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Performance Analysis of Castellated Steel I-Beam using FRP Stiffeners

Kirti Pawar[1], Popat Kumbhar[2]
[1]Department of Civil Engineering, UG student, Rajarambapu Institute of Technology, Rajaramnagar, Maharashtra, India
[2]Department of Civil Engineering, Head of Department, Rajarambapu Institute of Technology, Rajaramnagar, Maharashtra, India

Abstract: Castellated beams are now widely used for a variety of structural applications. Castellated beams are the ones which have perforations in their web part. However, these perforations increase stress concentration around the openings, and also get subjected to web post-buckling. To reduce these post-buckling failures and increase the load-carrying capacity, the castellated steel I-beams are provided with different types of stiffeners at various locations. In this paper, the behaviour of a hexagonal castellated steel I-beam (ISMB) under point loading is investigated using carbon fibre polymer (CFRP) strips as stiffeners. Two different types of CFRP strip stiffeners are provided in the transverse direction and around the openings of the castellated beam. The finite element analysis of these stiffeners has been carried out by using ABAQUS software. The results show that the use of CFRP stiffeners for castellated beams enhances load-carrying capacity up to 20% and reduces the deflection by 12% as compared to the control castellated beam. The use of transverse CFRP stiffener reduces the web buckling failure and increases the load carrying capacity effectively as compared to the stiffeners used along the openings. As a result, it is preferable to use transverse stiffeners instead of the stiffeners used along of the openings.
Keywords: Abacus software, Castellated beam, CFRP, Openings, Transverse stiffeners

I. INTRODUCTION

This document is a template. For questions on paper guidelines, please contact us via e-mail.Castellated beams have been popular in structural applications in recent years due to their excellent strength-to-weight ratio. They give good structural appearance as well. Castellated beams are the beams that are provided with perforations in the web part by castellation process. The castellated beam is made from its parent solid I beam by cutting it in a zig-zag pattern and then welding it back together (Fig-1). This increases the depth of the beam, resulting in a greater moment of inertia and load-carrying capability as compared to the original solid I-beam. However, these perforations increase stress concatenation around the openings, and also it is subjected to web post-buckling. To reduce these failures and increase the load-carrying capacity of castellated steel I-beam, different types of stiffeners are used at various locations [1]. Strengthening the web along the opening edges is a good option for increasing the strength capability of castellated beams [2].

Following types of failures are commonly associated with presence of perforations in the castellated steel I-beam [3]:

1) Formation of Flexure Mechanism
2) Lateral-Torsional Buckling
3) Formation of Vierendeel Mechanism
4) Rupture of the Welded Joint in a Web Post
5) Shear Buckling of a Web Post
6) Compression Web Post Buckling

The study reveals that the provision of stiffeners at a proper location can potentially reduce these types of failures [1]. Stiffeners are additional plates that are often placed in a vertical, diagonal, or around the opening edges [4]. The inclusion of steel stiffeners in castellated beams increases their weight and negates one of its benefits, which is a reduction in total weight.

A. Fibre-Reinforced Polymer

Fibre-reinforced polymer (FRP) is a type of composite material. FRPs are two phase composites, one is matrix, which is continuous and other is dispersed phase, which is embedded in the matrix. In FRP, continuous aligned long fibres are embedded in the matrix called polymer resins. There are different types of FRPs such as Glass Fibre-reinforced Polymer (GFRP), Aramid Fibre-reinforced polymer (ARFP), Carbon Fibre-reinforced Polymer (CFRP), etc. However, the properties of CFRPs appear to be promising for replacing steel stiffeners [5]. As a result, the effectiveness of CFRP strips as stiffeners for strengthening castellated beam must be investigated.

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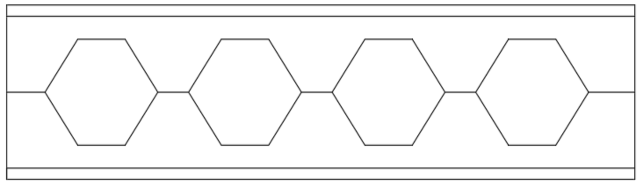

Fig. 1 Hexagonal Castellated Beam

II. LITERATURE REVIEW

Various research works related to the analysis and design of castellated beams with different types of perforations and stiffeners are carried out and are presented in the following section:

Armashiri et al. (2011) used CFRP laminates for the experimentation to evaluate the local stiffening of steel I-beams. Four steel I-beams were selected and tested for failure to investigate the influence of CFRP on local stiffening. The findings show that the application of CFRP on the web and compressive flange increases the load-bearing performance by 20% as compared to the original beam. Researchers have inferred that the provision of CFRP for local stiffening leads to a satisfactory reduction in vertical deflection, particularly in the plastic zone [6].

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. The results demonstrate that when castellated steel I-beam is reinforced using stiffeners, their load-bearing capacity improves significantly [1].

Morkhade et al. (2020) investigated the effectiveness of the stiffeners placed around the perforations in a finite element analysis of the castellated beam with strengthened web opening. The results reveal that the strength of castellated steel I-beam enhances by 44% compared to the original beam. Researchers inferred that providing stiffeners around the perforation can help to prevent web buckling failure [2].

A. Research Gap

Various research works have been carried out to analyze the castellated beams by altering several parameters such as the type of opening, welding length, a ratio of the depth of perforations to overall depth, and angle of cut. The studies show that the castellated steel I-beams are efficient as a structural solution than solid I-beams. The greater depth of this type of beam results in a high moment of inertia and load-carrying capacity as compared to the original solid I-beam. However, these perforations increase stress concatenation around the openings, and also get subjected to web post-buckling. This necessitate strengthening of the beams by providing stiffeners at key locations, to avoid the post buckling failure. Several studies have been carried out to determine the effectiveness of steel stiffeners of various sections on the strength of castellated beams; however, use of FRP stiffeners, in the form of strips, for strengthening castellated beams has not yet been reported.

According to the previous research, FRPs have been also used for structural repairing and strengthening. As, the existing literature does not address the use of FRP stiffeners to improve the performance of castellated beams, it is important to investigate the performance of these beams using FRP stiffeners.

III. PARAMETERS OF CASTELLATED BEAM AND STIFFENERS

A. Basic Terminology of Castellated Beam

The terminology used in the analysis and design of castellated beams is given in Fig 2.

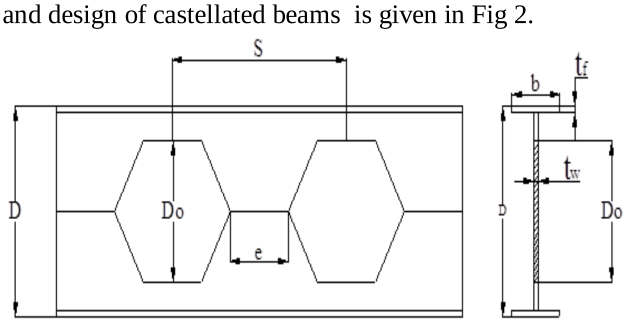

Fig. 2 Typical cross section of the beam [1]

Where,
D = Total depth of castellated beam
Do = Depth of the perforation
b = Width of the flange of castellated beam
S = Distance between the two perforations measured from centre to centre.
e = Clear distance between two perforations.
tf = Thickness of the flange of castellated beam
tw = Web thickness of the flange of castellated beam

B. Castellated Beam

The castellated beam of size 924 mm x 135 mm x 90 mm was fabricated with overall thickness of 5mm according to the guidelines provided by Euro Code 3 [7]. the D/Do of the castellated beam is maintained as 1.5 and S/Do is 1.7. Fig 3. shows the cross section specifications of the castellated beam analyzed by using CFRP stiffeners, in the form of strips.

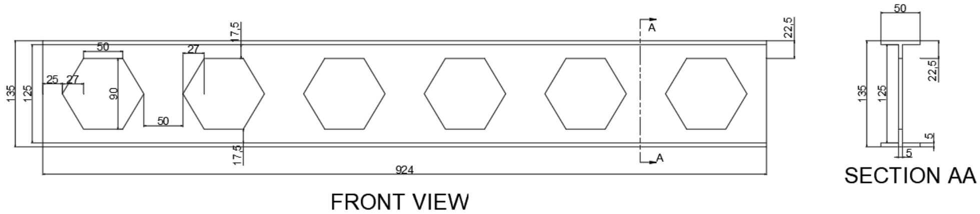

Fig. 3 Details of Fabricated castellated Beam

C. CFRP Stiffener

Euro Code 3 has provided a few standards for the provision of stiffeners [7]. There is currently no proper guideline and design for stiffeners of the castellated beam. It has been recommended that the stiffeners should be provided on both sides of the castellated beam and arranged in such a way that they are symmetric about the central axis of the web.
The provision of stiffeners can be done in various ways such as diagonal, transverse, longitudinal direction, or around the opening edges or they can also be used in combination. For this research work, CFRP strips have been used as stiffeners on castellated beams in a transverse direction to resist buckling failure and also around the openings of castellated beam to reduce the stress concentration. The behavioral study of castellated beams is carried out by varying the thickness of CFRP strips in the transverse direction and also along the opening for a specific width. The variation in the CFRP strip dimensions are given in Table 1.

TABLE I
Variations in the CFRP strip dimensions

Castellated beam with CFRP stiffener	Width (W), mm	Thickness (T), mm		
		T-1	T-2	T-3
Transverse direction	50	1.4	2.8	4.2
Along the opening	17.5	1.4	2.8	4.2

Fig. 4 and Fig. 5 shows the actual way of application of CFRP strips on castellated beam in transverse direction and along the edge of the openings respectively.

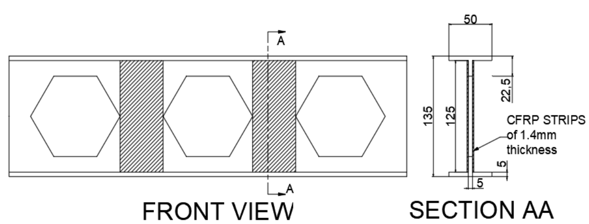

Fig. 4 Provision of transverse CFRP Stiffeners to castellated beam

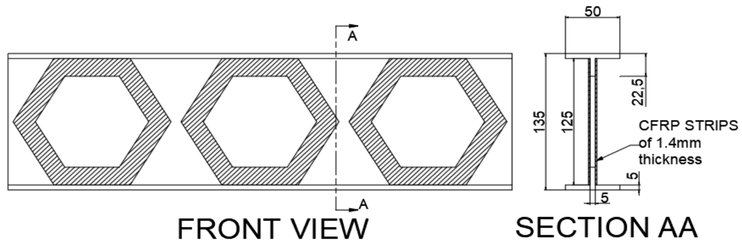

Fig. 5 Provision of CFRP Stiffeners to castellated beam along the edge of opening

IV. MATERIALS AND METHODS

Two castellated steel I-beams, one control beam and the other provided with transverse CFRP stiffeners (1.4mm thick), are tested under four-point loading test using digital universal testing machine (UTM) having loading capacity of 100 Tonne. These specimen are also analyzed using Abacus software to validate the experimental results. Details of the fabricated castellated beam and materials used are given below:

1) *Castellated Beam:* The castellated beam (924mm long) has been fabricated using parent ISMB mild steel beam (cross section 135mm x 50mm x 5mm). The material of the parent steel I-beam has yield strength of 250 MPa and elastic modulus of 200 GPa.
2) *CFRP:* Use of unidirectional CFRP material (brand name- Sika® CarboDur® S514/50) having elastic modulus of 165 GPa and mean tensile strength of 3100 MPa is done to strengthen steel castellated I-beam. The CFRP laminates, procured from 'Vihantechno', Ahmadabad, cut in the form of strips of 125mm x 50mm x 1.4mm size were used as stiffeners [8].
3) *Adhesive:* Araldite® AW 106 / Hardener HV 953 IN is used as adhesive for gluing the CFRP strips on the steel castellated I-beam. The adhesive has 1904.1MPa as its elastic modulus and 64.4 MPa as its flexural strength respectively[9].

V. FABRICATION AND TESTING

A. *CFRP Stiffener*

Fabrication of castellated beam involved following stages:

1) Preparation of DXF file
2) Cutting Specimen using plasma CNC machine
3) Grinding
4) Welding

In order to fabricate the castellated beam specimen of required dimensions and openings, a model was developed using AutoCAD software as per the designed cross-sectional details. The developed model (DXF file) was then transferred to the plasma CNC machine for the castellation process, in which the parent steel I-beam is cut in a zig-zag pattern by machine. The two separate halves of the parent steel I-beam were then aligned in such a way that the hexagonal openings get formed. After the alignment, electrode welding was done to fuse the two parts to make the castellated beam. The castellation process and the fabricated castellated beam with hexagonal openings are shown in the Fig. 6 and Fig. 7 respectively.

Fig. 6 Castellation Process (Cutting of I-beam using CNC machine)

Fig. 7 Final Specimen of castellated beam

Before the application of adhesive on the fabricated castellated beam, the beam surface was rubbed with sandpaper to create a proper bond between steel and CFRP. Then the surface of the beam was well cleaned. After this, the resin and hardener were properly mixed in appropriate proportions (Fig. 8) and a thin layer of this mixture was applied on both surfaces of the beam and then the CFRP strips of proper dimensions were applied on the beam at predefined locations (Fig. 9). Both materials were clamped and left overnight 24 hours for curing at a room temperature. After 24 hours, the castellated beam with CFRP strips was placed in the furnace for 1 hour by maintaining its temperature at 40°C, in order to get the adhesive fully dried and to also assure the proper bond between Castellated beam and CFRP strips.

Fig. 8 Mixing of resin with hardener

Fig. 9 Applying adhesive on castellated beam

Fig. 10 Final specimen of castellated beam with CFRP stiffener

B. Test Setup

In the laboratory, a two-point loading setup for testing of castellated beam was prepared. The schematic diagram of the set up is shown in the Fig. 11. The actual experimental set up for testing the beam is shown in the Fig. 12 and Fig. 13 for control castellated beam and the castellated beam provided with CFRP stiffeners respectively. The test was performed using the UTM. The deflections were noted after every 4kN increment of load till the load was reached to the ultimate point.

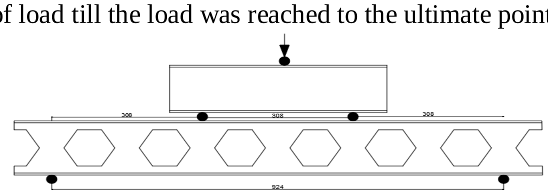

Fig. 11 Schematic diagram of two point loading test

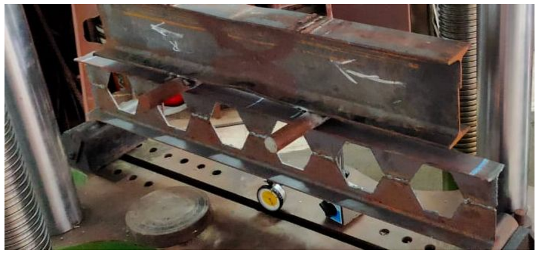

Fig. 12 Test set up of control castellated beam

Fig. 13 Test set up of hexagonal castellated beam with transverse CFRP stiffeners

VI. ANALYSIS OF CASTELLATED BEAM USING ABACUS SOFTWARE

The experimental results as obtained by testing the control castellated beam (i.e. without CFRP stiffeners) and the beam provided with CFRP stiffener are validated by analytical results obtained by Abacus software. After ensuring the validation of experimental results with software results, the analysis of castellated beams was carried out by developing its models by considering different locations of CFRP strips (in transverse direction and along the openings) and changing the strip thickness. The steps involved in the software analysis of the developed models are shown in Fig. 14.

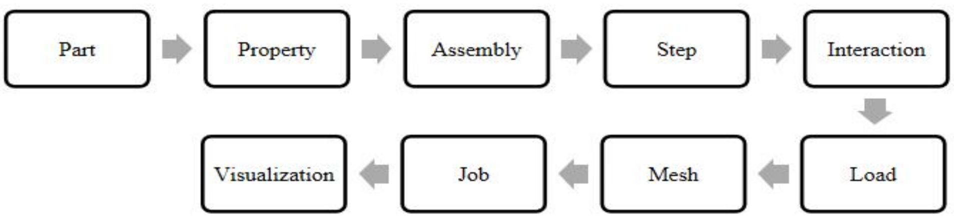

Fig. 14 Flow chart of FEM in Abaqus

VII. RESULTS AND DISCUSSION

The experimental and software results for the load carrying capacity and deflection as obtained in the control castellated beams and beam with CFRP stiffeners obtained are presented in Table 3. Table-3

Table 3
Comparative behavior of control castellated beam and castellated beam with CFRP stiffeners

Type of castellated beam		Control beam	Beam with transverse CFRP stiffeners	Error (%)
Load carrying capacity (kN)	Expt.	38.2	45.3	2.4
	Software	39.1	46.5	2.2
Deflection (mm)	Expt.	1.91	1.68	4.8
	Software	2.00	1.62	3.6

From Table 3., it is seen that the experimental and software results with respect to the load carrying capacity and deflection in the both types of castellated beams (i.e. control and with CFRP stiffeners) are approximately same with an average error of 2.3% and hence it confirms the validation of experimental results. The stress and deflection variations in the control castellated beam and beam provided with CFRP stiffener in transverse direction is shown in Fig. 15 to 18.

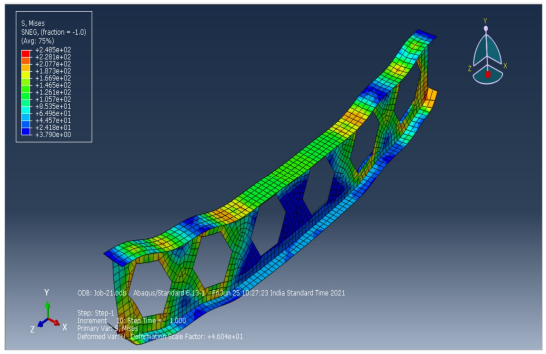

Fig. 15 Stresses in control castellated beam

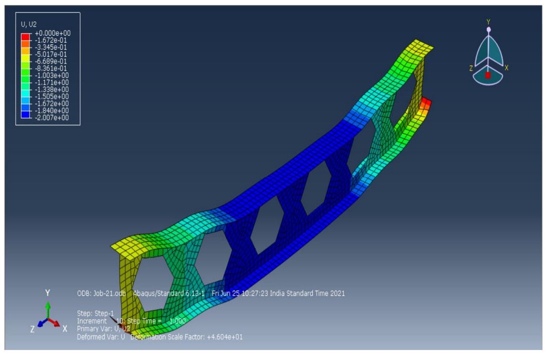

Fig. 16 Deflection of control castellated

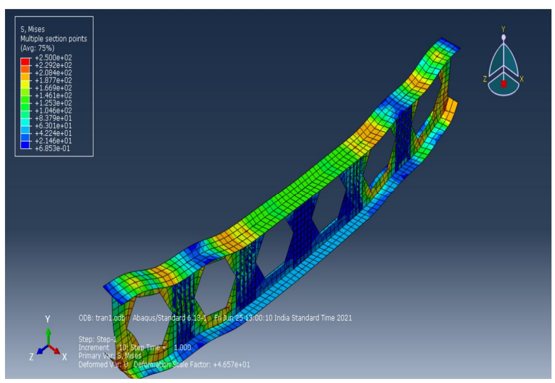

Fig. 17 Stresses in castellated beam with transverse CFRP stiffeners

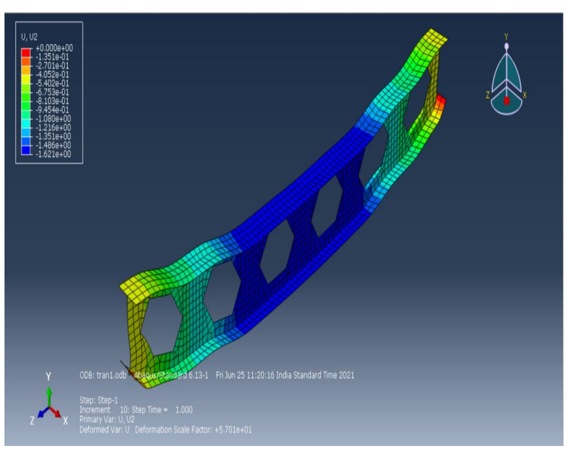

Fig. 18 Deflection of castellated beam with transverse CFRP stiffeners

A. Experimental results of Control Castellated Beam and Castellated beam with transverse CFRP stiffeners

The load vs deflection curve plotted for control castellated beam and beam provided with CFRP stiffeners in transverse direction is shown in Fig. 19.

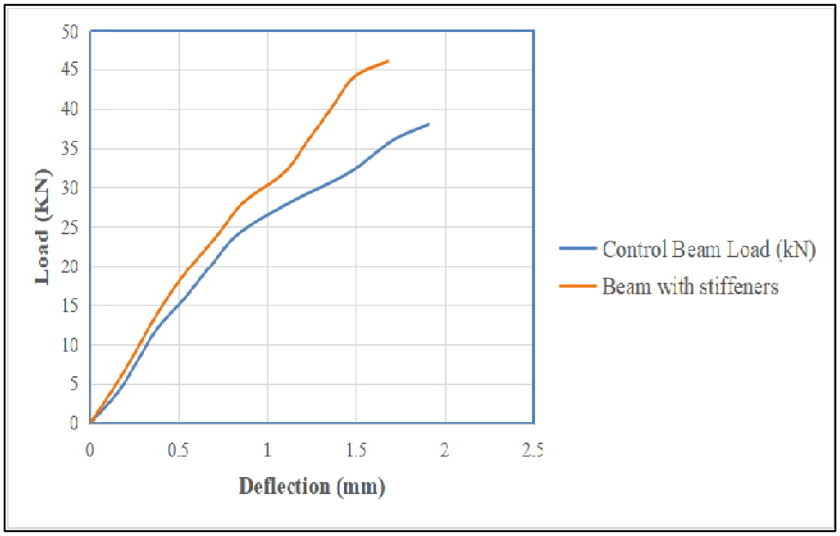

Fig. 19 Load vs. Deflection curve for control castellated beam and castellated beam with CFRP stiffeners

From the load vs deflection curve, it is observed that the castellated beam with CFRP stiffeners shows lesser deflections.7.2 Results of software analysis for castellated beam with CFRP stiffeners in transverse direction and along the opening The results of software analysis for castellated beam with CFRP stiffeners in transverse direction and along the openings by varying the stiffener (strip) thickness for a specific width are presented Table 4.

TABLE 4
LOAD CARRYING CAPACITY OF CASTELLATED BEAM USING CFRP STIFFENERS

Castellated beam with CFRP stiffener	Load carrying capacity for different thickness of the CFRP stiffeners (kN)		
	T-1 (1.4mm)	T-2 (2.8mm)	T-3 (4.2mm)
Transverse direction	46.5	49.7	51.2
Along opening	44.6	48.4	49.9

Fig. 20 presents a plot of load vs thickness of CFRP stiffeners giving variation in the load carrying capacities of castellated beams provided with CFRP stiffeners for different thicknesses.

From the Fig. 20 it is observed that, the load carrying capacity of castellated beams increases as the thickness of CFRP stiffeners increases. However, the load carrying capacity of the castellated beams provided with CFRP stiffeners in transverse direction is found to be more as compared to the beams provided with CFRP stiffeners along the openings.

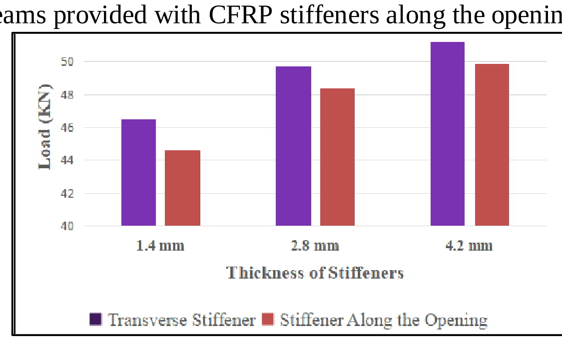

Fig. 20 Comparison of Load Carrying Capacity of Beam using Transverse CFRP Stiffeners and CFRP Stiffeners along the opening

VIII. CONCLUSION AND FUTURE SCOPE

A. Conclusion

Following are the conclusions drawn from the study:

1) The experimental results obtained for load carrying capacity and deflection of castellated beam get validated with results of Abacus software.
2) The use of CFRP stiffeners for castellated beams enhances load-carrying capacity up to 20% and reduces the deflection by 12% as compared to the control castellated beam. Thus, the CFRP strips can be used effectively as stiffeners for castellated beams.
3) The provision of transverse CFRP stiffeners to the castellated beam minimizes web buckling failure and, as a result, enhances load-carrying capacity. However, the provision of CFRP stiffeners along the opening reduces stress concentration around the opening, but does not contribute effectively in increasing the load-carrying capacity as compared to the transverse stiffener. Thus, the performance of transverse stiffeners is proved to be better as compared to the performance of stiffeners used along the openings.

B. Future Scope

A thorough investigation of the use of CFRP strips as stiffeners for various types of castellated beams provided with different shapes of openings needs to be studied.

REFERENCES

[1] Fatmir Menkulasiel et al. “Investigation of stiffener requirements in castellated beams” in Proc. Annual Stability Conf. Structural Stability Research Council Nashville, Tennessee, March 24-27, 2015.
[2] Samadhan G. Morkhade, Mrunmayi U. Chavan., “Structural behaviour of castellated steel beams with reinforced web openings.” Asian Journal of Civil Engineering, vol. 21, 1067-1078, 2020.
[3] Wakchaure M.R., Sagade A.V and Auti V. A., “Parametric study of castellated beam with varying depth of web opening.” International Journal of Scientific and Research Publications, vol. 2, no. 8, pp. 1-5, 2012.
[4] Yang Yang and Eric M. Lui, “ Behavior and design of steel I-Beams with inclined stiffeners” Steel and Composite Structures, vol. 12, no. 3, pp. 183-205, 2012.
[5] Rajak et al. “Fiber-Reinforced Polymer Composites: Manufacturing, Properties, and Applications” Article in Polymers, vol. 11, pp. 1667, 2019.
[6] Kambiz Narmashiri, Mohd Zamin Jumaat and N.H. Ramli Sulong, “Local Stiffening of Steel I-Beams by Using CFRP Materials.” Advanced Materials Research, Vols. 163-167 , pp. 3838-3843, 2011.
[7] EC3. Euro code 3: Design of steel structures part1-1, General rules for buildings. London (UK), British standard institution BS EN 1993-1-1,2005.
[8] Sika CarboDur® S, “ Pultruded carbon fiber plates” Product Data Sheet., 2014.
[9] Huntsman Advanced Material, “Araldite® AW 106 / Hardener HV 953 IN” Technical Data Sheet., 2010.
[10] Siddheshwari A.P and Popat. D.K., “Comparative Study of Transverse Stiffeners and Stiffeners along the Opening Edge used for Castellated Beam.” International Journal of Innovative Research in Science, Engineering and Technology, ISSN (Print) : 2347-6710. 2015.
[11] Liu et al., “Carbon Fiber Reinforced Polymers for Cable Structures - A Review” Polymers Journal,2015.
[12] Kim et al., “The effect of Moisture Absorption and Gel-coating Process on the Mechanical Properties of The Basalt Fiber Reinforced Composite” International Journal of Ocean System Engineering, 2011.
[13] J.G. Teng , T. Yu and D. Fernando, “Strengthening of steel structures with fiber-reinforced polymer composites.” Journal of Constructional Steel Research 78 (2012) 131–143. 2012.
[14] Vimleshkumar Agrawal and Darshna Bhatt, “A Design Comparison of Castellated Beam For Different Parameters.” Conference Paper, 2017.
[15] H W Al-Thabhawee and A Mohammed., “Experimental study for strengthening octagonal castellated steel beams using circular and octagonal ring stiffeners.” International Conference on Civil and Environmental Engineering Technologies, 012063. 2019.
[16] Jamadar A. M. and Kumbhar P. D., “Parametric Study Of Castellated Beam With Circular And Diamond Shaped Openings.” International Research Journal of Engineering and Technology, p-ISSN: 2395-0072. 2015.
[17] Pachpor P.D. et al. “Analysis and Design of Cellular Beam and its Verification” International Conference on Applied Computing, Computer Science, and Computer Engineering, 2014.