagonal, Diamond, etc., plays an important role in performance. For example, in terms of reducing stress concentration, circular and hexagonal openings show superior behavior compared to rectangular ones, while hexagonal openings show a higher load-bearing capacity. As some researchers recommend circular openings, while others prefer castellated or diamond openings, it is necessary to consider all the factors affecting the design and selection of the opening type to optimize the structural behavior.

Failure modes were also discussed comprehensively in this study. Most researchers have emphasized the importance of Web-Post Buckling (WPB), Literal-Torsional Buckling (LTB), and Vierendeel Mechanisms (VM) failure modes. However, modifying the geometry of the opening and the thickness of the web leads to various modes of failure. Therefore, knowing the failure modes and integrating stiffeners helps structural engineers to mitigate or prevent the risk of such modes. Moreover, [32] and [33] discussed the causes and the adverse effects of web-post buckling on strength and toughness.

In addition, this review also provides agreements and contradictions on the effect of open web shapes on structural behavior. Studies by Tsadaridis et al. [36] and [47] have described the risks posed by plastic hinges in web openings. On the other hand, innovations such as Double Castellated Beams (DCBs) and Zigzag Castellated Beams (ZCBs) have shown better load distribution and delayed failure.

However, in relation to this optimism, J. Nseir et al [44] suggest new design guidelines that allow for material savings while significantly increasing accuracy and safety.

Advancements in composite beams, which combine the advantages of both steel and concrete, also present opportunities for the use of such beams and innovation. However, the vulnerabilities and failure modes caused by web openings must be considered, because the geometry of the openings has a significant effect on the seismic response. Researches indicate that the composite beam with web openings has better energy absorption.

In addition to present studies on the shapes of openings, gaps remain in understanding the comparative performance of different openings, including uncommon openings.

While the use of stiffeners increases the load-bearing capacity of the beam and also prevents or reduces failure modes, research has been conducted on alternative materials such as CFRP, which require further investigations.

Despite the interaction of the concrete and web-opening steel beam enhancing the performance and behavior of the composite beam and providing many advantages, it also leads to some failure modes. Research shows that the dimensions of the web openings significantly affect the structural behavior, and if the openings are smaller, the shear resistance increases.

It is worth mentioning that rural people in developing countries live in mud and masonry houses that are more vulnerable to earthquakes. Moreover, if web-opening beams are used or connected to the concrete slab through shear connectors, on the one hand, the weight is reduced, and on the other hand, the composite nature of the slabs and beams provides earthquake resistance.

5. Conclusion

Nowadays, due to the advancement of technology and the growth of the construction industry, the use and production of various steel sections have also grown significantly in this field. One of these sections is open web steel beams, which has many advantages, such as increased cross-sectional depth without adding weight, a high strength-to-weight ratio, and integration of HVAC systems. However, specific failure modes also emerged from the existence of web openings.

Considering these issues and advantages, it was considered better to conduct a comprehensive review of all aspects and factors that influence the structural integrity and behavior of an open-web beam.

This includes the geometry of the openings, failure modes, the impact of earthquake and fire, the role of stiffeners, and considerations related to composite sections. The following conclusions can be drawn:

5.1. Effect of Openings

Circular openings cause decreased stress concentrations compared to rectangular openings, while hexagonal openings show improved load-carrying capacity compared to both circular and rectangular openings. However, Sinusoidal openings in castellated beams perform better than hexagonal openings, and diamond-shaped openings may offer more strength than circular ones.

Unstiffened openings are limited to a maximum length of 1.5D and a maximum depth of 0.6D. Stiffened openings are permitted a maximum length of 2 times their diameter (2D) and a maximum depth of 0.7 times their diameter (0.7D). Increasing the opening diameter and edge distance of openings, while decreasing the spacing between them, ensures the structural load-carrying capability.

5.2. Comparison of Cellular and Castellated Beams

Although they can result in stress concentrations under dynamic loads, castellated beams improve load-bearing capability by increasing depth. Cellular beams, on the other hand, are perfect for dynamic situations and a variety of applications because they provide superior fatigue resistance and stress distribution.

5.3. Failure Modes

Web Post Buckling (WPB), Lateral-Torsional Buckling (LTB), and Vierendeel Mechanisms (VM) are important failure modes for open-web beams, which are essential for structural reliability. These failures are greatly influenced by many factors such as geometry and load conditions.

- Web Post Buckling: The geometry and thickness of web posts have a significant impact on their failure modes, such as flexural failure and buckling. By improving load distribution, creative designs like double castellated beams can increase performance. Lateral Torsional Buckling: The load-bearing capacity of beams is greatly impacted by Lateral-Torsional Buckling (LTB), particularly in unbraced spans. Modifications to design guidelines can improve efficiency and safety in a range of loading scenarios.
- Vierendeel Mechanism: High shear forces cause Vierendeel failures, which result in the creation of plastic hinges at openings. Rigidity and load capacity are determined mainly by beam geometry, especially web thickness, which increases buckling resistance.

5.4. Seismic Performance and Fire Resistance

The findings showed that steel beams with open webs inherently exhibit superior seismic performance due to energy absorption and ductility. Further research is needed on the effects of different opening geometries on seismic response. Fire resistance is another concern, particularly with the risk of deformation and failure modes, such as the Vierendeel Mechanism, which require further investigation.

5.5. Role of Stiffeners

The addition of stiffeners can significantly increase the strength and stability of the beam and reduce the likelihood of failure. Instead of present stiffeners, the use of alternative materials, such as CFRP and other materials, needs further investigation.

5.6. Composite Beam Interaction

The interaction of a steel beam with an open web and concrete above it shows better structural performance, but also carries the risk of new failures.

6. Future Research Recommendations:

Even with the knowledge gathered from this review, there are still several relevant research gaps that need to be filled:

- Opening Geometries: Although meaningful results have been achieved in the review, various shapes, such as Curvilinear-Shaped, L-shaped, or C-shaped Openings, have not been discussed by previous researchers, as these shapes could lead to significant developments in the field. Additionally, an in-depth distinction has not been made between diamond-shaped and circular openings, which are notable areas for further investigation.
- Innovative Shear Studs: In connection with composite beams, further research is needed in the future to innovate new types of shear studs.
- Shallow Depth Beams: Despite the existing review, the behavior and performance of steel beams with shallow depths and open webs in masonry and traditional mud structures have not been discussed. This gap presents another opportunity for further research.

Researchers can enhance the performance and design of Open-Web Steel Beams by focusing on these areas, ultimately advancing the field further.

Acknowledgment

I want to thank everyone who helped us finish this review study sincerely. I would especially want to thank my supervisors and co-authors for their teamwork and priceless insights during this project.

Conflicts of interest

Regarding the publishing of this paper, the author declares that there are no conflicts of interest.

Author's Contribution Statement

Mohammad Naseer Sharifi: Proposed the research problem, carried out a thorough literature review, conceived and designed the study, and wrote the first draft of the paper.

Dr. Mohammad Haroon Sarwary: Contributed to data analysis, interpretation, and supervised the findings of the paper.

Dr. Abdulhai Kaiwaan: contributed to the paper's revisions for essential intellectual content and helped with the methodology.

Dr. Sayed Javid Azimi: arranged the categorization of reading datasets and guided research design.

All authors read and approved the final version of the paper and agreed to its submission to the journal.

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