A Review on Comparative Nonlinear Time History Analysis of Steel Structures with and without Castellated Beams under Seismic Loading

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***Abstract*—Castellated steel beams are increasingly used in modern construction due to their reduced self-weight, efficient material utilization, and ability to accommodate building services. However, limited research is available on their seismic performance under dynamic loading conditions. This study presents a comparative nonlinear time history analysis of steel structures with and without castellated beams subjected to seismic loading. A G+10 residential steel structure was modeled and analyzed to evaluate the seismic behavior of conventional solid beams and castellated beams with hexagonal and circular web openings.**

The analysis focused on important seismic parameters such as lateral displacement, inter-story drift, base shear, time period, and structural response under earthquake excitation. Nonlinear time history analysis was carried out using suitable structural analysis software in accordance with relevant IS code provisions. The results indicate that castellated beams significantly influence the dynamic characteristics of steel frames by reducing structural weight and improving stress redistribution. The migration of stress concentration away from beam-column joints enhances ductility and reduces the possibility of brittle failure during seismic events.

***Index Terms*—Castellated Steel Beam (CSBs), Time History Analysis, Steel Structure, Earthquake-resistant Design, Seismic Loading**

I. INTRODUCTION

Since the end of World War II, structural engineers have continually sought cost-effective strategies for designing steel structures. Despite the advantages of high-strength steel, its full potential is often limited by deflection criteria that restrict member flexibility. To overcome this challenge, innovative design approaches have emerged to improve member stiffness without increasing structural weight. Among these, castellated beams have proven to be particularly effective.

Castellated steel beams (CSBs), introduced in the 1940s, have gained widespread popularity due to their ability to create expansive interior spaces, reduce inter-floor heights, and enhance daylight penetration and architectural aesthetics. Unlike conventional solid beams, CSBs feature hexagonal or circular openings that increase the beam's depth and flexural rigidity while maintaining material efficiency. These openings also facilitate the integration of mechanical and electrical services, streamlining construction and improving spatial planning.

Compared to traditional steel sections, castellated and cellular beams offer superior span capabilities and reduced self-weight, making them ideal for long-span applications. Their integration with concrete deck slabs in composite systems has become increasingly common, offering improved load distribution, structural strength, and faster construction timelines. This synergy enhances both durability and overall performance, especially in buildings that require large, unobstructed areas.

The rise of pre-engineered buildings (PEBs) has further accelerated the adoption of castellated beams. PEBs are meticulously designed using bending-moment optimisation to ensure efficient material use and structural integrity. When combined with cellular beams and steel frameworks, these systems deliver high performance at reduced costs, making them a preferred choice for modern construction.

Structurally, a castellated beam frame system comprises CSBs paired with solid steel columns. The increased section height of CSBs contributes to greater load-bearing capacity, improved ductility, and enhanced energy dissipation. Their exposed geometry not only supports functional requirements but also adds to the visual appeal of the structure. Today, CSBs are extensively used in high-rise buildings, bridges, stadiums, and other large-scale projects. Their lightweight nature, superior bending stiffness, and aesthetic versatility make them a cornerstone of contemporary steel design, offering a balance between engineering efficiency and architectural expression.

A. Types of Castellated Beam

Castellated Steel Beams (CSBs) are categorized by the geometric shape of the openings cut into their webs. These openings can take various forms such as hexagonal, circular (cellular), diamond, sinusoidal, octagonal, square, and rectangular each influencing the beam's structural performance and visual appeal in distinct ways. The choice of opening shape directly affects factors such as load-bearing capacity, self-weight, and ease of fabrication. Structural designers select specific configurations to balance engineering efficiency with architectural intent, tailoring the beam's behaviour to meet the project's demands

1) Hexagonal Openings

Description: Formed by zig-zag cutting along the web, resulting in regular hexagonal holes.

Structural Impact: Offers a good balance between increased depth and load-bearing capacity.

Fabrication: Simple and cost-effective; widely used in industrial and commercial buildings.

Applications: Long-span floors, warehouses, and pre-engineered buildings.

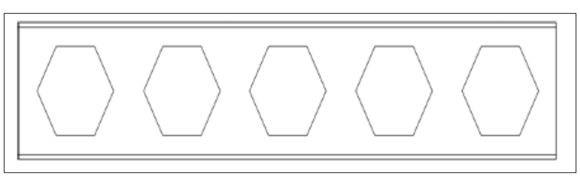

Fig 1 Hexagonal Castellated Beam

2) Circular Openings (Cellular Beams)

Description: Web openings are circular, created using advanced cutting techniques.

Structural Impact: Provides smoother stress distribution and higher torsional resistance.

Fabrication: Slightly more complex; requires precision cutting.

Applications: Architecturally exposed structures, bridges, and stadiums.

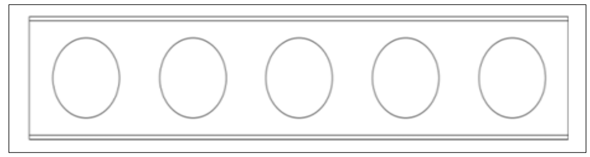

Fig 2 Cellular Castellated Beam

3) Diamond-Shaped Openings

Description: Diagonal cuts form diamond-shaped voids in the web.

Structural Impact: Enhances shear resistance and aesthetic appeal.

Fabrication: Moderate complexity; used where visual symmetry is desired.

Applications: Decorative structural elements, atriums, and public buildings

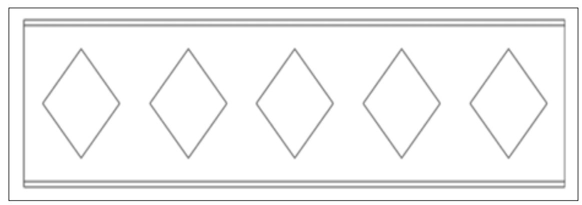

Fig. 3 Castellated Beam with Diamond-Shaped Opening

4) Sinusoidal Openings

Description: Wave-like pattern resembling a sine curve.

Structural Impact: Reduces stress concentration and vibration sensitivity.

Fabrication: Complex; requires CNC cutting and precise alignment.

Applications: Specialized structures with dynamic loads or vibration control needs.

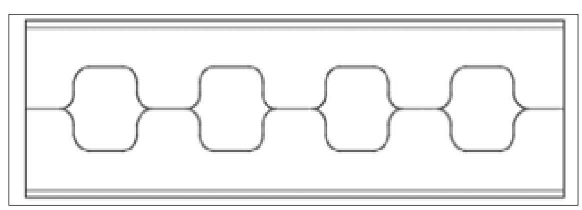

Fig 4 Castellated Beam with sinusoidal Openings

5) Octagonal Openings

Description: Eight-sided openings offering a hybrid between circular and hexagonal shapes.

Structural Impact: Balanced stress flow and moderate rigidity.

Fabrication: Requires advanced cutting; less common.
Applications: Custom-engineered buildings and aesthetic-focused designs.

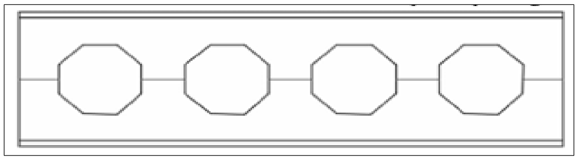

Fig 5 Castellated Beam with Octagonal Opening

6) Square Openings
Description: Simple square voids aligned along the web.
Structural Impact: Easier to fabricate, but may lead to stress concentration at corners.
Fabrication: Straightforward; suitable for basic utility integration.
Applications: Utility corridors, service buildings.

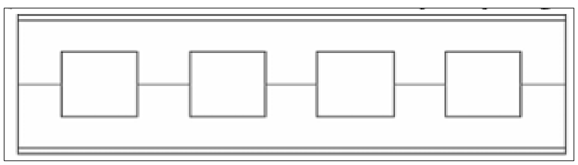

Fig 6 Castellated Beam with Square Opening

7) Rectangular Openings
Description: Elongated square openings providing more horizontal clearance.
Structural Impact: Useful for accommodating large ducts or pipes.
Fabrication: Easy to cut and align; moderate stress concentration.
Applications: Industrial buildings, mechanical floors.

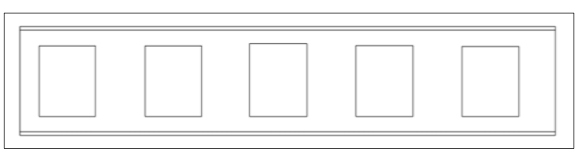

Fig 7 Castellated Beam with Rectangular Opening

II. STATE OF DEVELOPMENT

Castellated beams are widely used in modern steel structures because of their high strength-to-weight ratio, increased stiffness, and economical use of material. The presence of web openings improves structural efficiency and allows easy passage for building services. In recent years, researchers have focused on understanding the behaviour of castellated beams under static, cyclic, and seismic loading conditions. Various studies have investigated the influence of opening shape, stiffeners, strengthening methods, and connection details on the structural performance of castellated beams. The following literature review summarizes important findings related to the seismic and structural behaviour of castellated steel beams.

Hossein Khosravi et al. (2015) studied the seismic behaviour of castellated beams under explosion loading using Abaqus software. The study compared rigid and semi-rigid connections with concrete-surrounded and non-surrounded beams. The results showed that rigid connections provided better resistance against blast effects than semi-rigid connections. Surrounding the castellated beam with concrete significantly improved its performance and reduced local failures. The use of reinforcement plates also minimized local buckling near the openings.

Qingshan Yang and Bo Li (2009) investigated the aseismic behaviour of steel moment resisting frames with openings in beam webs. Experimental and numerical studies revealed that web openings improved ductility and shifted plastic hinge formation away from beam-column joints. The study confirmed that brittle weld fractures could be avoided due to stress redistribution around openings. Time history and pushover analysis showed improved seismic behaviour and higher displacement capacity in frames with web openings.

Dhiraj U. Bhuse and S.L. Bhilare (2018) carried out an analytical study on castellated beams using ANSYS 16 software. The study examined the effect of increasing web thickness by 10%, 20%, and 30% on the behaviour of castellated beams. Results indicated that increased web thickness reduced deformation and improved stress distribution. The study also highlighted the importance of web thickness in controlling local failure around openings.

Samadhan G. Mork hade (2019) presented a state-of-the-art review on the behaviour of castellated steel beams. The paper discussed different failure modes such as lateral torsional buckling, web post buckling, and Vierendeel mechanism formation. It also reviewed the influence of opening shape, spacing, and strengthening techniques on beam performance. The study concluded that more detailed research is required to establish reliable design methods for castellated beams.

Shakir Mahmood Hadeeda and Ahmad Jabbar Hussain Alshimmeri (2019) conducted a comparative study between rolled and castellated steel beams with different strengthening techniques using Abaqus software. The findings showed that castellated beams exhibited higher load carrying capacity and lower deflection than solid beams. Strengthening with high-strength concrete and lacing reinforcement significantly improved stiffness, ductility, and ultimate moment capacity. The study demonstrated that strengthened castellated beams can provide superior structural performance.

Bharat Singh Uikey and Dr. Umesh Pendharkar (2024) reviewed various studies related to castellated beams and their structural behaviour. The paper discussed bending, shear, buckling, fatigue, and failure characteristics under different loading conditions. It emphasized the importance of finite element analysis software such as Abaqus for understanding complex structural behaviour. The review highlighted the need for further experimental validation and optimization techniques in castellated beam design.

Dr. Hayder Wafi Al-Thabhawee (2017) experimentally investigated the effect of hexagonal hole dimensions on the ultimate strength of castellated steel beams. Six castellated beam specimens were tested and compared with the parent section. Results showed that optimized hole dimensions significantly increased stiffness and ultimate load capacity. The castellated beam achieved nearly 50% higher strength compared to the original beam section.

Vishvatej Vijaykumar Kshirsagar and Prof. S.R. Parekar (2018) reviewed the behaviour of castellated beams with and without stiffeners. The study identified common failure modes such as web post buckling, lateral torsional buckling, and welded joint rupture. The review concluded that providing stiffeners in the web portion improves strength and reduces deflection. It also suggested the need for detailed studies on stiffener size and placement.

Balgovind Mishra and Dr. Raghvendra Singh (2022) performed nonlinear time history analysis of a G+15 RC frame building with shear walls using ETABS software. The study compared parameters such as story displacement, drift, base shear, and overturning moment under seismic loading. Results showed that nonlinear time history analysis effectively predicts the seismic response of structures. The study highlighted the importance of dynamic analysis for earthquake-resistant design.

Jamadar A. M. and Kumbhar P. D. (2015) conducted a parametric study on castellated beams with circular and diamond-shaped openings. Finite element analysis showed that opening shape significantly affects structural performance. Diamond-shaped openings provided better strength and minimized local failures compared to circular openings. The optimized beam demonstrated improved load carrying capacity and structural efficiency.

Wakchaure M.R. et al. (2012) studied castellated beams with varying depths of web openings under two-point loading. Experimental results showed that increased beam depth enhanced bending stiffness and reduced deflection. However, larger openings also introduced local failure effects. The study concluded that castellated beams are efficient for long-span structures where deflection control is important.

Haider E. Al-Laban and Nassr Salman (2021) carried out a parametric study on reduced web section beam-column connections with hexagonal castellated beams under cyclic loading. The research focused on the spacing and location of web openings near the column face. Results indicated that proper placement of openings improved rotational capacity and stress distribution. The study emphasized the importance of opening distance in seismic performance.

III. FINDINGS FROM LITERATURE

- Castellated beams provide higher strength-to-weight ratio and improved stiffness compared to conventional solid steel beams.
- Web openings in castellated beams help in reducing structural self-weight and improve material efficiency without significantly reducing strength.
- Studies showed that castellated beams with optimized opening shapes and spacing exhibit better load carrying capacity and reduced deflection.
- Circular, hexagonal, and diamond-shaped openings influence the stress distribution and seismic performance of steel frames differently.
- The presence of web openings shifts plastic hinge formation away from beam-column joints,

thereby improving ductility and reducing brittle failure during earthquakes.

- Nonlinear and cyclic analysis indicated that castellated beams can improve seismic energy dissipation and structural resilience under earthquake loading.
- Strengthening techniques such as stiffeners, reinforcement plates, and concrete encasement significantly enhance the performance of castellated beams.

IV. GAP IDENTIFICATION

- Most previous studies focused mainly on the static and flexural behaviour of castellated beams, while limited research is available on their seismic performance under nonlinear dynamic loading.
- Comparative studies between conventional steel beams and castellated beams under earthquake excitation are limited.
- Very few studies have investigated the influence of different opening geometries, sizes, and spacing on seismic response parameters such as base shear, storey drift, displacement, and time period.
- Existing research primarily concentrated on individual beam behaviour rather than the overall seismic response of multi-storey steel buildings.
- Limited work has been carried out using Nonlinear Time History Analysis for steel structures with castellated beams.
- There is insufficient research on the seismic behaviour of castellated beams in G+ multi-storey steel buildings subjected to real earthquake records.
- Standardized seismic design recommendations and guidelines for castellated beams are still not adequately available in design codes.
- The effect of different web opening shapes on stress redistribution and structural ductility in steel buildings requires further investigation.
- Most available studies are experimental or analytical at component level, whereas system-level seismic performance assessment of entire steel frames remains limited.

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