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Nonlinear Performance of Castellated Steel Beams: Influence of Web Openings and CFRP Stiffening

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Abstract: *A castellated steel beam (CSB) is created by cutting a conventional steel I-beam along its centerline in a zig-zag pattern and rejoining the segments to form hexagonal web openings, resulting in increased depth and improved structural efficiency. This configuration offers benefits such as reduced self-weight, enhanced load-carrying capacity, and a better strength-to-weight ratio. However, the increased depth can lead to failure mechanisms like web post-buckling and lateral-torsional buckling under loading conditions, necessitating the use of stiffeners for reinforcement. Mild steel (MS) stiffeners are commonly employed and have been shown to improve load capacity and reduce deflection, but they add considerable weight and are susceptible to corrosion. In contrast, Carbon Fiber Reinforced Polymer (CFRP) has emerged as a superior alternative due to its lightweight nature, high strength, and excellent corrosion resistance. Research indicates that CFRP stiffeners can effectively enhance the structural performance of CSBs by increasing strength and minimizing deflection without the limitations of MS. This review focuses on the behavior of CSBs with different stiffening materials and concludes that CFRP offers promising potential. It also highlights the need for further exploration of the nonlinear behavior of CSBs with various web opening geometries and CFRP strengthening for more optimized structural applications.*

Keywords: Castellated beam, Non-linear stiffeners behavior, CFRP

I. INTRODUCTION

Castellated beams are a type of structural steel beam that feature regularly spaced openings in the web, created by cutting a standard rolled I-section along a zigzag or hexagonal pattern and then welding the two halves together to form a deeper section. This modification increases the beam's moment of inertia and depth without significantly increasing its weight, making it an efficient solution for spanning long distances with enhanced flexural performance.The web openings, which may be hexagonal, circular, diamond, or rectangular, reduce the beam's self-weight and allow for easier passage of utilities through floor systems. Due to these advantages, castellated beams are widely used in industrial buildings, bridges, and commercial structures where both structural efficiency and utility coordination are critical. However, these openings introduce stress concentrations and disrupt the uniform distribution of internal forces. This makes castellated beams more susceptible to unique failure modes such as web-post buckling, shear buckling, and Vierendeel bending near the openings. To mitigate these issues, stiffeners or reinforcement methods such as Carbon Fiber Reinforced PolymerCFRP) wrapping are often employed.

Castellation processes

A CSB is made-up by flame cutting of a steel I-section beam in a particular pattern, typically using a computer numerical control (CNC) machine. The flame-cutting process results into two separate halves of the I-beam. The sections are then welded back together along the edges of openings and waste parts of the beam are removed, thus creating the beam with hexagonal holes and overall increased depth called as castellated beam [1]. Fig.1 (a-d) illustrates the step-by-step manufacturing process of castellated beams.

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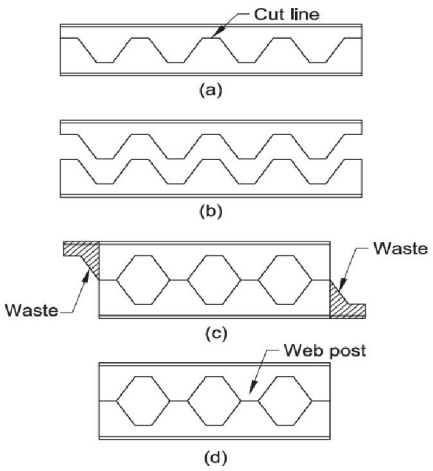

Fig.1(a-d) Castellation processes

Stiffeners

Stiffeners are elements incorporated in steel members to increase their ability to resist shear and bending force.The process of developing a CSB results into an increase in the overall beam depth and the load-carrying capacity of the beam. This increased depth can lead to the failure of CSB due to the mechanism of web post-buckling and lateral torsional buckling under the loading and hence the use of stiffeners becomes essential to strengthen against such failure mechanisms. While mild steel stiffeners (Fig.2) have been commonly used to reinforce steel beams, recent advancements have seen Fibre-Reinforced Polymers(FRPs) (Fig.3)increasingly adopted in the repair and strengthening of structural elements [2].

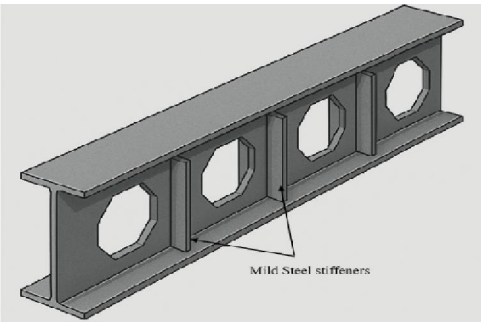

Fig.2 Mild steel stiffeners

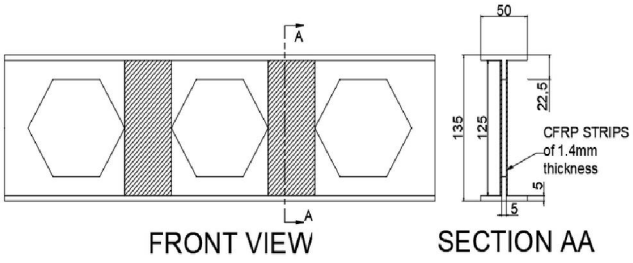

Fig.3 CFRP stiffeners

II. LITERATURE REVIEW

The research works published for several researchers in various national and international journals concerning the behavior of CSBs with different openings and without and with provisions of stiffeners is rigorously studied and presented in the following section.

Anupriya and Jagadeesan (2013) conducted a comprehensive numerical investigation using ANSYS 14 to evaluate the shear strength and deflection behavior of castellated steel beams (CSBs) featuring hexagonal web openings. Their study demonstrated that increasing the depth of the beam intensifies stress concentrations, particularly around the corners of the openings and at load application points. To mitigate these effects, they explored various stiffening strategies, including the use of diagonal stiffeners and a combination of diagonal and vertical stiffeners within the web. Among the configurations tested, the combined stiffener arrangement proved to be the most effective, resulting in the least deflection observed [3].

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Jamadar and Kumbhar (2015) carried out a series of parametric analyses on castellated steel beams (CSBs) incorporating circular and diamond-shaped web openings, utilizing ABAQUS software and adhering to the design provisions of EUROCODE 3. The objective was to optimize CSB geometry by evaluating the D/Do ratio (overall beam depth to opening depth) and the S/Do ratio (spacing between openings to their depth). Numerical results were validated through comparison with experimental data. The findings highlighted that diamond-shaped openings offer the highest strength when their size is approximately 0.67% of the beam's total depth. The study concluded that CSBs with diamond-shaped openings exhibit better performance than those with circular openings [4].

Kale et al. (2018) focused their study on the effect of different stiffener configurations in castellated or cellular beams, based on the geometry of the web openings. Due to the unique structural behavior and failure patterns of CSBs compared to conventional beams, both experimental and numerical analyses were conducted. Finite element simulations were performed using ABAQUS to predict critical load capacities for the tested specimens. The results demonstrated that incorporating diagonal stiffeners within the openings enhanced the load-bearing capacity by approximately 1 to 1.5%. The study concluded that CSBs with stiffeners provided on both sides exhibited greater strength than those with other stiffener types, including cross stiffeners placed inside the openings [5].

Elaiwi et al. (2019) have analytically and numerically studied the behavior of CSBs with a web of the opening effect of lateral-torsional buckling. Employing the principle of minimum potential energy for the analytical part, they used ANSYS for numerical analysis to capture elastic, inelastic, and nonlinear responses. The authors highlights that the lateral-torsional buckling response of CSBs is largely governed by parameters including the overall beam geometry, shape and arrangement of web openings, support conditions, and the mechanical properties of the material [6].

AL-Thabhawee and Mohammed (2019) conducted an experimental investigation on the performance of castellated steel beams (CSBs) with octagonal web openings, incorporating both circular and octagonal ring stiffeners for enhancement. The primary aim was to reinforce the web region and minimize the risk of failure due to web post-buckling. The findings revealed that the ultimate load capacity of beams strengthened with circular stiffeners increased by up to 188%, while those with octagonal ring stiffeners showed an improvement of 77.6% compared to the unstiffened beam. Based on the results, the study concluded that circular stiffeners offer superior strengthening performance over octagonal ring stiffeners [7].

Thomas and Baskar (2021) have experimentally investigated the behavior of thin-walled castellated beams (TCSBs) attached without and with CFRP strengthened. The study was conducted in two phases: the first phase involved examining the bond strength between the steel base and CFRP under different surface conditions and determining the ultimate load. The results show that the specimens prepared with copper-slag blasting may have had a stronger bond strength. The load-bearing capacity was enhanced in the plastic section and semi-compact section by 35.38% and 42.53% respectively. The authors conclude that the CSBs with CFRP strengthening is a better option [8].

Understanding the nonlinear behavior of castellated beams is essential for accurate structural analysis and design. Modern finite element tools like ABAQUS and ANSYSare often used to simulate these effects. Experimental studies also show that strengthening techniques, such as adding web stiffeners or CFRP wrapping, can improve the load-carrying capacity and delay the onset of nonlinear effects.

SUMMARY OF LITERATURE

Following are the research gaps identified through the rigorous literature review:

The majority of existing research has concentrated on analyzing the linear behavior of castellated steel beams (CSBs) using mild steel (MS) stiffeners to evaluate load-bearing capacity and deflection. In contrast, studies exploring the performance of CSBs with fiber-reinforced polymer (FRP) stiffeners remain relatively scarce.

Current literature predominantly examines linear responses under idealized or simplified loading scenarios, with insufficient emphasis on the nonlinear behavior of CSBs under realistic or complex loading conditions.

Only a few studies have explored the nonlinear performance of CSBs with different web opening geometries, such as hexagonal and diamond shapes, when strengthened with CFRP laminated stiffeners.

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