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Seismic Behavior of Castellated Steel Beams: A Comparative and Parametric Review of Web Opening Effects

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Abstract: *Castellated steel beams are increasingly favored in modern structural systems for their reduced weight, efficient material use, and accommodation of building services. Featuring web openings of varied shapes and sizes, they are ideal for long-span steel-framed buildings. While extensive research exists on their static and flexural behavior, studies on their seismic performance remain limited. This review evaluates how web opening geometry, including shape, size, and spacing, impacts seismic parameters such as lateral displacement, base shear, inter-story drift, and fundamental time period. Comparative studies between castellated and conventional beams under seismic loads are notably scarce, and no standardized seismic design guidelines currently exist for these systems. The review identifies critical research gaps and emphasizes the need for further dynamic analyses to support performance-based seismic design. By consolidating current findings, this study aims to guide future research efforts and promote the safe and effective use of castellated beams in earthquake-resistant steel structures.*

Keywords: Castellated steel beams (CSBs), Seismic performance, Steel structures, Web opening geometry, Earthquake-resistant design

I. INTRODUCTION

In recent years, the integration of steel structures with concrete deck slabs has become increasingly prevalent in the construction industry, owing to their enhanced strength, efficient load distribution, and accelerated construction timelines. These composite systems offer significant benefits in terms of structural performance, durability, and overall efficiency. Among recent advancements, the incorporation of castellated beams has emerged as particularly advantageous for structures requiring large open spans. Castellated beams effectively reduce the overall weight of the building while maintaining load-bearing capacity, thus providing an efficient solution in modern construction.

Moreover, the adoption of pre-engineered buildings (PEBs) has gained considerable momentum due to their cost-effectiveness. PEBs are designed through detailed bending moment analysis to optimize material utilization, ensuring both structural performance and economic efficiency. When combined with steel structures and cellular beams, PEBs further enhance structural behavior while minimizing construction costs, making them an attractive option for contemporary building projects.

A frame structure employing castellated steel beams and solid columns offers several advantages over traditional systems. Castellated beams, characterized by their increased depth, exhibit improved flexural strength and load-bearing capacity. This design facilitates efficient use of materials, delivering requisite strength while maintaining a lightweight structure. The web openings in castellated beams not only reduce material consumption but also provide convenient spaces for routing utilities such as pipes and electrical conduits (Yang Dong et al., 2021). These openings improve the functional utility of the structure by minimizing the need for additional space or complex installations. Furthermore, exposed castellated beams contribute to the architectural appeal by imparting a modern and industrial aesthetic. The

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design also preserves adequate ductility, allowing the structure to absorb and dissipate energy effectively under dynamic or seismic loading conditions.

Previous research has extensively examined the static behavior of castellated beams, focusing on aspects such as local buckling, shear performance, and load-carrying capacity. However, the effects of varying web opening shapes, sizes, and spacing on the seismic response of steel frames remain insufficiently investigated. Critical seismic design parameters, including lateral displacement, base shear, inter-story drift, lateral displacement, and time period, require further exploration in relation to castellated beam configurations.

Additionally, comparative studies on the seismic performance of steel structures incorporating castellated beams versus conventional beam systems are limited. Therefore, this review critically evaluates existing literature on the seismic behavior of steel buildings employing castellated beams, emphasizing the influence of web opening geometry and arrangement. The review also identifies key research gaps and proposes directions for future investigations aimed at enhancing the seismic resilience of steel structures utilizing castellated beams.

II. MANUFACTURING PROCESS OF CASTELLATED BEAM

The manufacturing process of castellated beams involves several precise steps that contribute to their structural efficiency and versatility in construction. Castellated beams, which are widely used in the construction of floors and roofs due to their high strength-to-weight ratio, are created by cutting wide-flange beams into a specific pattern. This process, typically performed using a computer-controlled cutting torch, enhances the beam's performance by creating a zigzag pattern along its web. The production process begins with cutting the beam into a zigzag shape (see Fig. 1a). After this, the beam is split into two halves (Fig. 1b). Next, the ends of these halves are trimmed to remove any excess material, ensuring a clean edge (Fig. 1c). Finally, the two trimmed halves are joined together through welding, resulting in the finished castellated beam (Fig. 1d). Fig. 2 shows an image capturing the cutting stage involved in producing a castellated beam (Fares et al., 2016).

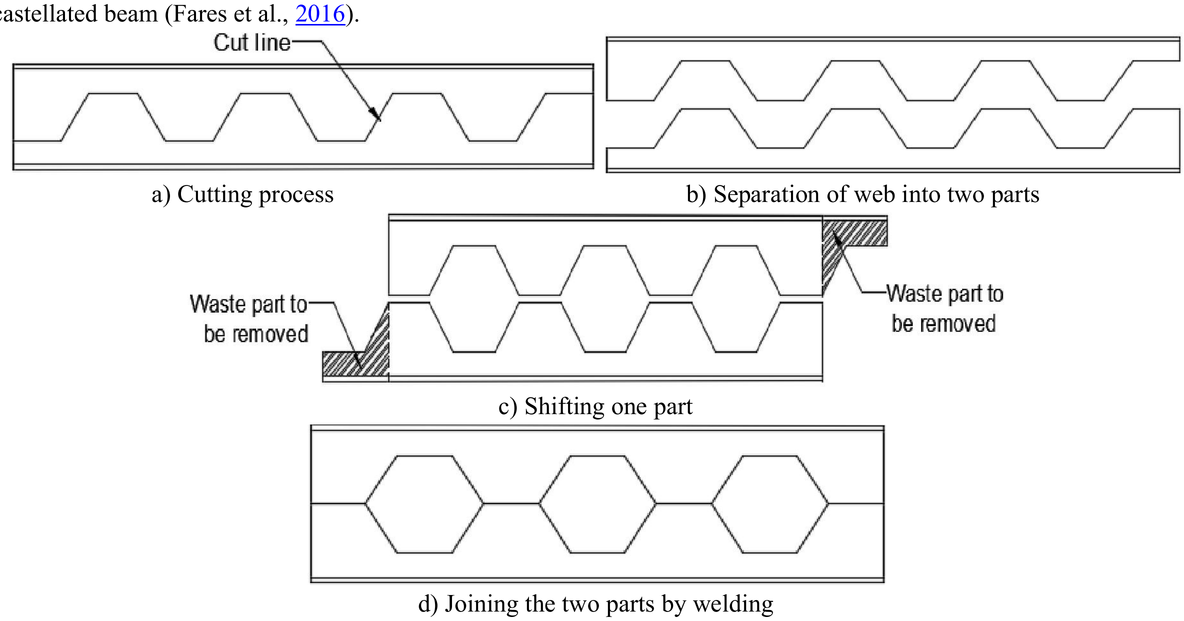

Fig. 1 (a-d) Manufacturing process of castellated beam

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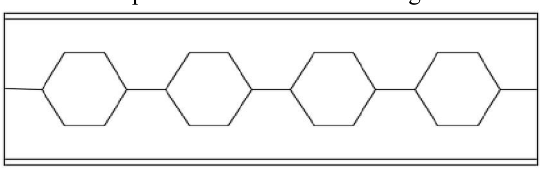
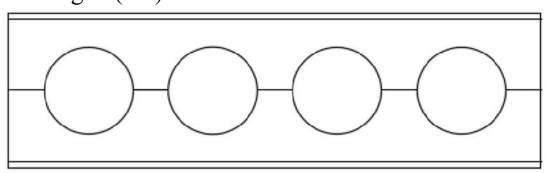
Fig. 2 Zigzag cutting process for castellated beam fabrication (Fares et al., 2016)

III. TYPES OF CASTELLATED BEAMS

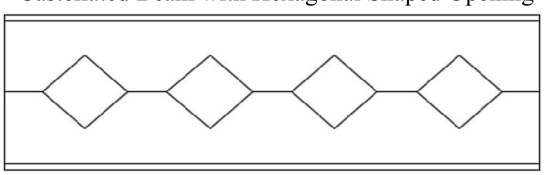
Castellated Steel Beams (CSBs) are classified based on the shapes of the openings created in their web sections. These openings can vary widely in geometry, influencing both the structural performance and aesthetic appearance of the beam. Typical shapes include hexagonal, circular (cellular), diamond, sinusoidal, octagonal, square, and rectangular patterns. Examples of these different configurations are illustrated in Fig. 3 (a–f).



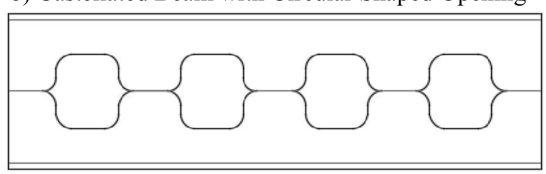
Castellated Beam with Hexagonal Shaped Opening



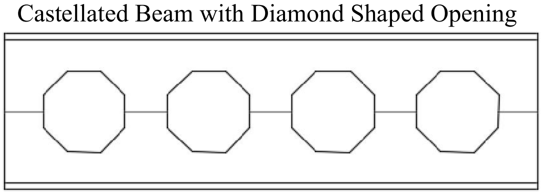
b) Castellated Beam with Circular Shaped Opening



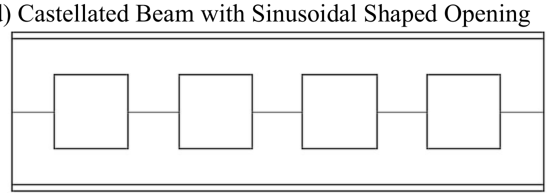
Castellated Beam with Diamond Shaped Opening



d) Castellated Beam with Sinusoidal Shaped Opening



e) Castellated Beam with Octagonal Shaped Opening



f) Castellated Beam with Square Shaped Opening

Fig. 3 (a-f) Types of castellated beam

IV. DESIGN GUIDELINES OF CASTELLATED BEAM AS PER EUROCODE 3

Terminology used in castellated beam

A basic understanding of the key terminologies related to castellated beam design is necessary before studying the applicable standards. Fig. 4 presents the terminology associated with castellated steel beams as defined by the Eurocode 3 standards.

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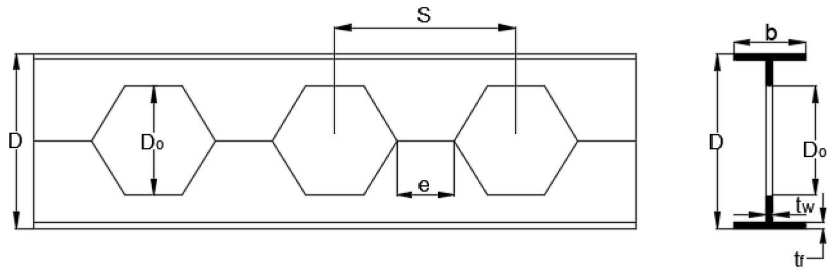

Fig. 4 Terminology used in castellated beam

Where,
Do =Depth of opening provided
D = Overall depth of the opening
S = C/C spacing between the two opening
e = Clear distance between two opening
b = Width of flange of I beam
tf = Thickness of flange of I beam
tw = Thickness of web of I beam

Web perforation guidelines

Eurocode 3 (EC3, 2003) provides guidelines for introducing perforations in the webs of castellated steel beams (CSBs) to enhance their structural performance. These provisions aim to optimize the geometry, size, and spacing of the openings to improve material efficiency and serviceability while maintaining the beam's load-bearing capacity and overall stability. The openings are precisely designed and strategically positioned along the beam's web to ensure effective load transfer and reliable structural behavior. The guidelines from Eurocode 3 (EC3, 2003) are outlined below:
1.25 < D/Do < 1.75
1.05 < S/Do < 1.5
Do ≤ 0.8 D
e ≤ 0.4 Do
Width of end post ≥ 0.5 Do

V. LITERATURE REVIEW

Research articles authored by different scholars and published in various journals have been thoroughly examined. The key points and findings from these studies have been compiled for clarity. A summary of this analysis is provided in the following section.

Yang Dong, et al. (2021) examined the seismic behavior of a two-story steel frame structure utilizing cellular beams with hexagonal web openings and composite concrete slabs, through quasi-static cyclic loading tests. The results revealed that plastic hinges formed at the corners of the beam openings, away from the beam-to-column joints, effectively protecting these joints from brittle failure. Cracking and damage were concentrated near the openings, particularly in the concrete slabs above them, while the beam-to-column connections remained intact. The structure exhibited full hysteresis loops, indicating strong energy dissipation capacity, and both frames demonstrated good ductility, with ductility coefficients exceeding 3.0. The composite action of the concrete slabs contributed to increased stiffness, delayed failure, and improved structural integrity by reducing stress on the top flange of the beams. Frame A experienced more rapid strength and stiffness degradation compared to Frame B, especially after yielding. Key findings include enhanced seismic performance due to the outward shift of plastic hinges, effective crack control provided by the concrete slabs, and minimal pinching in the hysteresis curves. Overall, the combination of cellular beams and composite slabs proved effective in enhancing energy absorption, ductility, and structural resilience, making it suitable for earthquake-resistant design.

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Li Bo, et al. (2009) explores the seismic behavior of steel moment-resisting frames (SMRFs) that have openings in the beam web, which are often needed for practical reasons like piping or ductwork. The study uses experimental tests and numerical analysis to evaluate how these openings affect the frame's strength, stiffness, ductility, and failure modes under earthquake loads. Results show that openings placed near the beam-column connection do not weaken the overall stiffness but help improve energy dissipation by creating local yielding zones, following the "strong column, weak beam" design principle. The formation of Vierendeel mechanisms around the openings leads to ductile failure modes and helps avoid brittle weld fractures often seen in conventional frames. A nonlinear analysis model was developed and validated with tests, showing good agreement. Furthermore, a case study on a 17-story building damaged in the Northridge earthquake demonstrated that adding web openings significantly improved the building's ultimate displacement capacity and overall ductility. Time-history analysis also confirmed that the maximum plastic deformation shifted to the weakened areas near openings, reducing connection damage. Overall, the study concludes that carefully designed openings in beam webs can enhance the seismic performance of steel moment-resisting frames without compromising safety.

Jamadar and Kumbhar (2015) investigated the structural performance of castellated steel beams with non-hexagonal web openings. Castellated beams, known for their efficiency and reduced weight, are modified by introducing circular (cellular) and diamond-shaped perforations in the web. Using finite element analysis (FEA) through Abaqus/CAE 6.13 and guided by Eurocode 3 standards, the study explored various configurations by varying the ratios of overall depth to opening depth (D/Do) and spacing to opening depth (S/Do). The results revealed that beams with diamond-shaped openings exhibited superior load-bearing capacity and greater resistance to local failure modes. Specifically, a diamond-shaped opening with a D/Do ratio of 1.5 and an S/Do ratio of 1.4 achieved the highest yield load of 34 kN. Experimental validation confirmed the FEA results, demonstrating good agreement between theoretical predictions and practical outcomes. In comparison, circular openings (D/Do = 1.36, S/Do = 1.4) produced slightly lower strength, with a yield load of 32.5 kN. The study concludes that diamond-shaped castellated beams provide improved strength and reduced susceptibility to local failures, making them more structurally reliable than their circular or hexagonal counterparts. This research supports the optimization of castellated beam designs for enhanced performance in construction applications.

Vahid Akrami, et al. (2020) investigated the seismic performance of steel moment-resisting frames (SMRFs) with reduced web section (RWS) beams, which feature strategically placed openings to improve ductility and reduce stress at beam-column connections. Using finite element analysis, six different multi-story frame models were analyzed in three configurations: conventional (MRF), RWS with end openings (RWS-E), and RWS with openings near one-third of the beam length (RWS-I). The study found that RWS-E and RWS-I models experienced moderate reductions in initial stiffness (2.5% for RWS-E, 8.5% for RWS-I) and ultimate strength (6% and 3.5%, respectively), with RWS-I performing better due to beneficial second-order effects at large drifts. Plastic hinges shifted from beam-column joints to web openings, supporting the "strong column–weak beam" design philosophy. RWS-I models exhibited the highest period-based ductility and significantly reduced plastic strain at critical connections up to 50% compared to traditional frames. Key findings include improved force redistribution, better lateral deformation profiles, and enhanced energy dissipation in RWS-I models. The study also introduces a design algorithm for optimizing opening size and location, ensuring structural safety while leveraging the benefits of web perforations. In conclusion, RWS beams particularly those with interior openings offer a practical and effective strategy for improving the seismic resilience of steel frames without significantly compromising stiffness or strength.

Several studies have investigated the use of beam web openings (BWOs) as a means to improve the seismic performance of steel moment-resisting frames (SMRFs). Vahid Akrami, et al. (2012) conducted a comprehensive analytical study using nonlinear pushover analyses to evaluate how different BWO configurations affect both local and global structural behavior. Their findings revealed that placing openings near the ends of beams effectively shifts inelastic flexural demands away from vulnerable regions such as beam-column connections and panel zones, thus reducing the likelihood of brittle failure. Frames with BWOs demonstrated improved energy dissipation and plastic hinge formation in non-critical areas, leading to more favorable stress distribution compared to conventional frames. The study also found that the incorporation of BWOs had minimal adverse effects on global performance metrics, with

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only a 4% reduction in strength and a 5% decrease in initial stiffness. Furthermore, the effectiveness of BWOs was found to be insensitive to variations in gravity loads but diminished with increased bay width. Overall, the research concluded that BWOs act as reliable structural fuses, enhancing ductility and seismic resilience without compromising overall structural integrity. These findings support the use of BWOs as a practical and efficient strategy for seismic design and retrofitting of steel frame structures.

Nikos D. Lagaros, et al. (2008) studied an optimized design approach for steel structures incorporating web openings in I-section beams. These openings are often used to accommodate building services and reduce material usage but can compromise structural integrity if not properly designed. The study formulates the problem as a combined sizing, shape, and topology optimization task, using both beam and shell finite element discretizations to analyse structural performance. Shell elements, which allow for more detailed modelling, enable the consideration of web opening shape and placement as variables in the optimization process. The authors employ an evolutionary algorithm to find optimal configurations that minimize structural weight while satisfying constraints related to strength, stability, and deflection, in line with Eurocode design standards. Results from a two-storey 3D frame test case showed that shell element models with circular web openings reduced structural weight by up to 20% compared to models without openings. Moreover, shell element discretization alone resulted in a 5% weight reduction over beam element models due to more accurate stress evaluations. Overall, the study demonstrates that integrating web openings with advanced optimization techniques significantly improves material efficiency without compromising safety or performance.

Yossef and Taher (2018) investigated the cost optimization of internal composite floor bays using castellated steel beams through the application of a genetic algorithm. A comprehensive computational model was developed, incorporating a flowchart, input variables, constraints, and output variables. The cost objective function was formulated based on the market prices of various floor components. The model's validity was confirmed by comparing its results with two established examples from the literature. Parametric studies were performed to assess the influence of different design variables, including the number of floor divisions, dimensions of hexagonal web openings, and the total number of openings. The findings indicated that changes in floor divisions and web openings had minimal impact on the overall bay cost. To optimize structural efficiency, limitations on web opening lengths were established to reduce material waste. Furthermore, design recommendations were provided to guide the selection of web opening dimensions to prevent buckling.

Estrada, et al. (2006) examined the use of castellated beams and emphasized their long-standing application due to the significant material and cost savings they provide. Although their fabrication costs have limited their adoption in the USA, these beams are widely used in other countries, mainly in building structures. The distinctive open-web design of castellated beams allows for straightforward and economical routing of utilities such as electrical conduits and plumbing without the need for additional hanger supports or increasing floor heights. This feature not only simplifies construction but also reduces overall project costs. Additionally, the lighter weight of castellated beams decreases the demand on supporting structural elements and foundations, offering further economic benefits. Beyond functionality, castellated beams offer architectural advantages by enhancing the visual appeal of structures. Comparative cost analyses with traditional wide flange beams show that castellated beams are more cost-effective when designed for the same load capacities, especially in large projects requiring numerous beams. These advantages make castellated beams an attractive option for modern building designs and suggest that they should be considered more widely in structural engineering practice. Continued research and development are needed to optimize their fabrication and broaden their application in the industry.

III. RESEARCH GAP

While the seismic performance of steel buildings has been widely studied, limited research has specifically focused on steel structures incorporating castellated beams. Most existing studies concentrate on the static and flexural behavior of these beams, with relatively few addressing their dynamic response under seismic loading. This is noteworthy given the growing use of castellated beams in modern construction due to their structural efficiency and architectural appeal.

A critical gap in the literature lies in understanding how variations in the shapes (e.g., circular, hexagonal, diamond and rectangular), size, and spacing of web openings affect seismic response parameters such as lateral displacement, base

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shear,inter-story drift, and time period. These geometrical configurations, which are central to the design of castellated beams, remain underexplored in seismic contexts.

Moreover, comparative studies between conventional steel frames and those utilizing castellated beams under seismic excitation are scarce. This lack of evaluation limits our understanding of the influence of web opening geometry on the overall seismic performance and structural integrity of steel buildings.

Addressing these gaps through a comprehensive review and synthesis of existing research will offer valuable insights into the optimization of castellated beam design for seismic applications. Such investigations are essential for guiding future research and informing design practices in earthquake-prone regions.

IV. CONCLUSION

A detailed study of the existing literature was conducted. Based on this review, the following conclusions are drawn:

Castellated beams enhance structural performance by increasing flexural strength, improving load distribution, and reducing overall weight. In seismic applications, they help dissipate energy more effectively and relocate plastic hinges away from beam-column joints, improving ductility and protecting critical connections.

The shape, size, and spacing of web openings are critical factors affecting the seismic behavior of castellated beams. Variations in these parameters can influence key response metrics such as lateral displacement, base shear, inter-story drift, and time period. However, current research provides limited data on how these geometric variations impact dynamic performance.

Comparative analyses between conventional steel frames and those with castellated beams under seismic loads are scarce. This restricts a comprehensive understanding of the structural trade-offs and benefits associated with using castellated systems. Without such comparisons, designers lack clear guidance on their relative seismic efficiency.

Future research should focus on parametric studies and large-scale testing to evaluate the seismic response of different castellated beam configurations. There is also a strong need to develop standardized, performance-based design guidelines that incorporate seismic considerations. Such efforts will facilitate the safe and efficient application of castellated beams in modern structural systems.

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