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Review on Structural Behaviour of Castellated Steel I-Beam using FRP Stiffeners

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Abstract - In recent years, castellated beams are widely used in structural applications due to their high strength to weight ratio. A castellated beam is fabricated from its parent solid I beam by cutting it in a zigzag pattern and again recollecting it by welding. This gives an increase in depth of beam which ultimately gives a high moment of inertia and load carrying capacity compared with the original solid I beam. However, this makes it weaker in web post buckling and stress concentration along the opening edges also increases. Studies show that use of stiffener for castellated beam reduces these failures and increases the load carrying capacity.

In recent years, fibre-reinforced polymer (FRP) composites are being used widely in Civil Engineering applications due to their distinctive advantages like high strength to weight ratio, excellent corrosion resistance, high fatigue resistance, etc. Especially, the use of FRP for strengthening existing steel structures has been increased considerably. The main objective of this paper is to review the available literature to forecast the scope of using various types of FRPs in strengthening the castellated beams.

Key Words: Castellated beam, Fibre-reinforced Polymer (FRP), Stiffeners, Web opening

1. INTRODUCTION

A castellated beam is a beam that has openings/perforations in its web portion. Castellated beams are provided with different types of perforations such as circular, hexagonal [Fig-1], diamond, or square in shape. The key advantage of using such beams is that it reduces the overall weight of the structure and therefore requires less quantity of steel material [1]. Castellated beams are typically used for power plants factory buildings, and multi-story structures where the load is usually less and the span is longer.

The presence of openings in the web portion of castellated beams is generally associated with the following modes of failures [2]:

i. Formation of Flexure Mechanism
ii. Lateral-Torsional Buckling
iii. Formation of Vierendeel Mechanism
iv. Rupture of the Welded Joint in a Web Post
v. Shear Bucking of a Web Post
vi. Compression Web Post Buckling

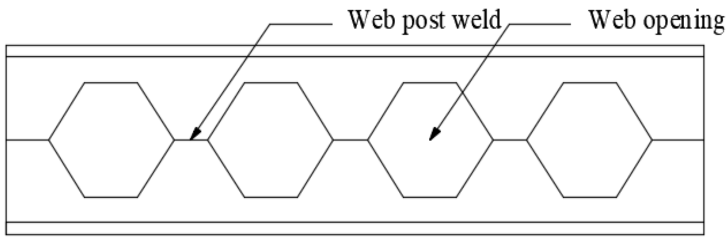

Fig -1: Hexagonal Castellated Beam

It is observed that these failure modes are avoidable with the placement of the stiffeners in beams at the appropriate position [3]. Stiffeners are secondary plates usually provided in a transverse, longitudinal direction or around the opening edges. Transverse stiffeners are mostly used to improve the resistance of webs of the beam to shear, whereas longitudinal stiffeners are mainly used to enhance the bending and shear strength of the beams [4].

The different types of stiffeners used for castellated beam and I-beam are intermediate transverse web stiffener, load-carrying stiffener, bearing stiffener, torsion stiffener, diagonal stiffener, and transverse stiffener. Sometimes, stiffeners are also used in the combined form [5].

Provision of steel stiffener in the castellated beam increases its weight and curtail one of its advantage that is the reduction in the total weight.

1.1 Fibre-reinforced polymer

Fibre-reinforced polymer (FRP) is made up of fibers embedded in polymer resin. In FRP, the fibers serve as reinforcement, and the polymer resin acts as a matrix to hold the fibers [6]. There are various types of fibers available and are mainly classified as natural fibers (such as flax, hemp, jute, ramie, etc) and synthetic fibers (such as aramid, basalt, carbon, glass, etc) [7].

The mechanical properties of commonly used synthetic fibers with steel are listed in Table 1.

Table -1: Mechanical properties of synthetic fibers compared with steel material.

Fiber	Density(Kg/m³)	Tensile strength (GPa)	Young's Modulus (GPa)	Reference
Aramid	1400	3-3.15	63-67	[7]
Glass	2500	4.57	86	
Basalt	2800	3.1-4.84	85-95	[8]
Carbon	1760	3.53	230	[6]
Steel S355	7850	0.50	210	

FRPs enhance the structural performance of civil engineering materials, specifically concrete and steel. They have excellent structural advantages, including high strength, anti-corrosion, and high durability properties [7].

Carbon fibre-reinforced polymer (CFRP) is commonly used advanced composite material used for strengthening the structures. Studies on the use of CFRP for strengthening of steel structures have been significantly increased in the recent years. Researchers have investigated the efficacy of shear strengthening of steel I-beam by using different CFRP ratios in the shear zone. The application of CFRP materials is beneficial for the local stiffening of I-beam steel. Appropriate use of CFRP for local stiffening causes a reduction in vertical deflection, mainly in the plastic zone. [9].

Properties of CFRPs seem promising for replacement with steel stiffeners. Hence, the potential of CFRP strips as stiffeners for the strengthening of the castellated beam needs to be explored.

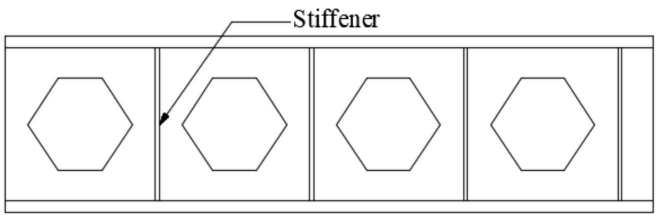

Fig -2: Hexagonal Castellated Beam provided with Stiffeners in Transverse Direction

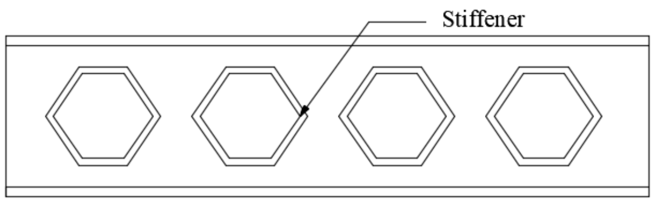

Fig -3: Hexagonal Castellated Beam provided with Stiffeners along Edge of Openings

2. LITERATURE REVIEW

Various research studies carried out for analysis and design of castellated beams with different openings and provided with and without the stiffeners are presented in the following section:

Armashiri et al. (2011) have carried out the experimental studies on the local stiffening of steel I-beams by using Carbon Fiber Reinforced Polymer (CFRP) strips. Four steel I-beams were selected and tested for failure to study the effects of applying CFRP to local stiffening. The results show that the use of CFRP on the compressive flange and web increased the load-bearing capacity by 20% relative to the non-strengthened beam and minimized the local and total deformations accordingly. Researchers have concluded that the use of CFRP for local stiffening results in an acceptable decrease in vertical deflection, especially in the plastic zone [9].

Yang and Lui (2012) have investigated the effect of inclined stiffeners on the load-carrying capacity of simply-supported hot-rolled steel I-beams under different load conditions. Results of the analysis showed that the potential benefits of the stiffeners were mainly related to their location on the beam. Researchers suggest that the potential benefit of the stiffeners is more significant for longer beams and where the vertical angle of inclination increases [4].

Teng et al. (2012) have rigorously reviewed the use of FRP in strengthening steel structures where the benefits of FRP are properly explored. Researchers concluded that external FRP confinement is an efficient reinforcement technique for circular steel tubes with or without concrete infill, but not so effective for square or rectangular columns. Also in FRP-strengthened steel structures, the weak bond in the adhesive layer caused the adhesive/steel interface failure and the FRP/adhesive interface can be evaded by adequate surface preparation [10].

Wakchaure et al. (2012) carried out experimental investigation on simply supported hexagonal castellated beam under two concentrated loading. Modes of failure of the castellated beam were studied at various depths of the openings. Researchers conclude that the castellated beam works in a satisfactory manner up to a maximum depth of 0.6 times the depth of beam (0.6D) and recommend that Vierendeel effects can be avoidable by strengthening the beam using stiffeners [2].

Jamadar and Kumbhar (2015) carried out a parametric analysis of castellated beams with circular (cellular beam) and diamond-shaped openings to optimize their size by taking into account the ratio of the total depth of castellated beam to the depth of opening given (D/Do) and the ratio of the opening spacing to the opening depth (S/Do) [Fig-4]. Results indicate that the beam with a diamond shape opening with an opening size of 0.67 times the total depth of the beam gives better strength results. The researchers have concluded that the castellated beam with a diamond shape opening has more load-carrying capacity than other shape openings [1].

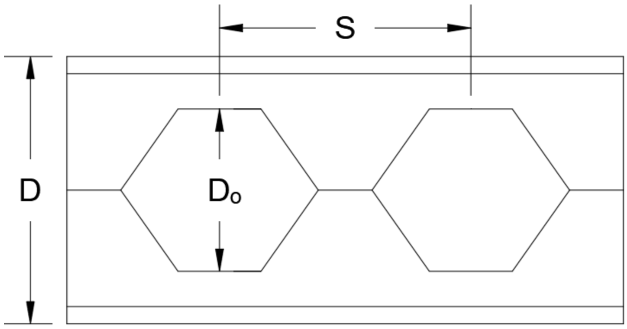

Fig -4: Front View of Castellated Beam [1].

Fatmir Menkulasi et al. (2015) have investigated the need for stiffeners in castellated beams under concentrated load. Several castellated beams provided with or without stiffeners and with varying depths are tested using a non-linear finite element analysis to analyze their failure behavior when subjected to point loads. Results have shown that load carrying capacity gets substantially improved when castellated beam sections are strengthened with stiffeners [3].

Patil and Kumbhar (2016) have analyzed the castellated beam using the transverse stiffeners and stiffeners around the opening edges. The study was carried out by placing the stiffeners along the transverse axis (transverse stiffeners) and around the edge of the openings for testing. The percentage of steel used for the transverse stiffeners was relatively low compared to the stiffeners provided around the edge of the opening. However, results were not appropriate for stiffeners provided around the opening in terms of load-carrying capacity, notwithstanding an increase in the percentage of steel. Therefore, researchers recommended the provision of transverse stiffeners instead of stiffeners around the opening edge [5].

Agrawal and Bhatt (2017) have compared castellated beams with solid I-beams for different design parameters of beam. By comparing the castellated beam with the solid I-beam, it is concluded that a higher section of the solid I-beam is required. Results show that by changing the welded length, the maximum stress occurs at 0.25 times the depth of the opening and the stress is less at a length of 0.33 times the depth of the opening. Researchers conclude that the welded length relies on the depth of the opening of a castellated beam [11].

Thabhawee and Mohammed (2019) carried out an experimental investigation on octagonal castellated steel beams with circular and octagonal ring stiffeners. The key finding in this analysis is that the use of ring stiffener has a significant effect on load-carrying capacity. It is observed that the use of circular ring stiffeners for strengthening octagonal castellated beams with expansion plates was more effective than the use of octagonal ring stiffeners [12].

Rajak et al. (2019) have rigorously reviewed the manufacturing, properties, and applications of fiber-reinforced polymer composites. Various changes have been made to the material properties of composite materials. There are various types of fibres are available for the manufacturing of fiber-reinforced composites, namely natural and synthetic. Researchers have concluded that synthetic fibers have more rigidity, whereas natural fibers are economical and eco-friendly [7].

Morkhade et al. (2020) have carried out a nonlinear numerical study of the castellated beam with reinforced web opening to examine the efficacy of the stiffeners provided around the openings. Results show that the strength of the castellated beams improves by 44 percent compared to the standard steel I-beam. The provision of stiffeners along the opening increases the strength of the castellated beam by 36% on average over an unreinforced opening. Researchers conclude that the provision of stiffeners along the openings can avoid a web buckling failure [13].

3. RESEARCH GAP

From the existing literature review, it is observed that a lot of studies have been carried out for analyzing the castellated beams by changing various parameters like the shape of openings, welded length, ratio of depth of openings to total depth, and angle of cut. The parametric studies reveal that, castellated steel beams are effective as a structural solution as compared to the conventional solid web beams. The advantage of this type of beam is its increased depth, which essentially results in a high moment of inertia and load-carrying capacity compared to the original solid I-beam. However, this makes it weaker in web post-buckling and the stress concentration along the opening edges also increases. To prevent these types of failure, strengthening of the beam by providing stiffeners at an appropriate location becomes essential. Several researchers have investigated the effect of steel stiffeners of different sections for strengthening the castellated beams; however, use of FRP (in the form of strips) as stiffeners for strengthening the castellated beams has not been yet reported.

The studies have also indicated that the FRPs have been used for structural repairing and strengthening. As, the available literature does not deal with the use of FRP stiffeners for enhancing the performance of the castellated beam it is necessary to study the behavior of the castellated beam using FRP strips as stiffeners at different locations.

4. CONCLUSION

Use of FRP for strengthening the castellated beams can be advantageous in view of reduction in the weight compared to the beams with steel stiffeners. Also, performance of the castellated steel I-beam with FRP strips as stiffeners would be advantageous in preventing the failure of the beam.

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BIOGRAPHIES

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