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REVIEW ON BEHAVIOUR OF CASTELLATED BEAM

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Abstract
This paper provides a comprehensive analysis of the behavior of steel castellated beams, which is currently an understudied area compared to conventional beams. Castellated beams feature various shaped openings in their web, including circular, hexagonal, rectangular, octagonal, and oval openings, introducing additional failure modes such as lateral-torsional buckling of web posts, shear force-induced buckling of web posts, formation of four plastic hinges around the corners of openings, and rupture of welded joints. The paper reviews both experimental and analytical work conducted on castellated steel beams. Furthermore, it examines the influence of different characteristics on the behavior of steel beams with web apertures, such as the type, size, and spacing of openings, aspect ratio, varying numbers of openings, and beam strengthening techniques.

Keywords*:* castellated beam , conventional beam, , Lateral-torsional buckling, conventional beam

Introduction

Since the 1940s, numerous researchers have been dedicated to finding innovative approaches to reduce the cost of steel constructions. One of the earliest methods employed during World War II was the utilization of steel beams with web openings. These beams allowed for increased stiffness of steel elements without adding extra weight. As a result, castellated and cellular beams, which feature web holes, have gained significant popularity. Integration of technical utilities, such as ventilation pipes and water conduits, through the web openings (depicted in Figure 1), has further contributed to their widespread use. Compared to the conventional arrangement where services are positioned beneath the beams, this integration reduces the clearance between the ceiling and the floor, consequently decreasing the building's height. However, in the case of castellated beams, the clear height increases by 0.5 per floor. The process of transforming a standard I-section beam with a depth (d) into a castellated beam involves slicing it in a manner that generates a consistent pattern of holes in the web, while increasing the section's depth (D). As illustrated in Figure 2, the web is flame-cut in a "Zigzag" pattern along the horizontal x-x axis, and the two resulting pieces are welded together, creating a beam with a larger depth and a hexagonal web opening. This increase in depth enhances the section modulus by 1.5 times, consequently improving the bending rigidity without adding extra weight. This feature renders the design lighter and more cost-effective. Despite the availability of alternative options such as stub girders and trusses, steel beams with web openings continue to be frequently employed in various structures such as office buildings, parking garages, shopping malls, industrial halls, sports arenas, and hospitals. These beams offer long clear spans and great flexibility for incorporating services when used as floor beams. This paper provides the most up-to-date insights into the behavior of steel beams with web openings under different failure modes. It addresses current issues and recommends potential areas for future research in this field. Furthermore, it aims to gather and critically evaluate the existing knowledge on the subject matter.

Literature

Hideo o Takabatake, et.al., (1991)- The researchers conducted a study to examine the lateral buckling behavior of an I-beam, comparing cases with and without web stiffeners. Stiffeners and batten plates were installed along the entire length of the beams. To prevent twisting and lateral translation, the beams

were securely fastened. The experimental findings demonstrated that the presence of web stiffeners and battens effectively delayed the occurrence of lateral buckling in the I-beams.

Fig 1(castellated Beam)

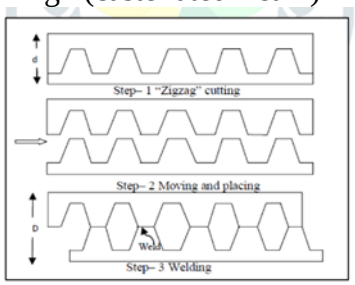

Fig 2 (Process of castellation battens delayed the lateral buckling of I beams

C.weng(2002)- An experimental investigation was conducted to examine the shear splitting failure in composite concrete encased steel beams. Nine full-scale specimens were constructed and subjected to testing. Among the tested specimens, five exhibited significant horizontal cracks, known as shear splitting failures, along the interface between the steel flange and concrete. The results of the experiments indicate that the occurrence of shear splitting failure in composite beams is primarily influenced by the steel flange width ratio, which is the ratio of the steel flange width to the gross section width. Based on the test results, it was observed that a composite beam tends to experience shear splitting failure when the steel flange width ratio reaches 0.67. Furthermore, the use of shear studs was found to be effective in preventing shear splitting failure in beams with high steel flange ratios. In addition to the experimental study, a novel approach for predicting the failure mode of composite beams is proposed. The proposed technique demonstrates accurate predictions when compared to the test results.

Finally, a new equation is developed to calculate the design of stirrups aimed at preventing shear splitting failure in naturally bonded composite beams. This equation provides guidance for the appropriate design of stirrups to ensure structural integrity. Sung

C. Lee, et. al.(2002) The buckling behavior of plate girders was investigated using three different numerical models in the ADINA program ("Automatic Dynamic Incremental Nonlinear Analysis", 1999). The models were evaluated with the inclusion of three stiffener plates. To analyze the buckling behavior of the shear web, a shear analogy model was employed. The results indicated that the presence of transverse stiffeners greatly enhances the strength of the beam's web. However, it should be noted that the stiffeners do not experience compressive forces.

Chung et al. (2003).- A comprehensive parametric analysis was performed to analyze and compare the load-carrying capacity of steel beams with web openings of different sizes and shapes. As a result, an empirical design method for steel beams with web openings was developed, utilizing a generalized moment-shear interaction curve. This paper presents the complete design method, along with detailed worked examples, to provide a comprehensive understanding of the topic. **Ellobody(2011)** - An extensive investigation was conducted to explore the interaction buckling failure mechanisms of castellated beams, considering both normal and high strength materials. The study involved six full-scale beams of varying length and depth. Numerical simulations were performed and subsequently validated through experimental testing. Additionally, a parametric analysis was carried out to evaluate the influence of beam length, cross-section geometry, and steel strength.

The findings indicate that the occurrence of web buckling significantly reduces the failure load of the beam. Moreover, the results demonstrate that the use of high strength steel enhances the failure load. Furthermore, it was observed that lateral torsional buckling is more likely to occur in normal strength castellated beams, whereas high strength castellated beams tend to exhibit web distortional buckling as a dominant failure mode.

M. R. Soltani et.al. (2011)- A comprehensive investigation was conducted to analyze the behavior of castellated beams with different opening shapes, including hexagonal and octagonal, using a nonlinear

numerical model. The depth of the opening was varied during a parametric analysis. The obtained numerical results were validated by comparing them to the existing literature using the MSC/NASTRAN program. Furthermore, the study examined the failure patterns of beams with various sizes.

Ehab Ellobody (2012)- A detailed analysis was conducted on castellated beams with circular openings using nonlinear analysis, considering various modes of buckling. The study focused on the behavior of beams with high strength, accounting for factors such as geometric imperfections, residual stresses, and nonlinear material properties. The nonlinear finite element method facilitated the prediction of deflection, failure modes, and loads leading to failure. The parametric study revealed that the failure of cellular beams is primarily attributed to the combined effects of web distortional and web post buckling modes, significantly reducing the failure load. In the case of high-strength cellular beams, both web distortion and web post buckling were observed, while lateral torsional buckling was observed in normal-strength cellular beams.

Wakchaure M.R et.al(2012) An ongoing parametric experimental study is being conducted to investigate the impact of different failure mechanisms on the depth of castellated beams with hexagonal web openings. The beams are subjected to a two-point load system for support. During the castellation process, the depth of the main beam is increased by 40%, 50%, and 60% with a hexagonal opening angle of 60 degrees. The experimental results reveal that as the depth increases, the moment carrying capacity also increases, and the castellated beam demonstrates satisfactory behavior up to a maximum depth increase of 40%, 50%, or 60% of the parent beam. To prevent local failure, it is recommended to include a transverse stiffener and reinforce the weak sections of the beam.

D. F. Erdal and M. P. Saka (2013) - The researcher conducted a study on the optimal loadcarrying capacity of a castellated beam with different numbers and spacings of holes. Using ANSYS software, the study investigated failure patterns and confirmed them through finite element modeling of beams subjected to centrally applied point loads. Despite the relatively short spans of the members, the study revealed that lateral supports play a crucial role in analyzing beams due to torsional buckling. Furthermore, when the load is applied above the opening, the beam fails in the Vierendeel mode, whereas when the load is applied on other portions, the beam fails due to web post buckling.

T.C.H. Liu and K.F. Chung(2013)- The researcher conducted an extensive finite element analysis on steel beams with various shapes and sizes of web openings. It was observed that when subjected to external loads, castellated steel beams with large web holes exhibit consistent behavior. At the point of failure, plastic hinges form at both ends of the openings. Among the parameters influencing the failure of castellated beams, the critical opening length plays a significant role. This critical opening length determines the magnitude of local Vierendeel moments acting on the castellated beam. The Vierendeel effect, which leads to Vierendeel failure of the beam, involves the transfer of vertical shear forces through the web openings, resulting in the generation of local bending moments. Additionally, the impact of fillet corner web opening dimensions on the load-carrying capacity of castellated structures is examined using the finite element method.

Jamadar and kumbhar (2015) - The research focused on a parametric study aimed at optimizing castellated beams with circular and diamond opening shapes. Two key factors were considered: the ratio of the overall depth of the castellated beam to the depth of the openings, and the ratio between the spacing of openings and the opening depth. Numerical models were developed using the ABAQUS finite element software, and the models adhered to the provisions outlined in Eurocode 3. The results indicated that the optimal dimensions for castellated beams with circular openings were achieved when the opening depth was 0.73 times the overall beam depth. For diamondshaped openings, the optimal dimensions were achieved when the total beam depth was 0.67 times the original beam depth. Furthermore, the castellated beams with diamond-shaped openings exhibited better strength characteristics compared to alternative opening shapes.

Mr. Dhanraj K. Shendge, Dr. B.M. Shinde (2015)- This review report presents a comprehensive approach and software program for optimizing the topology, size, and shape of castellated beams through the utilization of finite element analysis. The primary objective of this study was to determine the load carrying capacity of steel beams, specifically focusing on simply supported castellated beams that are susceptible to web post buckling. Finite element analysis is employed to assess the load carrying capacity of castellated beams, and parameter studies are conducted to examine cross-section categorization and compare the ultimate load behavior.

The research thoroughly investigates the load carrying capacity of castellated beams, with a particular emphasis on different types of openings. It is found that castellated beams with fillet corner openings exhibit a higher load carrying capacity compared to those with hexagonal or rectangular openings, assuming the same opening height. However, the load carrying capacity of castellated beams with fillet corner openings is lower than that of beams with circular openings. The study provides valuable insights into the load behavior of castellated beams and highlights the significance of various opening shapes in determining their load carrying capacity.

Richard Fras, Herman Parung (2016)- In their study, the researchers aimed to find the optimal opening angle and spacing between two openings in a hexagonal castellated beam using numerical modeling techniques. They considered three different opening angles (50°, 60°, 70°) and various opening spacings (6mm, 9mm, 12mm). Through their analysis, they obtained noteworthy results. The findings indicate that an opening angle of 60° and an opening spacing of 60mm yield the best outcomes for the hexagonal castellated beam. These optimal parameters resulted in a deflection at yield of 0.7867, a load at yield of 78.4812 KN, and a von-Mises stress of 247.4 MPa. These values signify the most favorable performance of the beam under the given conditions, as determined by the numerical modeling.

Resmi Mohan, Preetha Prabhakaran (2016)-In this study, the deflection of an ISMB 150 section steel beam was compared using finite element analysis, considering both beams with and without web holes. The analysis was performed using ANSYS14.5 software. The purpose was to examine the behavior of different beam configurations and their load-carrying capacity. The results obtained from the analysis revealed some significant findings. The castellated beam with a hexagonal opening exhibited superior load-carrying capacity and lower deflection compared to the solid beam and the steel beam with a circular opening (cellular beam). The numerical research showed that steel beams with hexagonal openings demonstrated higher loadcarrying capacity compared to solid beams and beams with circular openings. Moreover, it was found that the deflection of the beams can be further reduced by incorporating diagonal stiffeners along the shear zone of the web openings. This additional reinforcement helps to enhance the structural performance and decrease deflection in the beams with web holes. Overall, the study highlights the advantages of castellated beams with hexagonal openings in terms of load-carrying capacity and deflection, and suggests the use of diagonal stiffeners for improved performance.

Conclusion

By reviewing the above papers, it can be concluded that

1. Castellation is a straightforward process that doesn't require extra materials, which lowers the cost of building.
2. Perforated web steel beams with hexagonal, octagonal, square, or circular openings have undergone extensive research to determine the best dimensions for flexural behaviour.
3. The provision of stiffeners with the right dimensions and locations has been suggested, but very little work has been done to prevent the failure of castellated beams.
4. In addition to geometrical characteristics, it has been observed that the span length, material strength, number, form, and placement of the hole all influence how a castellated steel beam responds.

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