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Preliminary report

Failure modes of steel beams with web openings

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ABSTRACT

As an alternative to trusses and open-web joist systems, beams with web openings are lightweight, long-spanning structural elements that bind structural role (efficient load distribution) and functionality in a visually acceptable way by allowing service routes to be installed within their cross-section height. Owing to its specific production process, this beam type has a beneficial impact on rational use of material for low-carbon structures. In recent years, extensive scientific research has been conducted to assess the structural behavior and ultimate capacity of beams with web openings. Due to the presence of web openings, load transfer is accompanied by complex stress distributions in the section web, causing failure modes that are distinguishable from those of solid I-section beams. This paper summarizes the different failure modes of the beams with web openings that have been discovered and confirmed in numerous experiments of reference scientific researches. Based on the state-of-the art in this structural area, the predictions of different failure modes that are affected by influencing geometric parameters are provided.

1 Introduction

Steel floor structures consisting of solid beams often require the formation of large web openings for the transit of service ducts. Economical solutions, which integrate installation routes within beam cross-section height (see Figure 1a), should include simple design, automated fabrication methods and minimum costs. The costs can be further minimized if it is shown that no stiffeners (reinforcements) are required; if this is not possible, simple stiffener configurations are required that allow straightforward manufacturing. Compared to conventional steel structures, the beams with web openings possess a better strength-to-weight ratio, classifying them as lightweight and long-span structural components. To maximize efficiency, they are most commonly used in composite structures [1,2]. Additionally, they can be applied in non-composite structures as beams, slender columns, or cantilever elements [3–6]. Beyond structural advantages, these elements are also appreciated for their attractive appearance. The most common opening shapes are hexagonal and circular. Beams with hexagonal openings are called castellated beams, while those with circular openings are referred to as cellular beams. Cellular beams exhibit the highest load-bearing capacity but also result in the greatest material waste among other shapes configurations [7]. However, the introduction of the Angelina beam, featuring sinusoidal shaped openings, achieves a balance, providing sufficient capacity while optimizing material usage. Other shapes such as rectangular, oval, and octagonal can also be utilize.

The manufacturing process of steel structural elements with web openings consists from three stages (see Figure 1b): (1) flame cutting of a solid hot-rolled I-section beam along a specified path determined by the opening shape; this results in two Tee sections that are (2) subsequently separated, (3) re-assembled, and welded together [8]. Castellated beams are fabricated by using a computer-controlled cutting torch to cut a zigzag pattern along the section web, whereas cellular beams are fabricated in a similar manner using a nested semicircular cutting pattern. The waste at the ends of the beam (castellated and circular) and along semicircular pattern (circular) is removed. Through this process, the parent I-section can achieve a significant increase in flexural stiffness without any increase in weight. Moreover, welded I-section beams with web openings can enable efficient hybrid structural compositions by rationally using different geometries and/or steel grades for the cross-section elements (parts). Additional material savings, up to 40%, can be achieved using corrugated webs instead of flat webs [9].

As part of second generation of the Eurocodes, new code EN 1993-1-13 [10] will provide supplementary provisions and design rules that extend the application of EN 1993-1-1 [11] and EN 1993-1-5 [12] to the design of rolled and welded steel sections with various shapes of web openings. The design of beams with web openings is also addressed in American national standard, AISC Steel design guide 31 [13].

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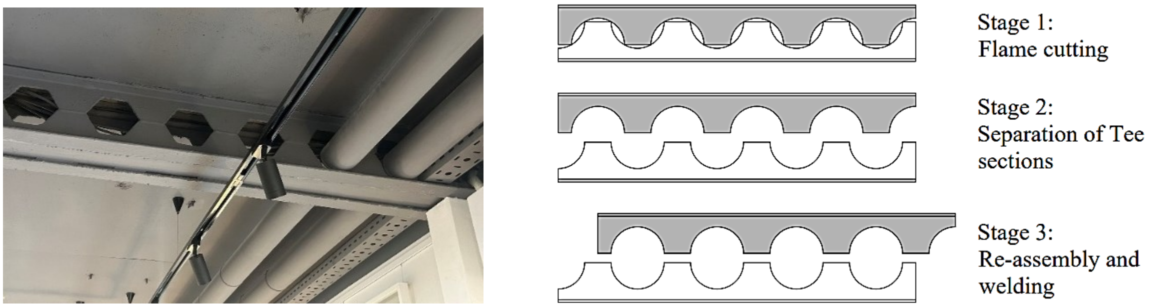


(a) application in floor structures

(b) fabrication process

Figure 1: Steel beams with web openings

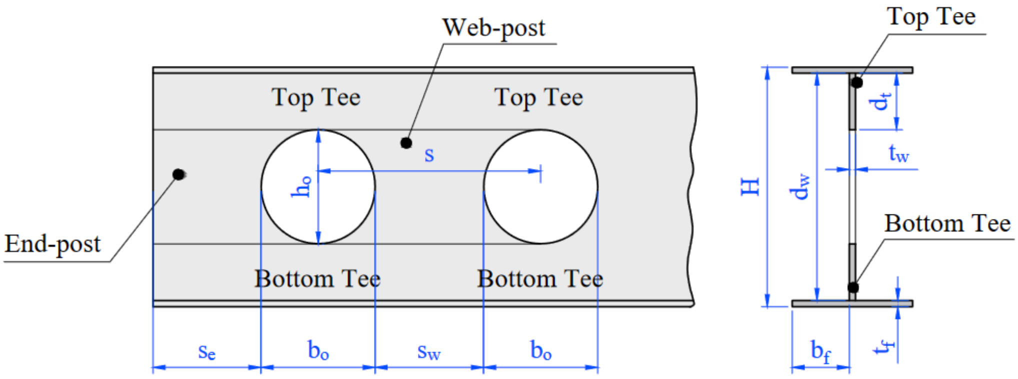


Figure 2: Definition of terms commonly used for beams with web openings

The failure modes of beams with web openings are diverse and influenced by load distribution, structural solution of floor structure (composite or non-composite), boundary conditions, steel grade, beam span (length), opening parameters (opening shape, dimensions and spacing), cross-section parameters (beam depth, flange width-to-thickness ratio and web thickness) and stiffener geometry and position. The collapse mechanism is not uniform and can include the multi-failure mode interactions.

The interaction between the failure modes and the mechanical properties of beams with web openings has been extensively investigated. The history of experimental tests reaches back to the 1940s, particularly emphasizing studies on castellated beams with hexagonal openings. Today, research databases have expanded to include various opening shapes, parent I-sections, and steel grades.

This paper briefly summarizes the key finding of experiments conducted on beams with web openings, with a focus on failure mode identification. The aim is to define the limit ranges for cross-section and opening parameters that affect a particular (specific) failure mode.

2 Failure modes

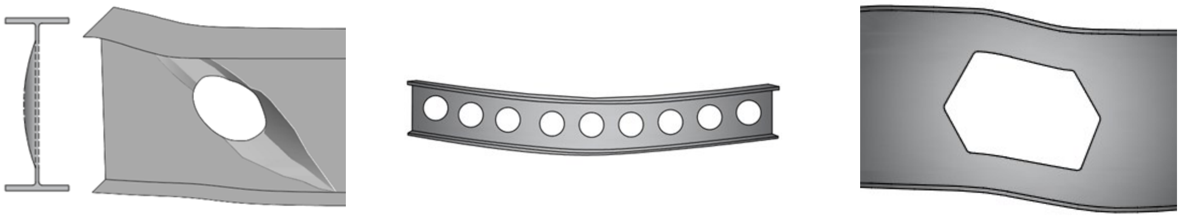
In the case of beams with web openings, localized internal forces are developed both around the openings and at the web posts (part of the web between adjacent openings); therefore, additional failure modes can occure beyond those which are common for conventional solid web beams. In general, failure modes are categorized into those related to loss of cross-section strength and stability (local failure mode), and those related to loss of overall beam stability (global failure mode). Common local failure modes include shear and flexural failure, Vierendeel mechanism, buckling of the compressed Tee section, and failure of the web-post due to bending, shear, and compression. The global failure mode that can occur is lateral-torsional buckling.

2.1 Local failure modes

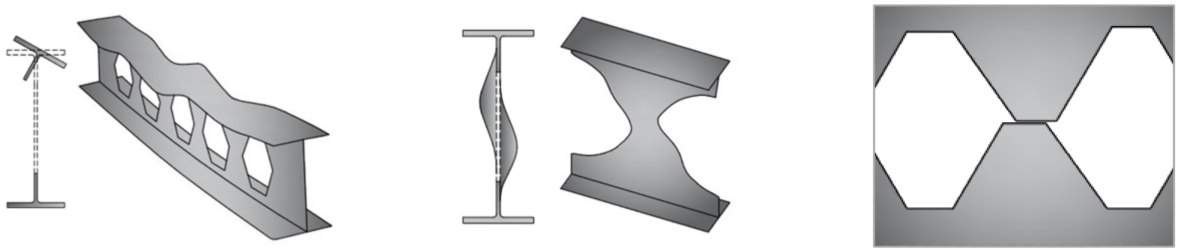
Characteristic local failure modes that occur (localized) around openings and web posts are shear failure, flexural failure, Vierendeel mechanism failure, yielding or local buckling of Tee sections (flange and web), web post buckling, local web buckling. The failure modes related to shear and moment resistance, already familiar in case of solid I-sections, are altered due to the presence of the openings.

When openings are positioned near beam supports or loading points, or when widely spaced openings (between transverse stiffeners) are present, web vertical shear failure (in opening area) can occur. In the post-peak regime, when the shear capacity of the web post is exceeded, the failure pattern is featured by a diagonally formed buckle around the opening, as illustrated in Figure 3a. The vertical shear, caused by the global shear force, should be resisted by the net cross-section at each web openings, or the gross section at web posts.

The flexure mechanism is characterized by noticeable vertical deflection [14–17] and the yielding of the top and bottom Tee sections (primarily flanges) in the critical cross-section under the action of extreme bending moments, see Figure 3b. The failure mode can also be accompanied by local buckling of the wide flange of the beam (compressed Tee section). Hence, the yielding pattern is similar to that of a beam with solid I-section.



(a) Shear failure (b) Flexure mechanism (c) Vierendeel mechanism



(d) Tee buckling (e) Web-post buckling (f) Rupture of the welded joint

Figure 3: Local failure modes of beams with web openings under bending (adapted from [36])

The structural behaviour of beams with web openings under bending is usually explained through the Vierendeel analogy: the design approach involves an integral model consisting of individual horizontal components (Tees around the openings) and individual vertical components (web posts between the openings). The presence of web openings alters stress distributions around them, making the critical sections approximately at the opening corners [18]. Under a global moment and a global shear force, three local actions are induced in the Tees above and below the web opening: (i) axial force in the Tee section, due to the global moment, (ii) shear force in Tee section, due to the global shear force, (iii) local Vierendeel moment in the Tee section, due to the transfer of shear force across the opening length. The high stress interaction leads to the yielding of Tee sections and the formation of four plastic hinges, above and below the web opening, see Figure 3c. This failure mechanism is known as the Vierendeel mechanism [19]. Vierendeel mechanism is critical in beams with single large web openings or widely spaced web openings [20]. In composite beams, Vierendeel bending distribution is similar to that in non-composite beams. Composite action results in smaller forces in the Tees, resulting in a more favourable structural response [21–24]. However, at web openings near the ends (supports) of the beams, the composite action provides lower strength due to the limited number of studs between the end of the beam and the end opening. As a result, the concrete transmits less internal forces, and the Tee sections transmits the greater internal forces which should be taken into account during design.

In the case of thin-webbed beams with openings of a smaller height, the yielding of deeper Tee section under compression in Vierendeel action can be limited by its instability leading to different failure mode known as buckling of Tee section web. The local buckling of the Tee section web may cause torsional deformations of the Tee section flange, see Figure 3d. The mode of failure is dependent on the geometrical dimensions (slenderness) of Tee sections. Additionally, this type of failure may affect the load-carrying capacity of castellated beams made of high-strength steel [25]. To avoid plastic deformations and local yielding around the openings, the webs of the Tee sections can be reinforced with additional stiffening [26–28]. The research shown that long horizontal stiffeners provide the better section strengthening compared to framed and vertical ones [29].

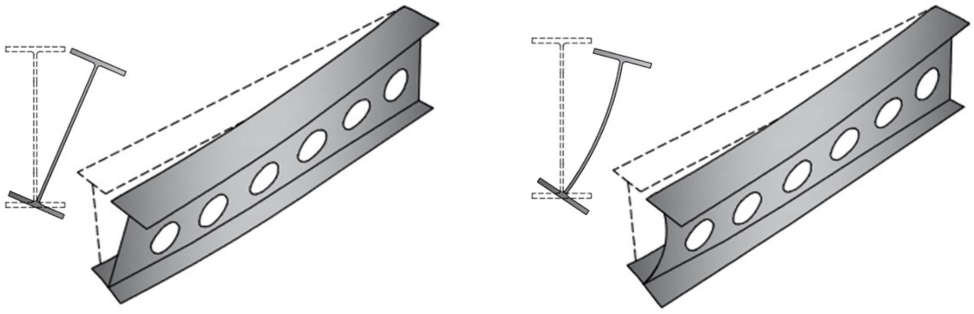
Web post buckling is caused by the horizontal shear force passing through the web post. The failure of the web post is governed by one of three modes: (i) flexural failure caused by the development of a plastic hinge in the web post, (ii) buckling failure of the web post (see Figure 3e) and (iii) rupture of the welded joint (see Figure 3f). The mode of failure is dependent on the geometry and the thickness (slenderness) of the web post [30–35].

2.2 Global failure modes

The lateral-torsional buckling failure of beams with web openings under pure bending is similar to that of the equivalent beams with solid web [37,38]; in this case, the openings have less effect on the ultimate structural response, see Figure 4a. The failure mode is characteristic of narrow flanged beams with insufficient lateral stiffness [39], or when lateral stability within the length of the beam is not provided by sufficient lateral restraints to the compression flange. Along with lateral-torsional buckling, web distortion can occur, leading to a combined failure mode known as lateral-distortional buckling [40], see Figure 4b.

2.3 Review of research on failure modes

Structural behaviour and ultimate response (failure modes) of beams with web openings have been extensively investigated over the past years. Initially, research focused on castellated beams, and later it expanded to include different shaped openings. Table 1 provides a summary of the gathered database for failure modes occurred in steel beams with web openings under pure bending moment. The collected database covers a wide range of cross-section and opening parameters, structural steels and numbers of tests.



(a) Lateral-torsional buckling (b) Lateral-distortional buckling

Figure 4: Global failure modes of beams with web openings under bending (adapted from [36])

Table 1: Summary of research on failure modes of beams with web openings

Reference	E / FE	Load type	Number of tests	Failure modes
Castellated beams with hexagonal openings				
Altfillisch, Cooke and Toprac, 1957. [41]	E	2P	2	TB
Toprac and Cooke, 1959. [42]	E	2P	8	VM, TB, LTB
Sherbourne, 1966. [43]	E	1P 2P	1 5	FM, WPB, FM + LTB
Bazile and Texier, 1968. [44]	E	U	6	WB, LTB, WPB
Hussain and Speirs, 1971. [45]	E	1P 2P	4 2	WR
Hussain and Speirs, 1973. [46]	E	1P 2P	6 3	FM, WB, VM
Zaarour, 1995. [47]	E	1P	4	WPB, TB, LTB
Redwood and Demirdjian, 1998. [35]	E	1P	4	WPB
Zirakian and Showkati, 2006. [48]	E	1P	6	LDB
Ellobody, 2011. [49]	FE	1P	96	LTB, LDB, WD
Sonck and Belis, 2016. [50]	E	2P	3	LTB
Weidlich, Sotelino and Gardoso, 2021. [51]	FE	1P	17	LTB, TB, FM
Morkhade and Gupta, 2022. [52]	FE	1P	6	VM, WPB + VM
Tas, Erdal, Tunca and Ozcelik, 2024. [53]	E	1P 2P U	1 1 1	VM, WPB
Cellular beams with circular openings				
Redwood and McCutcheon, 1968. [54]	E	1P 2P	7 2	FM, VM
Surtees, 1995. [55]	E	1P	1	WD + WPB
Warren, 2001. [56]	E	1P 2P	4 3	VM, FM
Tsavdaridis, D'Mello and Hawes, 2009 [57]	E	1P	2	WPB +FM
Tsavdaridis and D'Mello, 2011. [58]	E	1P	2	WPB
Ellobody, 2012. [59]	FE	1P	120	LTB, LDB, WPB + WD, LDB + WPB, LTB + FM
Erdal and Saka, 2013. [60]	E	1P	4	LTB, WPB, VM + WPB
Lawson, Basta and Uzzaman, 2015. [61]	E	1P	7	WPB, WPB + TB
Sonck and Belis, 2015. [62]	E	2P	3	LTB
Morkhade and Gupta, 2017. [63]	E	1P	6	WPB, WPY, VM + WPB, TB + LTB
Ferreira, Rossi and Martins, 2019. [64]	FE	1P U	180 180	LTB, LDB, WPB, VM
Morkhade and Gupta, 2022. [52]	FE	1P	7	VM, WPB + VM

Abbas, 2023. [65]	E	1P	5	FM
Tas, Erdal, Tunca and Ozcelik, 2024. [53]	E	1P 2P U	1 1 1	VM, WPB

E – experiments; **FE** – finite element analysis; **1P** – one point load; **2P** – two points load; **U** – uniform distributed load; **FM** – flexure mechanism; **VM** – Vierendeel mechanism; **WB** – web buckling (shear failure); **WPB** – web-post buckling; **WPY** – web-post yielding; **WR** – weld rupture; **WD** – web distortion; **TB** – local Tee buckling; **LTB** – lateral-torsional buckling; **LDB** – lateral-distortional buckling

In addition to the experimental tests and numerical analysis performed on simple beams with circular and hexagonal openings (as listed in Table 1), a comparatively smaller number of study have been carried out on beams with sinusoidal [18,53,66–71], rectangular openings [4,52,54,63,72,73] and other shapes such as oval and octagonal [74–81].

3 Influence of different parameters on failure modes

Different parameters can result in different failure modes. Based on the knowledge and experience gained through numerous experimental tests, it is possible to predict the most common failure mode that will occur in a particular case. For example, short-length beams with web openings can experience high shear forces, leading to web buckling or vertical shear failure, particularly near supports. Mid-length beams can exhibit Vierendeel bending and web post buckling. Long-length beams are more susceptible to global lateral-torsional buckling.

The collected database is made according to Table 1 and is limited to the domain of simple I-section beams with unstiffened openings, due to the number of available experiments in this field. It includes information on various parameters such as steel grade, beam length, cross-section dimensions and slenderness, opening parameters, and additional details on lateral bracings and web stiffeners.

Morkhade and Gupta [63] highlighted that adopting spacing-to-diameter ratio of circular openings (s/b_o according to Figure 2) in the range of 1.5 to 2.0 can provide enough web post width to achieve vertical shear resistance. However, there are tested specimens with hexagonal and circular openings where web post buckling occurs for spacing-to-diameter ratios such as 1.47, 1.6, 2, and 2.5 [46,52,60]. It is worth noting that to prevent web post buckling, beside adequate s/b_o ratio, the transverse stiffeners should be provided at the supports and load point. Morkhade and Gupta [63] also noted that web post buckling failure modes are predominant when (s/b_o) was between 1.07 and 1.4; in these cases, beams can fail by web post buckling before the Vierendeel mechanism occurred (featured by formation of four plastic hinges around the openings) [52]. Another group of authors [82] likewise observed and noted that buckling generally occurred when the spacing ratio s/b_o was equal to 1.2. Based on numerous studies [41-53], predictions can be made using edge-to-edge spacing-to-opening height ratio (s_w/h_o). For circular and hexagonal openings, web post buckling occurred when s_w/h_o is less than 0.3. For higher values of this ratio, Vierendeel failure take place. When close to limit value, determining factor is not clear. The long-length beams can be more susceptible to Vierendeel mechanism before web-post buckling. In some cases, where web between openings is not slender and h_o/d_w ratio does not exceed 0.8, mid-length beams failed due to flexure mechanism before web post buckling.

For long-length beams, where L_{cr}/H ratio (where L_{cr} is length between lateral bracings) is higher than approximately 7, a global failure mode is more likely to occur, regardless of the openings' size. Sweedan [83] revealed that widely spaced web opening configurations provide higher shear stiffness, resulting in minute or no web distortion. In this case, the beam failure is governed by lateral buckling (LTB or LDB) modes [83]. However, web distortion is found to be dominant even for widely spaced openings in cases where Tee section web is very slender [49]. Whether global lateral instability or web distortion occurs depends on the web slenderness at the opening. When d_t/t_w is 25 or higher, web distortion occurred without any lateral movement [49]. For less slender Tee section web, with a d_t/t_w of about 13, the failure mode is governed by lateral displacement. The smaller the difference between the slenderness of the web and the flange, the greater the chance for lateral-torsional buckling without any web distortion.

In case of very slender beams ($L/H > 18$, where L is beam length), if sufficient lateral bracings are provided, rupture of welded joint will take place before flexure mechanism or web post buckling. Otherwise, in case of short-span beams with a shallow tee depth, such as h_0/d_w equal to 0.8 or higher, Vierendeel failure is generally observed [82]. In such cases, yielding in the tees around opening may occur prior to buckling in the web-post. Nevertheless, plastic deformations may begin in the web-posts and spread to the tee sections, potentially leading to a combination of Vierendeel and web-post buckling failure modes. Notably, only a few experimental studies have investigated this specific opening geometry, particularly with h_0/d_w ratios of 0.8 and higher. Four studies were conducted by Morkhade and Gupta [63] which focused on a single point load where web-post buckling occurred. In contrast, Toprac and Cooke [42] carried out one study under two points load, resulting in Vierendeel failure.

As shown in Table 1, shear failure is less common in these structural elements. This may be because there is sufficient space between the supports and the first opening, allowing for full web engagement in shear transfer at the location of maximum shear force, and the bigger issue is the interaction between other inner forces leading to Vierendeel or web-post buckling failures. Notably, some literature does not even mention this failure type [36]. However, the shear failure with the buckle around the opening, as illustrated in Figure 3a, was captured in experimental tests that had been conducted by Lian and Shanmugam [84].

The presence of irregular openings that are offset from the beam axis can significantly enhance the buckling capacity of tees; however, it may also reduce the buckling capacity of the adjacent web post [85,86].

Table 2 summarizes expected failure modes considering different cross-section and opening parameters, as explained above, where:

Table 2: Predicted failure modes for $s/b_o \leq 1.5$

$L_{cr}/H < 7$				$L_{cr}/H > 7$		
$s_w/h_o < 0.3$			$s_w/h_o > 0.3$	$d_t/t_w < 25$		$d_t/t_w > 25$
$h_o/d_w > 0.8$	$h_o/d_w < 0.8$ **			$\lambda_w/\lambda_f < 7$	$\lambda_w/\lambda_f > 7$	
	W K1-3*	W K4*				
WPB/VM	FM	WPB	VM	LTB	LDB	WD

FM – flexure mechanism; **VM** – Vierendeel mechanism; **WPB** – web-post buckling; **WD** – web distortion; **LTB** – lateral-torsional buckling; **LDB** – lateral-distortional buckling

* Web classification according to prEN 1993-1-13 [10]; For example, W K1-3 stands for web class one to three

**For large-span beams (L/H > 18, where L is the total beam length), failure is characterized by weld rupture. Otherwise, the failure type depends on the web slenderness according to Table 2.

λ_w is web slenderness d_w/t_w,

λ_f is flange slenderness b_f/t_f.

Table 2 refers to beams with circular and hexagonal openings as well as to beams with transverse stiffeners at the supports and load points. If there are no adequate stiffeners, web post buckling can occur at higher values of s_w/h_o than specified in Table 2. All parameters are in accordance with Figure 2.

Although the use of beams with web openings is becoming more commonplace and there is a growing body of scientific literature on the topic, there are very few technical publications that include comprehensive design recommendations (there is small amount of data available for different steel grades and load types, such as pure axial compression [87–91] or axial force–bending moment interaction [92]). Meanwhile, research results are being incorporated into code documents as conclusive design methods become available. As part of second generation of the Eurocodes, new code EN 1993-1-13 [10] which provides design rules for the design of I-section beams with web openings, is due to be published within the next three years in Europe.

4 Conclusions

Numerous research projects that aim at accounting for the post-ultimate strength degradation of steel beams with web openings have been undertaken to achieve the objectives: (i) to determine and quantify the influencing parameters (for e.g. opening shape and rates, beam depth, flange width-to-thickness ratio and web thickness) on the particular failure mode, (ii) to develop new or improving the available design rules predicting the ultimate strength based on failure mode with high accuracy and reliability, and thus achieve the full efficiency of these structural elements.

The prediction and analysis of failure modes in I-section beams with unstiffened web openings, as discussed in this paper, highlight the intricate interactions among various geometric parameters. Key factors such as beam length, opening spacing, slenderness ratios, and web-flange interactions play a critical role in determining the manifestation of failure, whether it is local buckling, Vierendeel mechanisms, or global instability. While short beams are more susceptible to shear-related failures, long beams typically exhibit lateral-torsional or distortional buckling, particularly when the compressed flange lacks adequate stabilization. Furthermore, opening configurations — including spacing-to-diameter ratios and edge-to-edge spacing ratios — significantly impact the buckling behavior of web posts and the limits for Vierendeel failure. These findings underscore the importance of carefully balancing design parameters to mitigate failure risks and enhance beam performance. The specific threshold values and critical relationships, as outlined in this research, are presented in tabular form, providing practical insights and a concise reference for engineers and researchers. Future experimental investigations on less-studied parameters, such as irregular opening geometries and h_0/d_w ratios above 0.8, are essential to further refine predictive models and broaden design applications.

CRediT authorship contribution statement

Maja Ranisavljević: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jelena Dobrić**: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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