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Original Article

Influence of Web Opening Geometry on the Structural Performance of Castellated Composite Beams

Riza Suwondo[1], Adelia Nataadmadja[1], Mohammed Altaee[2]

[1]*Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta 11480, Indonesia.*
[2]*Environmental Research and Studies Centre, University of Babylon, Iraq.*

[1]*Corresponding Author : riza.suwondo@binus.ac.id*

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Abstract *- Castellated composite beams comprise a steel-castellated section and a concrete slab. Modern floor systems increasingly employ these beams owing to their high strength-to-weight ratio and versatility in service accommodation through web openings. Despite their advantages, web openings lead to significant, intricate, and complex local and global behaviors pertaining to strength and serviceability. This study focuses on the geometrical configuration of web openings, specifically the height, width, and spacing, and how these attributes define the structural behaviour of castellated composite beams. ETABS was used to create the finite element models, and design checks were carried out according to the provisions delineated in the AISC Design Guide 31. In the parametric analysis, the opening height (220-280 mm), width (240-300 mm), and spacing (270-330 mm) were varied. An assessment was performed on the overall behaviour in terms of ultimate strength, deflection, and local failure modes. The results show that the opening height has the most significant impact on the overall performance; increasing the height enhances the top-tee strength and reduces deflection, improving both the load-carrying capacity and stiffness. In contrast, the opening width and spacing mainly affect the local web-post stability. Wider or closely spaced openings increase the susceptibility to web-post buckling, whereas larger spacing restores tee interaction as the governing failure mode. Deflection remained within the serviceability limits, except for the smallest opening height. These findings demonstrate that an optimised combination of opening geometries can enhance structural efficiency while maintaining serviceability. This study offers practical guidance for designing castellated composite beams and contributes to the development of safer, lighter, and more sustainable long-span floor systems.*

Keywords *- Castellated Composite Beams, Web Opening Geometry, Structural Performance, Serviceability, Web-Post Buckling, AISC Design Guide 31.*

1. Introduction

A castellated composite beam is composed of a castellated steel beam and a concrete slab connected by shear studs to function as a single load-bearing unit. To fabricate a castellated beam, the steel section was cut along the web centreline, and the pieces were reconnected and offset to form a sequence of evenly distributed openings. This shape offers a number of benefits, such as lighter weight, enhanced flexural strength, better service integration by enabling the passage of mechanical and electrical services through the web openings, and enhanced service integration. Consequently, composite castellated beams have found numerous applications in structural engineering [1-5].

The outstanding flexibility of floor systems contributes to the adoption of profiled concrete slabs within steel-concrete composite beams. This composite action enables the efficient spanning of beams with lengths of approximately 12-20 m [6, 7]. However, the structural behaviour of composite beams is more complex because of the addition of profiled steel decks relative to solid steel beams with no web openings [8]. New complexities have been introduced with a steel deck, as profiled slabs, with the addition of springs, become susceptible to multiple buckling modes and interacting collapses under loads [9-12]. The positive effect of the composite slab on the total capacity of the beam is especially true for long-span scenarios, as the comparative nondurability in flexural resistance to non-composite beams becomes much more visible [13].

The main aim of structural design is to refine the structural elements to achieve economic feasibility along with an adequate level of service functionality. One standard method is to increase the load-carrying ability of the beams while trying to decrease the waste of resources. This is the case with castellated and composite beams, as both systems increase the moment of inertia and thus enhance the member's capacity to endure the bending moment [14-16]. However, each system has some limitations and side effects that need to be resolved. For example, castellated beams suffer from additional shear forces caused by the openings, which sometimes means that the end openings need to be filled to relieve the stress [17-19].

Early investigations into composite castellated beams were performed by Redwood and Cho [20], who studied the effects of web openings and the failure modes of hexagonal castellated beams. Jackson [21] carried out some experimental tests and demonstrated that the procedures contained in the AISC design guide for composite prismatic beams are applicable to predicting the natural frequencies of beams with web openings. Further understanding of the composite behaviour was advanced by Wang and Li [22], who researched the effect of edge restraints on the flexural strength of composite beams. In a related area, Ellakany and Tablia [23] created a numerical model for elastic composite beams with end shear restraints and elastic composite beams focusing on static and free vibration analysis, and concluded that end shear restraints do affect beam behaviour significantly, particularly in cases of incomplete composite interaction of the steel beam and concrete slab.

Regarding optimisation tactics, Kaveh and Ghafari [24] used several metaheuristic algorithms, including particle swarm optimisation, colliding body optimisation, and enhanced colliding body optimisation, to find the best semi-rigid semi-rigid jointed composite castellated beam. The semi-rigid joints provided the most benefits, with total costs decreasing by 21% to 35%, while partial fixity alone provided additional savings of 5% to 25%.

Considerable advances have been made in numerical modelling with respect to the behaviour of composite castellated beams. Salah [25] created and validated numerous ABAQUS models using experimental data to conduct a parametric study. The results showed that the slender composite beam sections primarily failed owing to bending, and excessive distortion, lateral buckling, and cross buckling occurred before the in-plane Vierendeel mechanism could be activated. Subsequently, Grezejowski and Salah [26] focused on the behaviour of continuous composite cellular beams, casting them in the context of geometrically nonlinear analysis.

Their work showed that, in short-span beams, the buckling mode includes both lateral-distortional buckling and web-post buckling, whereas in long-span beams, the dominant mode shifts to lateral-distortional buckling. Overall, previous investigations have provided valuable insights into the flexural and shear behaviours of castellated and composite beams, including the development of analytical models, experimental validations, and numerical approaches for assessing web-post stability and connection performance.

Despite extensive research on castellated and composite beams, most previous studies have focused either on the general behaviour of composite systems or on specific aspects, such as edge restraints, failure modes, and joint optimisation. However, the influence of web-opening geometry, specifically the width, height, and spacing of openings, on the structural performance of castellated composite beams remains insufficiently explored. These geometric parameters play a crucial role in determining both the local and global responses of the beam, affecting the flexural strength, shear resistance, stiffness, and vibration characteristics, as well as failure mechanisms such as Vierendeel bending and web-post buckling.

To address this gap, the present study systematically investigates the effect of opening geometry on the performance of castellated composite beams, focusing on key response parameters, including flexural capacity, stiffness, and failure modes. Unlike previous studies that typically examined single parameters or non-composite castellated beams, this study evaluated the combined influence of opening height, width, and spacing under realistic composite action. These findings provide a more comprehensive understanding of how geometric variations govern both strength and serviceability, offering practical design guidance for optimising castellated composite beams in modern long-span floor systems.

2. Methodology

In this study, an 8 m-long castellated beam with simple supports was evaluated, as shown in Figure 1. A composite castellated-section beam was configured to calculate the beam under uniformly distributed loads. The loading conditions included beam self-weight, superimposed dead load of 0.5 kN/m^2, and live load of 2.0 kN/m^2, which are floor system conditions in building applications.

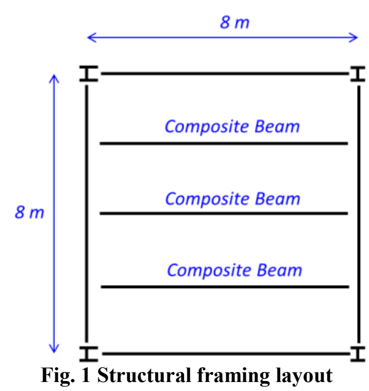

Fig. 1 Structural framing layout

The fabricated castellated beams were made of structural steel A992 with a nominal yield strength of 345 MPa. The original castellated section, W12×14, was castellated to obtain a CB18×24 profile, as shown in Figure 2. This study primarily aimed to determine the impact of the web opening geometry on the structural performance, specifically the opening height (h), opening width (w), and spacing (S), and their respective combinations. These combinations were varied within a reasonable range to obtain information on the strength and deflection properties of the beam.

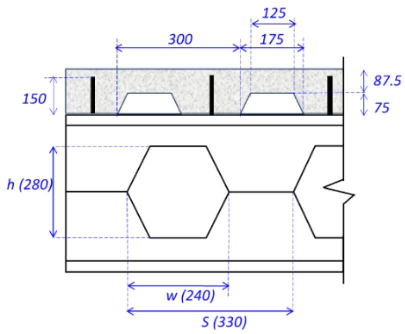

Fig. 2 Cross-sectional configuration of the castellated composite beam (unit in mm)

Structural analysis and design were performed using ETABS [27]. The castellated beam was modelled using frame elements, whereas the concrete slab was modelled as a shell element. The castellated beam and concrete slab were modelled as an integrated system, with shear connectors represented in accordance with the composite design provisions. Shear connectors were explicitly included in accordance with the composite design provisions to ensure a realistic simulation of the slab-beam interaction.

The design and verification of the castellated composite beam followed the recommendations provided in the AISC Design Guide 31 [28], which outlines the procedures for the design of castellated and cellular beams. This guide includes checks for flexural capacity, shear capacity (including Vierendeel bending effects at the openings), web-post buckling, and lateral-torsional buckling. Serviceability criteria, such as deflection limits, were also evaluated based on the AISC provisions [29].

Particular attention has been given to the strength-related failure mechanisms that govern the ultimate capacity of castellated composite beams. The analysis considered bending failure, tee-section interaction at openings, web-post bending, and shear failure. These modes are particularly critical in castellated beams, because web perforations modify the stress distribution and reduce the effective cross-sectional area. Identifying the governing failure mechanism for different opening geometries provides important insights into the effects of geometric variations on the beam strength, stiffness, and overall safety. Composite action involves dealing with concrete slabs and shear connectors to determine the flexural stiffness and load-carrying capacity of a beam. The provision of the AISC design indicates this. The terminology and variables for the castellated beam design are shown in Figure 3.

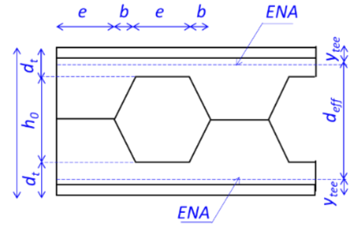

Fig. 3 Terminology used in castellated beam design

To address the complex geometry and multiple failure modes associated with castellated beams, this study applied a comprehensive design procedure following AISC Design Guide 31[28], as summarised below. The analysis explicitly considers the following.

1. Axial and flexural strengths of tee sections: The top and bottom tees formed by the cut web resist the primary bending stresses.
   Required flexural strength in the tee due to Vierendeel action
   $$M_{vr} = V_r \left(\frac{A_{tee}}{A_{net}}\right)\left(\frac{e}{2}\right) \tag{1}$$
   Available flexural strength of the tee
   $$M_c = 0.9F_y S_x \tag{2}$$
   Required axial force in tee (from couple equilibrium)
   $$P_r = \frac{M_r}{d_{eff}} \tag{3}$$
   Available axial compressive strength of the tee
   $$P_c = 0.9F_{cr}A_g \tag{4}$$
   Axial-flexural interaction
   $$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{vr}}{M_c}\right) \leq 1.0\ for\ P_r/P_c \geq 0.2 \tag{5}$$
   $$\frac{P_r}{2P_c} + \left(\frac{M_{vr}}{M_c}\right) \leq 1.0\ for\ P_r/P_c < 0.2 \tag{6}$$
2. Web Post Buckling: Local buckling of vertical web posts caused by horizontal shear between adjacent openings is evaluated by comparing the required flexural strength with the available capacity of each web post.

   The required horizontal shear through the web post is.
   $$V_{rh} = \left|\frac{M_{r(i+1)} - M_{r(i)}}{d_{eff}}\right| \tag{7}$$
   Required web-post flexural strength
   $$M_{rh} = V_{rh}h_{tee} \tag{8}$$

Available web-post flexural strength

$$M_p = 0.25t_w(e + 2b)^2 F_y \quad (9)$$

3. Horizontal and Vertical Shear: Shear forces were assessed in both the net and gross sections. The horizontal shear capacity of the web posts and the vertical shear through the openings were checked using code-based expressions with coefficients dependent on the beam geometry.

Available horizontal shear in the web post

$$V_{ch} = 0.6F_y e t_w \quad (10)$$

Available vertical shear at the net section (through openings)

$$V_{cvn} = 0.6F_y(d_{t-top} + d_{t-bot})t_w C_{v2} \quad (11)$$

Available vertical shear at the gross section (web post)

$$V_{cvg} = 0.6F_y d_g t_w C_{v1} \quad (12)$$

4. Deflection: Castellated beams typically behave similarly to prismatic sections in terms of deflection, although shear deformations around openings can have minor effects. Serviceability was checked against the L/240 limit [29].

Where V_r is required shear; A_{tee} is tee area; A_{net} combined top+bottom tee net area; e is solid-web length along centerline; F_y is yield stress; S_x is elastic section modulus of tee; M_r is required moment; d_{eff} is distance between tee centroids; F_{cr} is critical compressive stress; A_g is tee gross area; $M_{r(i)}$ is required moment at opening i; h_{tee} is tee depth; t_w is web thickness; b is horizontal half-opening length parameter; d_{t-top}, d_{t-bot} is net web depths above/below opening; d_g is gross web depth at post; C_{v1}, C_{v2} is shear coefficients per geometry; I_{net} is second moment at net section.

3. Results and Discussion

This section presents the analysis and interpretation of the data regarding the different geometries of web openings and the structural functional performance of composite castellated beams. Each of the openings is organised from the tallest to the lowest, followed by the width of the openings from the narrowest structural configuration to the widest, and lastly the spacing of the openings. Each of these parameters is related to the performance of the composite castellated beams, which consists of the ultimate strength and deflection at the mid-span of the beam, which yields the working geometry of the openings for the composite castellated beams.

3.1. Effect of Opening Height

The performance of castellated composite beams with opening heights ranging from 220 mm to 280 mm was evaluated, as illustrated in Figure 4, which presents the demand-to-capacity ratios for different failure mechanisms. Across all cases, the top tee region was consistently identified as the weakest under flexural loading, exhibiting the highest demand-to-capacity ratio. This confirms that the top tee interaction governs the strength behaviour of composite castellated beams under bending.

A clear trend was observed in the top tee interaction as the opening height increased. As the opening height increased, the demand-to-capacity ratio decreased, indicating that the load-carrying capacity of the top tee improved significantly. This enhancement can be attributed to the increased separation between the top and bottom tees, which effectively raised the moment of inertia and lever arm of the section, thereby improving the flexural stiffness and reducing the stress concentration around the openings. Consequently, a larger opening height resulted in a more uniform stress distribution and greater resistance to flexural deformation. Quantitatively, increasing the opening height from 220 to 280 mm resulted in an approximate 8-12% improvement in bending capacity, accompanied by a 10% reduction in mid-span deflection, confirming that the opening height strongly governs both the strength and stiffness performance.

By contrast, the effect of the opening height on the other failure modes was less pronounced. Web-post bending exhibited minor sensitivity to the opening height, with slight variations in the demand-to-capacity ratio that remained well within the design limits, indicating that web-post stability was largely unaffected. Similarly, the influence of the opening height on shear, global bending, and bottom tee interaction was negligible across the studied range, suggesting that these modes were not significantly affected by geometric changes in the opening height.

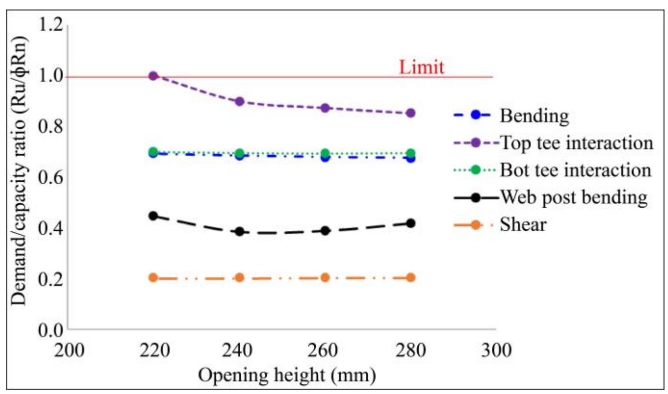

Fig. 4 Effect of opening height on the demand-to-capacity ratio for different failure mechanisms

The difference in the opening height clearly affected the performance of the castellated composite beams in terms of deflection, as shown in Figure 5. The midspan deflection consistently decreased as the opening height increased from 220 to 280 mm. This occurred because larger openings increased the adequate depth of the section, thereby improving the flexural stiffness of the section and causing a decrease in the deformation of the beam with larger openings. Additionally, the 220 mm opening height resulted in deflection exceeding the L/240 serviceability limit. This demonstrates that smaller opening heights, although they may provide weight savings, are also ineffective in meeting the required serviceability deflection. On the other hand, opening heights greater than 220 mm meet the deflection limit, which shows that within this range, increasing the opening height improves the flexural stiffness and meets the serviceability limit.

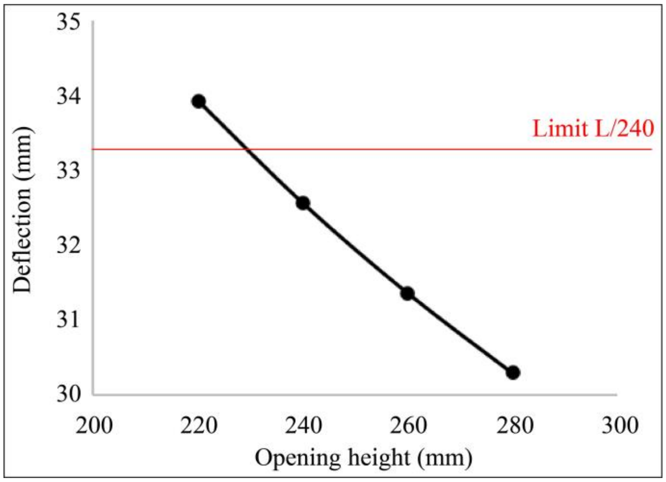

Fig. 5 Effect of opening height on mid-span deflection

Opening height is one of the most important geometric parameters in the design of castellated composite beams. Even with the parameters studied, larger openings enhanced the strength capacity of the beams and lowered the deflection. This improvement positively impacts both the ultimate and service performance of the beam. However, tiny openings may cause serviceability problems even if the strength levels are still acceptable. These insights are most helpful in refining the design, where the opening height must be proportional to the structural efficiency, code compliance, and practical use in long-span floor systems.

3.2. Effect of Opening Width

In this subsection, the opening width is varied from 240 to 300 mm to study its effect on the structural behaviour of the castellated composite beams. The data in Figure 6 show that out of the various failure mechanisms, only web-post buckling is substantially influenced by the changes in opening width, while the rest, which include bending, top tee interaction, bottom tee interaction, and shear, maintain capacities that are relatively constant over the range studied.

With the opening width set to smaller values, the top tee interaction dominates the structural response, thereby underscoring its importance in controlling the strength of castellated composite beams within their typical configurations. Nevertheless, larger opening widths result in important changes in the failure mechanism. The demand-to-capacity ratio linked to web-post buckling increases rapidly, surpassing the values representative of tee interactions and approaching the design limit. This shift underscores the susceptibility of web-post stability to the width of the opening, whereby larger openings diminish the effective web-post area and increase the risk of local buckling.

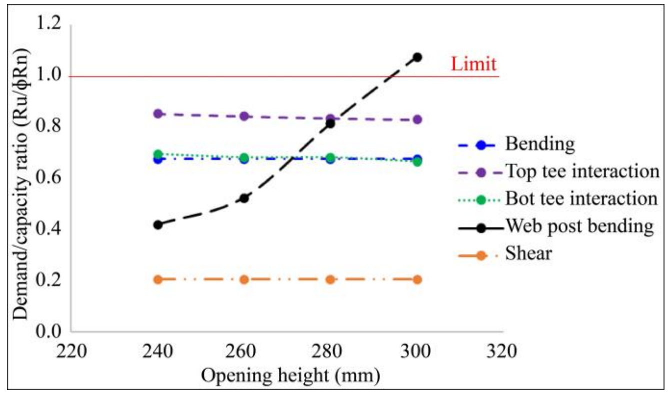

Fig. 6 Effect of opening width on the demand-to-capacity ratio for different failure mechanisms

Therefore, wider openings reduce the safety margin against web-post buckling and change the critical failure mode of the beam. While the top tee interaction remains the governing mechanism for failure, larger openings shift the weakness to web-post instability and possible premature failure. The web-post buckling limitation of castellated composite beams indicates that the opening width must be designed more conservatively.

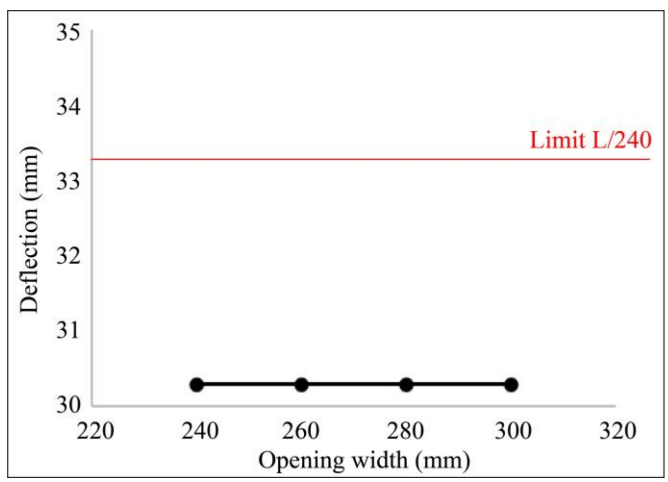

Fig. 7 Effect of opening width on mid-span deflection

Figure 7 illustrates how the midspan deflection of the castellated composite beams changes with respect to the opening width. The deflection values did not exceed the serviceability limit of L/240, indicating their consistency across the studied range. The opening width changes did not significantly affect the stiffness of the global composite beam. This outcome results from the deflection being primarily determined by the section's adequate depth, the composite action of the steel beam and concrete slab, and the opening width. While wider openings do impact the local behaviour, particularly web-post buckling, they do not significantly impact the overall beam flexural stiffness. Consequently, the variation in the opening width has no effect on the serviceability performance in terms of deflection.

The opening width affects the strength-related failure mechanisms predominantly concerning web-post stability, without affecting the serviceability limit state. For these reasons, the design requires controlling the opening width to prevent web-post buckling and acknowledges that deflection criteria are not responsive relative to the opening width.

3.3. Effect of Opening Spacing

In this subsection, the opening spacing was assessed from 270 to 330 mm to study its impact on the structural performance of castellated composite beams. As shown in Figure 8, similar to the impact of the opening width, the spacing of the openings mostly affects the web-post bending performance of the beams. In contrast, the magnitudes of the other failure mechanisms (overall bending, top-tee interaction, bottom-tee interaction, and shear failure) did not change significantly within the studied range.

The trend between spacing and web-post performance was clear. With increasing opening spacing, the demand-to-capacity ratio of the bending web-post shifted downward considerably, and thus the web-post bending stability improved. This is because a large spacing implies more continuity between openings, which increases the stiffness of web-posts and reduces the chance of local buckling. This is the opposite when the spacing is small, that is, when the distance between openings decreases and the web posts are further weakened, thus increasing the demand-to-capacity ratio in and around the design and increasing the chance to cross the demand-to-capacity ratio design limits.

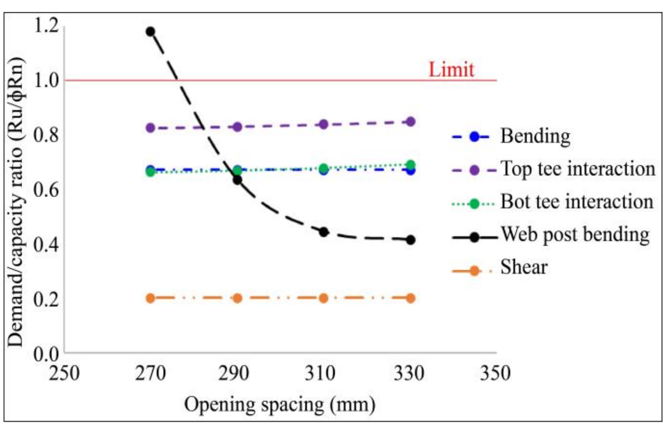

Fig. 8 Effect of opening spacing on the demand-to-capacity ratio for different failure mechanisms

The specific spacing variation changed the failure mechanism, dominantly controlling the system. For smaller opening spacings, web-post bending failure is the dominant mode owing to the concentrated weakening of stressed web segments. Conversely, when the spacing increases, the web posts are no longer weak elements, and the top-tee interaction becomes the critical mechanism. This shift illustrates the importance of spacing in design. Small spacings are likely to cause instability due to web-post failure, while larger spacings actually improve stability at the expense of shifting the criticality of the failure mechanism back to tee interaction.

The effect of opening spacing on the mid-span deflection of the castellated composite beams is illustrated in Figure 9. The results showed that the deflection remained essentially constant across the entire range studied, with all values well below the serviceability limit of L/240. This indicates that changes in the distance between adjacent openings have a negligible influence on the global flexural stiffness of the composite beam.

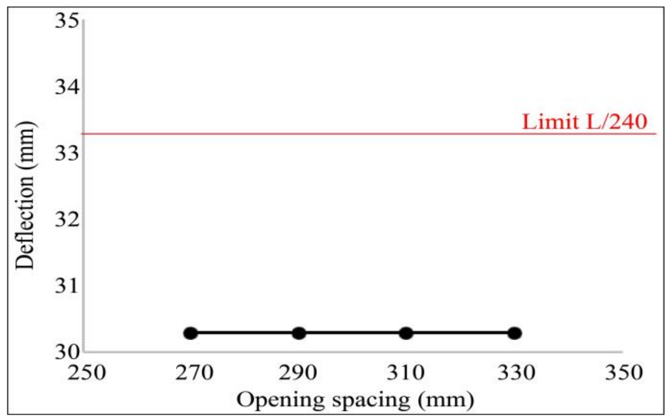

Fig. 9 Effect of opening spacing on mid-span deflection

The insensitivity of deflection to opening spacing can be attributed to the fact that serviceability behaviour is primarily governed by the composite action between the steel beam and concrete slab and the overall section depth, rather than the longitudinal distribution of openings. While smaller spacing affects the local web-post behaviour and increases susceptibility to local buckling, it does not substantially alter the global stiffness of the beam. Consequently, the deflection performance remained unaffected, even when the spacing was varied.

3.4. Design Implications

This study offers valuable insights into the relationship between the web opening geometry and structural efficiency of castellated composite beams. The findings reinforce the inherent advantages of castellated systems, that is, lightweight construction, high flexural capacity, and integrated service routing, while highlighting the necessity of optimising opening dimensions to maintain these benefits. Among the investigated parameters, the opening height exhibited the most pronounced influence on both strength and serviceability. Increasing the opening height enhances the beam efficiency by improving the top-tee flexural capacity and reducing the mid-span deflection owing to the greater separation between the compression and tension zones. However, excessive or insufficient opening heights can compromise performance. Overly small openings may lead to excessive deflection and serviceability issues despite adequate strength, whereas overly large openings could introduce local instability. Therefore, careful proportioning of the opening geometry is essential to balance the strength, stiffness, and serviceability in the design of castellated composite beams.

Open spacing and widths, on the other hand, affected the local stability, but not the global performance. Increased web openings lead to uncontrolled web-post buckling, which may become the governing failure mode. Similarly, a small spacing between openings increases the concentration of stress on web posts, which contributes to buckling failure. While deflection may not be affected by either parameter, they must be managed in terms of local stability to avoid beam strength failure as a result of local instability. The results indicate that the most effective castellated composite beams will have moderately large opening heights, whereas the widths and spacings will need to be maintained at reasonable levels for web-post stability. In the real world, this means that for the sake of practical height opening improvements, designers have to consider opening width and spacing as limits to contain instability. All of these observations point to the importance of a harmonious opening shape that meets serviceability and strength demands and delivers the functional benefits that castellated beams offer through service integration.

4. Conclusion

This study focused on the structural performance of castellated composite beams, considering the effects of the geometry of the web openings, specifically the height, width, and spacing of the openings. In compliance with the provisions of the AISC Design Guide 31, numerical analyses were performed, and the beams were assessed according to strength-related failure mechanisms and serviceability performance. The results outlined the fundamental design parameters that control the response of castellated composite beams.

The opening height is the most important determinant of both ultimate strength and serviceability performance. The strength requirements are most likely to be exceeded when the control of the top tee interaction failure mechanism is relaxed. This is because the increased mid-span deflection and negative section stiffness result from the interaction of the top tee with the castellated opening. However, inadequate opening height and strength provisions will likely lead to serviceability deflection issues.

In contrast, the configurations of the openings affected the local stability, but to a lesser extent, and, much less, the deflection. An opening width that is too significant increases the demand-to-capacity ratio for the bending of a web post and may change the governing failure mechanism from tee interaction to web post buckling. Closely spaced openings also increase the probability of local buckling because they concentrate and amplify the stresses in web posts. More spaced openings, on the other hand, alleviate the problem by restoring tee interaction, where the critical failure mode is located. Because the deflection was still within the specified limits, the serviceability was primarily a function of the opening height.

Consequently, the most important contribution of this work to the design and optimisation of castellated composite beams is the ability to provide a structurally efficient and serviceable floor system that conforms to the functional advantages of castellated construction, while also ensuring that the floor system is safe to use and withstands the stresses to which it is subjected.

In light of these findings, several directions for future research are suggested. First, the experimental validation of the numerical results presented here, particularly for large opening heights and reduced opening spacings, would further confirm the applicability of the proposed design implications. Second, extending the parametric study to other opening shapes (circular, sinusoidal, or hybrid castellated-cellular configurations) would help generalise the conclusions beyond the hexagonal openings considered. Third, this study focused on static loading; therefore, investigating the effects of fatigue, fire, and vibration serviceability on castellated composite beams with large openings would be of practical interest for long-span floor systems. Finally, developing simplified design expressions or charts based on current parametric trends could support direct application in design offices and inform future updates to AISC design provisions.

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Author Contribution

RS wrote the manuscript, AN edited the manuscript, and MA reviewed the manuscript.

Data availability

Data analysis https://zenodo.org/records/16945609

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