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Structural Behaviour of Castellated Beam: A Review

Muthukkumaran C[1], Karthikeyan S[2], Satheesh Kumar K R P[3]
Post Graduate Student, M.E Structural Engineering, Department of Civil Engineering[1]
Assistant Professor, M.E Structural Engineering, Department of Civil Engineering[2, 3]
Kumaraguru College of Technology, Coimbatore, Tamil Nadu, India

Abstract: *The use of castellated beams has gained popularity due to their excellent performance in terms of strength, stiffness, and economy. Castellated beams are fabricated by cutting I-sections or H-sections along the web in the desired shape and re-joining the two halves on one another through welding in order to improve the beam's overall depth. Most often, hexagonal, circular, diamond, and sinusoidal shapes are used for the web opening. This pattern increases the surface area and reduces the weight of the beam without compromising its structural integrity. The idea incorporates the technique of offering the best section in accordance with the most essential need. This paper presents an overview of the behavior of castellated steel beams with several shape openings having an I-shaped cross-section, modeling is conducted using the finite element software package ANSYS14 and ABAQUS. With uniform distributed load and simply support conditions, an analysis is conducted. The investigation of various failure patterns and the deflection at the middle of the beam are done.*

Keywords: Castellated beam, Web opening, ANSYS and ABAQUS, Failure patterns

I. INTRODUCTION

The Latin word "castellatus," which means "constructed like a castle having regular apertures in walls like a castle," is the source of the term "castellatus beam." Castellated beams were created as structural channels to extend the depth and strength of the beam without adding more weight or material. Castellated beams have been the best building material since the 1950s. When there was a scarcity of steel following World War II, engineers realised that these beams were inexpensive to build and had a great strength-to-weight ratio. Although about the same in weight, castelled beams are 1.5 times deeper than their parent section.

1.1 Terminology

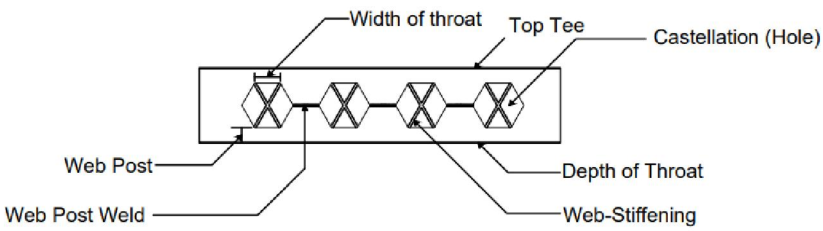

Fig 1: Terminology

- **Web:** The vertical part of the castellated beam that connects the top and bottom flanges.
- **Flanges:** The horizontal parts of the castellated beam that support the load.
- **Web-Stiffening:** The technique of reinforcing the web of the castellated beam with additional material.
- **Web Post**: The castellated beam's cross-section, which is represented as a solid cross-section.
- **Throat Width:** The length of the root beam's horizontal cut. The distance along the web where the flanges are present.
- **Throat Depth:** The throat depth is the height of the section of a web connecting two flanges to form a tee section.

II. LITERATURE REVIEW

Christovam et.al [2021], this paper looked at the relationship between lateral-torsional and compression tee local buckling modes and the instability of castellated beams. The study involved eigenvalue and fully nonlinear finite element analyses, and an approach based on the Direct Strength Method was proposed to derive strength prediction equations. The developed method was compared with current standard procedures, and the results showed that the proposed equation predicts better strength values in all cases, especially those in which local or interaction failure modes dominate the behavior of the beam. By taking into account the interplay between the global buckling mode and plasticisation, several of the methods recommended in standards and guidelines for the design of castellated beams under flexure were shown to either underestimate or overestimate the failure moment [1].

Kamable [2019], castellated beam studies were conducted in pre-engineered building structures where excess steel is avoided by tapering the sections. It was concluded that castellated beams with sinusoidal web openings have better load-carrying capacity and structural performance compared to castellated beams with hexagonal web openings. The sinusoidal web opening castellated beams have a higher shear capacity and less deflection. Shear stress is easily redistributed at the fillet corner of castellated beams with sinusoidal web openings, according to experimental analysis [2].

Richard Frans et.al [2017], various space openings (6 cm, 9 cm, and 12 cm) with various cutting angles (50°, 60°, 70°) have been considered with a finite element model with ABAQUS finite element package. The model was developed to obtain the maximum yield load for each variation model. Through several simulation modeling and validation of the numerical models with experimental results, it was concluded that the maximum yield load was achieved when the opening space and cutting angle are 6 cm and 60 respectively. Hexagonal castellated beam with an e/d ratio is 0.2857 (e = 6 cm) have a greater yield load than the others (e = 9 cm and e = 12 cm) [3].

Ajim and Pankaj [2016], castellated beams in cantilever action were studied. The prime advantage of the castellated beam is it causes an increase in vertical bending stiffness, easy service provision, and attractive appearance primarily. In castellated beams with cellular openings, the depth of the section was increased earlier up to a certain limit and under the consideration of the web shear. In castellated beam to avoid local failure of beam provision of the plate below-concentrated load, to reinforce the weak sections of the beam, and to avoid the Vierendeel effect (to avoid stress concentration) corners of the holes are to be rounded were concluded. It was concluded that the composite moment of inertia of the castellated beam section as found in catalogs and section properties should be used to calculate the flexure strength of the castellated beam [4].

Kim et.al [2016], this study present an analytical solution for determining the critical moment of lateral-torsional buckling of simply supported castellated beams under uniform load and coupled bending moment. Finite element analysis is used to verify the solution. The study concludes that the effect of web openings on the lateral-torsional buckling of castellated beams is mainly due to the reduction in torsional rigidity and that the reductions in warping rigidity and lateral flexural rigidity can generally be ignored. For most castellated beams, web openings have only a marginal influence on their lateral-torsional buckling behavior, and principles found in I-beams can be applied to castellated beams. The proposed principle can also be applied to beams with other boundary conditions [5].

Jamadar and Kumbhar [2015], a parametric study was conducted to optimize the size of castellated beams with circular and diamond-shaped openings by considering the D/Do and S/Do ratios. Using the features of Eurocode 3 and the software ABAQUS/CAE 6.13, finite element analysis was performed. Von-Misses failure criteria were used to find the failure load on the beam, and the results were validated through experimentation. Castellated beams with diamond-shaped openings were found to be better in terms of load-bearing capacity due to the availability of more shear transfer area, and it was observed that local modes of failure were the main cause of the collapse [6].

Kumbhar and Jamadar's [2015], the study presents an optimization of the size of castellated beams with sinusoidal openings. Castellated beams usually fail due to local failure modes and stress concentrations at opening edges. The use of sinusoidal openings improves the performance of the beams by providing increased stress distribution area and smooth stress distribution due to curved edges. Finite element analysis and Eurocode were used to validate the experimental results obtained for different opening sizes. Castellated beams with sinusoidal openings of size 0.55 times the overall depth of the beam an S/Do ratio of 1.4 and a D/Do ratio of 1.41 can withstand a maximum load of 34 kN, making them superior to other shapes of openings. The study concludes that castellated beams with sinusoidal openings are stronger and have uniform stress distribution near the corner portion of the opening [7]

Jamadar and Kumbhar [2014], a review of numerous studies on the flexural behavior of castellated beams with varied sizes and forms of apertures has been attempted, and conclusions have been formed. Due to the lack of shear transfer area in the castellated beam, one of the main problems is a local failure. As a result, optimization of the apertures' size and form is crucial. The castellated beams with circular, square, and diamond-shaped openings give better shear transfer area and hence the castellated beams with such openings can be used. Also, the flexural behavior of a castellated beam has been investigated using the Abaqus software (finite element analysis), and it was discovered that the results were in good agreement with those from the literature that is currently available (IS code method analysis) [8].

Pachpor et.al [2014], the behavior of cellular beams was analyzed using both design methods according to BS: 5950 and finite element analysis software ANSYS. The design method is based on plastic and elastic analysis of the beam section at ultimate and serviceability loads, respectively. Results showed less than a 5% variation between theoretical and ANSYS results due to dimensional linearity, material properties, and localized effects. The design method can be applied to different beam sections with various opening ratios and spacing, and web stiffeners can be used to strengthen beams under point loads near the support [9].

Ferhat and Mehmet [2013], the ultimate load-bearing capacity and finite element analysis of steel cellular beams with the best design are presented in this article. The harmonic search technique was used to design the beams, and BS 5950 requirements were used to apply design limitations. The experimental work was also simulated by using ANSYS-workbench finite element integrated software program to verify the test results [10].

Anupriya and Jagadeesan [2013], through a detailed FE study (ANSYS14), the behavior of the shear strength of a castellated beam was investigated. Due to its web opening, stress concentration rises at all corners and load application points. Additionally, as the depth of opening increases, the castellated beams' stiffness decreases. Shear stiffeners are thus added along the web opening to strengthen the castellated beam in shear and decrease deflection. Deflection without stiffeners is 9.75 mm; with stiffeners provided diagonally, it is reduced to 7.85 mm; and with stiffeners provided vertically along with diagonal stiffeners, it is still reduced to 3.99 mm. This was determined from the results of the ANSYS14. As a result, adding shear stiffeners along the shear zone can increase the shear strength of a castellated beam [11].

Wakchaure et.al [2012], Castellated beams were fabricated from a selected steel section with increased depth of web openings. These beams provide benefits such as improved vertical bending stiffness, the convenience of service providing, and an appealing look. However, the presence of web openings results in various local effects. Experimental testing showed that the structural behavior of castellated steel beams differs from that of solid web beams, with Vierendeel effects prominently increasing at hole corners. Reinforcement and rounding of corners improved beam performance. Castellated beams are widely used in industrial buildings, power plants, and multi-storied structures with long spans and low loads. Testing concluded that satisfactory serviceability is achievable with castellated beams up to a maximum depth of opening of 0.6D [12].

Wakchaure and Sagade [2012], Using ANSYS14 finite element software, this study examined the behavior of castellated steel beams with an I-shaped cross-section. The deflection at the center of the beam and various failure patterns were evaluated, together with a two-point load and a simply supported support condition. The study concluded that the castellated steel beam behaves satisfactorily up to a maximum web opening depth of 0.6h, with stress concentrations increasing as the depth of the opening increases. The study also found that the flexural stiffness of castellated beams decreases as the depth of the opening increases, but measures such as rounding hole corners and providing reinforcement can improve serviceability performance [13].

Ehab [2012], a nonlinear finite element model for simply supported cellular steel beams has been developed and verified against published tests. Parametric studies have been conducted on 120 cellular steel beams, showing the effects of cross-section geometries, beam length, steel strength, and slenderness on failure loads and buckling behavior. The findings show that for cellular steel beams failing in combined web distortional and web-post buckling modes. When the assumptions from the finite element model are compared to Australian Standards, it can be seen that they are quite conservative for high-strength cellular steel beams that fail by lateral torsional buckling and unconservative for cellular steel beams that fail by combined web distortional and web-post buckling [14].

Soltani et.al [2012], a numerical model was developed to predict the behavior of castellated beams with hexagonal and octagonal openings. The model accounts for material and geometric nonlinearities and was used in a parametric study to compare the ultimate load behavior of castellated beams with different openings. The results were compared with the design method presented in ENV1993-1-1 Annex N and found to be close and safe. The study concluded that thin webbed castellated beams with higher height web openings would fail by web-post buckling, and those with deeper tee-sections would fail by local buckling of the web. Castellated beams with intermediate plates were found to be more susceptible to web-post buckling, and their use should be restricted to certain beam classifications [15].

Kerdal and Nethercot [1984], the strength assessment of castellated beams considers two modes of failure, flexural mechanism formation, and lateral-torsional instability, similar to solid web beams. For unbraced beams, lateral-torsional instability leads to collapse, while laterally restrained beams collapse due to the formation of a flexural mechanism. Special failure modes occur when shear dominates, and reasonable strength estimates can be determined. A computer program can predict the load causing the formation of a Vierendeel mechanism, but no satisfactory method is available for predicting vertical buckling of the web post under concentrated loads or at reaction points [16].

Deflection and failure load of castellated beam along with their shape of openings

Sr. No.	Type of castellated beam (shape wise)	Depth of opening (mm)	Failure load by von-misses criteria (kN)	Deflection by FEA (mm)	Deflection by experiment (mm)
1	Hexagonal opening	0.6	30	1.3	1.36
2	Circular opening	0.73	32.5	1.85	1.82
3	Diamond opening	0.67	34	2.84	2.84
4	sinusoidal openings	0.55	34	1.594	1.42

III. CONCLUSION

In castellated beam, depth of opening increases then the flexural stiffness of castellated beams decrease. Increase in load causes beams to be failed in different failure mode, which resist them to take load up to their actual carrying capacity. So we cannot compare beams with different modes of failure directly for strength criteria. So by taking corrective measures (i.e. corners should be rounded, provision of reinforcement) we can expect improvement in performance of beam. And also it is possible to analyze castellated beams using ANSYS and ABAQUS software (finite element analysis) as the result is in good agreement with the result obtained in experimental work.

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