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Parametric study of castellated beam with coupled stiffener

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ABSTRACT

The castellated beam is artificial from its parent solid I beam by cutting it in a zigzag pattern and again amalgamation it by welding so that the depth of the beam increases. Therefore, due to an increase in depth of beam load carrying capacity of the parent I section is greater than before with the same quantity of material. The increase in depth of the castellated beam leads to web post-buckling and lateral torsional buckling breakdown when these beams are subjected to loading. Generally, the opening provided for castellated beams are hexagonal shaped openings, which are dispersed at regular intervals on the web portion of the castellated beam. Castellated beams are comprehensively used as flexural members in steel construction. The inexpensive and structural advantages of these rudiments have prompted many researchers to investigate the failure performance of such structures. In this paper steel I section ISMB 150 is selected, castellated beams are fabricated with an increase in the thickness of stiffener and stiffener is provided between the two openings and beam is analyzed with the help of Finite Element Analysis (ABAQUS) software. Experimental testing is conceded out on beam with two points loading. The deflection at the centre of the beam and various failure patterns are studied. The prevalent use of castellated steel beam as a structural constituent has prompted several explorations in their structural behaviour. The aim of this manuscript to find out increase or decrease the load carrying capacity of the optimized stiffener is provided within the hexagonal opening of the castellated beam. Study shows that the use of stiffeners in the web portion of the beam helps in minimizing these failures.

Keywords— *Castellated Beam, Stiffener, Finite Element Analysis*

1. INTRODUCTION

Engineers are constantly trying to improve the materials and practices of design and construction. One such improvement occurred in built-up structural members in the mid-1930, an engineer working in Argentina, Geoffrey Murray Boyd, is castellated beam. Castellated beams are such structural members, which are made by flame cutting a rolled beam along its centerline and then rejoining the two halves by welding so that the overall beam depth is increased by 50% for improved structural performance alongside bending. Since the Second World War, many attempts have been made by structural engineers to find new ways to decrease the cost of steel structures. Due to limits on smallest amount allowable deflection, the high strength properties of structural steel cannot always be utilized to best advantage. As a result, several new methods aimed at increasing stiffness of steel member, without any increase in weight of steel required. The castellated beam is one of the best solutions.

The re-routing of services (or increasing the floor height at the design stage for accommodating them) leads to additional cost and is generally unacceptable. The provision of beams with web openings has become an acceptable engineering practice and eliminates the probability of a service engineer cutting holes subsequently in inappropriate locations. Beams with web openings can be competitive in such cases, even though other alternatives to solid web beams such as stub girders, trusses etc are available. This form of construction maintains a smaller construction depth with the placement of services within the girder depth, at the most appropriate locations. The introduction of an opening in the web of the beam alters the stress distribution within the member and also influences its collapse behaviour.

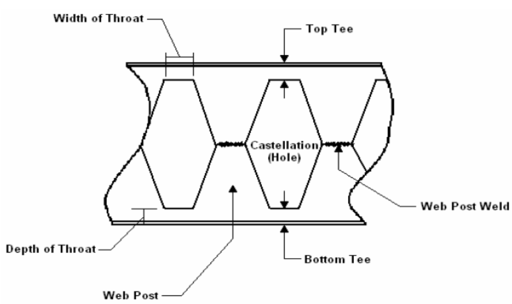

Fig. 1: Terminology

- **Web Post:** The cross-section of the castellated beam where the section is assumed to be a solid cross-section.
- **Throat Width:** The length of the horizontal cut on the root beam. The length of the portion of the web that is included with the flanges.
- **Throat Depth:** The height of the portion of the web that connects to the flanges to form the tee section.

In steel structures, the concept of the pre-engineered building (PEB) is most popular due to its ease and simplicity in the construction. Pre-engineered buildings have very large spans but moderately less loading. Generally, steel section satisfies strength requirement, the difficulty is that section contains to satisfy serviceability obligation i.e. deflection criteria in safety check. This necessitates the use of beams with greater depth to satisfy this requirement. Use of castellated beams is the best solution to overcome this difficulty. The castellated or perforated web beam is the beam which has perforation or openings in its web portion. Generally, the openings are with hexagonal or square or circular in shapes. The beams with circular openings are called cellular beams. The advantage of using such beams is that it causes a reduction in the total weight of the structure and hence requires less amount of steel. Use of castellated beam with the hexagonal opening is very common in recent years because of the simplicity in its manufacture.

Castellated Beams: Castellated beams are classified according to their shape of openings provided in the web portion. Most common shapes for the openings are hexagonal, circular also called cellular opening, octagonal, diamond, etc. However, due to simplicity in fabrication mostly hexagonal and circular openings of beams are used in industries. Also, most of the research on the optimization of the hexagonal and circular shape is done. Following figures give an idea about openings provided for the castellated beam.

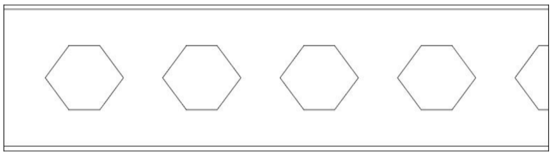

Fig. 2: Castellated Beam with Hexagonal Shaped opening

Stiffeners: The stiffener is those structural components which are used to strengthen shear and moment resistance of steel plates along the longitudinal, Coupled or/and along the edge of the opening. But if the castellated beams are subjected to concentric loading (for example Gantry girders) in such case castellated beam prove to be inappropriate. In such cases, castellated beams must be reinforced at the places where these load concentrations occur. For example by inserting plates called as stiffeners, into one or more of the web openings by additional fitting and welding work. It is observed that there is no regulated knowledge of how a beam with web openings would behave if a stiffener is placed.

2. LITERATURE REVIEW

2.1 Shear buckling behaviors of web-post in a castellated steel beam

Shear buckling behaviors of web-post in a Castellated Steel Beam (CSB) with hexagonal web openings under vertical shear were investigated using the finite element method. Through treating the upper part of the web-post as a free body under horizontal shear force, whose shear buckling strength can be calculated by the thin-plate shear buckling theory, design equations for the vertical shear buckling strength of the web-post were proposed. Parameters that affected the vertical shear buckling strength of the web-post were studied, which were the opening height to web thickness ratio h0/tw, the web-post width to web thickness ratio e/tw, the web height of Tee section above the opening to the web thickness hf/tw, the web thickness tw and the incline angle of the opening edge α. After obtaining the vertical shear buckling strength of a CSB through finite element model, the shear buckling coefficient k can be obtained through inverse analysis. Research results showed that k decreased nonlinearly with the increase in e/tw and hf/tw and it increased linearly with the increase in α and h0/tw. Practical calculating method for k was proposed based on parameter analysis results. The vertical shear buckling strength of the web-post calculated using the proposed shear buckling coefficient k agreed well with that obtained from the finite element simulation. For the proposed method was based on the elastic buckling of the web-post, it overestimated the shear buckling strength when the web-post buckled in the elastic–plastic state.

2.2 A comprehensive FE parametric study

In recent years, researchers study alternative connection designs for steel seismic-resistant frames by reducing the beam section in different ways including that of creating an opening in its web (RWS connections). A similar design is applied in the fabrication of perforated (i.e. cellular and castellated) beams mostly used to support the service integration, as well as the significant mass reduction in steel frames. This paper presents a comprehensive finite element (FE) analysis of extended end-plate beam-to-column connections, with both single and multiple circular web openings introduced along the length of the beam while subjected to the cyclic loading proposed by the SAC protocol from FEMA 350 (2000). The three dimensional (3D) FE solid model was validated against FE and experimental results and the chosen configuration was capable of representing the structural behaviour of a partially restrained connection, without the necessity to be idealized as fully fixed. The study focuses on the interaction of such connections and the mobilization of stresses from the column to the perforated beam. The parameters introduced were the distance from the face of the column, S, and the web opening spacing, So, with closely and widely spaced web openings. It is found that RWS connections with cellular beams behave in a satisfactory manner and provide enhanced performance in terms of the stress distribution when subjected to cyclic loading. The design of partially restrained RWS connections should be primarily based on the distance of the first opening from the face of the column.

2.3 Stiffener

Now-a-days the use of castellated beam has been admired due to its beneficial functions like a light in weight, easy to erect, economical and stronger. The castellated beam is manufactured from its parent solid I beam by cutting it in a zigzag pattern and again joining it by welding so that the depth of the beam increases. Hence, due to the increase in depth of beam load carrying capacity of the parent I section is increased with the same quantity of material. The increase in depth of the castellated beam leads to web post buckling and lateral torsional buckling failure when these beams are subjected to loading. There are many other modes of failure like the formation of flexure mechanism, lateral torsional buckling, and formation of vierendeel mechanism, rupture of the welded joint in a web post and shear buckling of a web post which needs to be taken care of. Study shows that the use of stiffeners in the web portion of the beam helps in minimizing these failures. Therefore, a detailed study in respect of a number of stiffeners, size of stiffener and there locations in the web portion of the castellated beam needs to be carried out. Hence, in the present paper, an attempt has been made to review existing literature, concerned with the strength of a beam using stiffeners. The literature survey indicates that the use of stiffeners in the web portion of castellated beams helps in increasing the strength and also minimizing the deflection. Researchers have suggested using stiffener along the edges in order to reduce the stress concentration along openings.

2.4 Ultimate load carrying capacity of optimally designed steel cellular beams

The objective of the current research is to present the ultimate load carrying capacities and finite element analysis of optimally designed steel cellular beams under loading conditions. The tests have been carried out on twelve full-scale non-composite cellular beams. There are three different types of NPI_CB_240, NPI_CB_260 and NPI_CB_280 I-section beams, and four tests have been conducted for each specimen. These optimally designed beams which have beginning span lengths of 3000 mm are subjected to point load acting in the middle of the upper flange. The design method for the beams is the harmony search method and the design constraints are implemented from BS 5950 provisions. The last part of the study focuses on performing a numerical study on steel cellular beams by utilizing finite element analysis. The finite element method has been used to simulate the experimental work by using finite element modeling to verify the test results and to investigate the nonlinear behavior of failure modes such as web-post buckling and Vierendeel bending of steel cellular beams.

2.5 Experiments on elastically braced castellated beams

Castellated beams are widely used as flexural members in steel construction. The economical and structural advantages of these elements have prompted many researchers to investigate the failure behavior of such structures. Despite numerous reported researches on the buckling stability of castellated beams, no experimental study is found on lateral–torsional buckling of these elements with elastic bracing. In this paper, the experimental study of nine full-scale castellated beams is reported with the aim of investigation of the performance as well as the effect of elastic bracing on the buckling stability of these structural elements. In addition to the presentation of the experimental observations and findings, the current test results are compared with the results of other reported experimental, analytical and numerical studies. Ultimately, the experimental findings and results are evaluated by considering the AISC 360–05 code requirements and predictions.

3. MATERIAL AND METHODOLOGY

For achieving the aims and objectives of the given research, the following methodology was used:

(a) For studying the behaviour of Castellated beams reinforced with stiffeners, the different shape web openings which were considered as below;
- Rectangular Shape
- Circular Shape
- Diamond Shape

(b) The stiffener used in the web portion were of Double Vertical Stiffeners types

(c) Initially, all the castellated beams were modeled in ABAQUS Software with double stiffeners reinforced in the web region.

(d) After carrying out the buckling analysis of all the models, the beam models compare with & without stiffeners.

3.1 Methodology

3.1.1 Guidelines for stiffeners according to Euro Code

(a) According to Euro code 3, the stiffener should be provided at:
- Area of stiffener should be equal to $30\mathcal{E}t_w$ provided at spacing $15\mathcal{E}t_w$.
- If $15\mathcal{E}t< S$ then we can provide it at the middle of the clear distance between two openings.

(b) End stiffeners and stiffeners at internal supports should normally be doubled sided and symmetric about the centerline of the web.

(c) Stiffeners at locations where significant external forces are applied should preferably be symmetric.

3.1.2 Selection of method of analysis

In order to optimize the dimension of the stiffener of the castellated beam, it is very important to decide the proper analytical method. Due to the complex geometry of the castellated beam the finite element analysis (FEA) is the best available to analyze the beam. FEA is done by the simulation software “ABAQUS/CAE 6.13”.

3.1.3 Selection of section for parent Hot Rolled Steel (HRS) I beam

Considering the market availability, economy and inspecting the practical difficulties during the testing section of the span was chosen. The span of the section chosen is 1000mm and also by considering the capacity of UTM (1tone) the section was not chosen of greater depth.

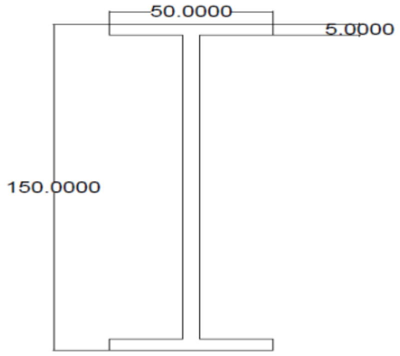

Fig. 3: Cross section of the parent I beam

4. EXPERIMENTAL SETUP

The specimens were tested in a servo-hydraulic Dennison8032 test machine with a maximum capacity of 1000 KN, subjected to either a two-point bending set up. The clear span was 1.0 m and the loading points were 333.33 mm apart for the four-point bending tests. The schematic test setup for the two-point bending case is shown in Fig. 4. The specimens were supported on two saddle supports, which allowed the specimens to behave in a simply supported manner, but which also limited the amount of longitudinal and transverse movement that could develop during the test.

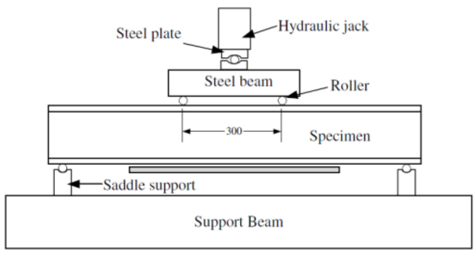

Fig. 4: Schematic Two -Point bending setup

4.1 Experimental performance

Fig. 5: Without Stiffener

Fig. 6: With FRP Stiffener

Fig. 7: With FRP (Glass) Stiffener

Fig. 8: With Steel Stiffener

5. RESULTS AND ANALYSIS

5.1 Analytical for hexagonal opening with and without coupled stiffener

(a) Hexagonal opening without coupled stiffener

Table 1: Result for load carrying capacity of model without stiffener

Hexagonal						
S. no	Names	Thickness (mm)	Width (mm)	Area (mm^2)	Load (KN)	Ratio of load to area in percentage
1	0 X0	0	0	0	45.754	-

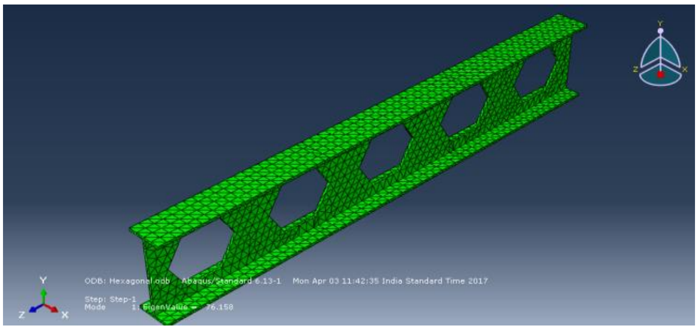

Fig. 9: Result for load carrying capacity of model without stiffener

(b) Hexagonal opening with coupled FRP stiffener

Table 2: Result for load carrying capacity of model with stiffener (1mm)

Hexagonal opening with FRP stiffener						
S. no	Names	Thickness (mm)	Width (mm)	Area (mm^2)	Load (KN)	Ratio of load to area in percentage
1	1 X 10	1	10	10	45.955	4.60
2	1 X 20	1	20	20	46.248	2.31
3	1 X 30	1	30	30	46.476	1.55
4	1 X 40	1	40	40	46.679	1.17
5	1 X 50	1	50	50	48.328	0.97

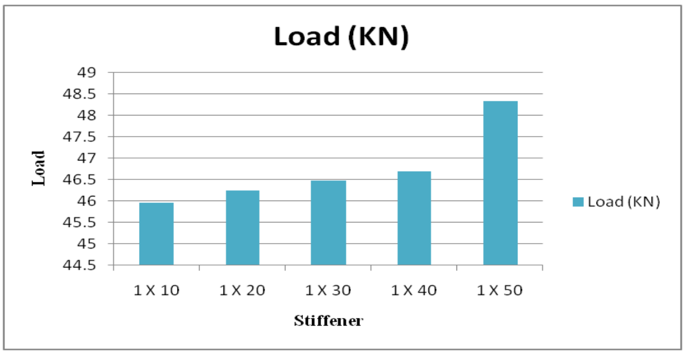

Fig. 10: Result for load carrying capacity of model with stiffener (1mm)

Table 3: Result for load carrying capacity of model with stiffener (1.67 mm)

Hexagonal opening with FRP stiffener						
S. no	Names	Thickness (mm)	Width (mm)	Area (mm^2)	Load (KN)	Ratio of load to area in percentage
1	1.67 X 10	1.67	10	16.7	46.128	2.76
2	1.67 X 20	1.67	20	33.4	46.822	1.40
3	1.67 X 30	1.67	30	50.1	46.886	0.94
4	1.67 X 40	1.67	40	66.8	47.19	0.71
5	1.67 X 50	1.67	50	83.5	47.542	0.57

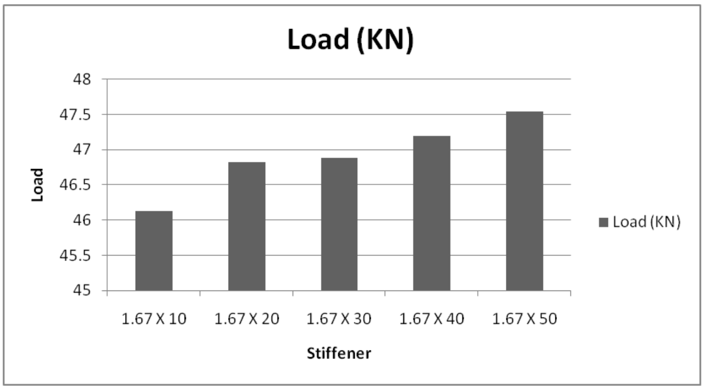

Fig. 11: Result for load carrying capacity of model with stiffener (1.67mm)

Table 4: Result for load carrying capacity of model with stiffener (2mm)

Hexagonal opening with FRP stiffener						
S. no	Names	Thickness (mm)	Width (mm)	Area (mm^2)	Load (KN)	Ratio of load to area in percentage
1	2 X 10	2	10	20	46.181	2.31
2	2 X 20	2	20	40	46.619	1.17
3	2 X 30	2	30	60	47.065	0.78
4	2 X 40	2	40	80	47.444	0.59
5	2 X 50	2	50	100	47.855	0.48

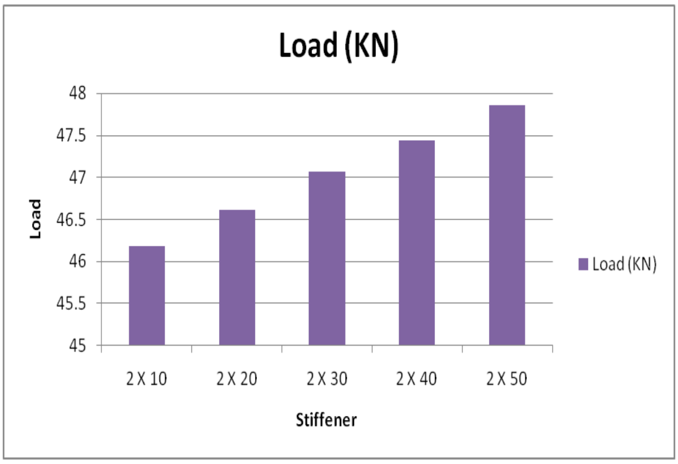

Fig. 12: Result for load carrying capacity of model with stiffener (2mm)

(c) Hexagonal opening with coupled steel stiffener

Table 5: Result for load carrying capacity of model with stiffener (1mm)

Hexagonal Opening With Steel Stiffener						
S. no	**Names**	**Thickness (mm)**	**Width (mm)**	**Area (mm²)**	**Load (KN)**	**Ratio of load to area in percentage**
1	1 X 10	1	10	10	46.039	4.60
2	1 X 20	1	20	20	46.44	2.32
3	1 X 30	1	30	30	46.774	1.56
4	1 X 40	1	40	40	47.054	1.18
5	1 X 50	1	50	50	48.816	0.98

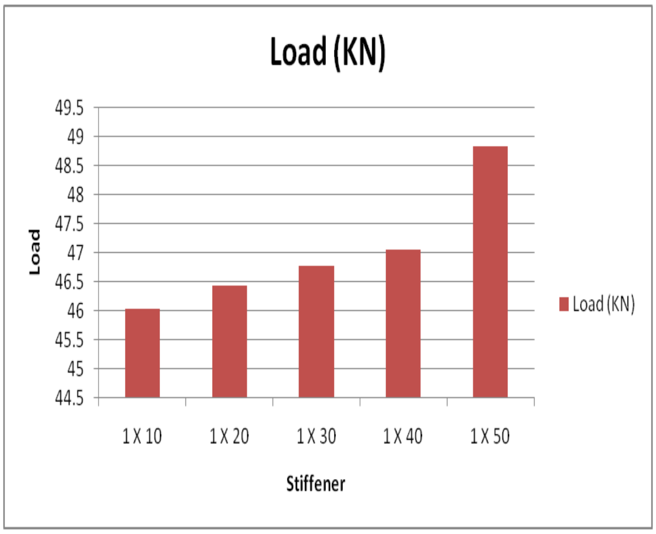

Fig. 13: Result for the load carrying capacity of the model with stiffener (1mm)

Table 6: Result for load carrying capacity of model with stiffener (1.67 mm)

Hexagonal Opening With Steel Stiffener						
S. no	**Names**	**Thickness (mm)**	**Width (mm)**	**Area (mm²)**	**Load (KN)**	**Ratio of load to area in percentage**
1	1.67 X 10	1.67	10	16.7	46.248	2.77
2	1.67 X 20	1.67	20	33.4	47.079	1.41
3	1.67 X 30	1.67	30	50.1	47.218	0.94
4	1.67 X 40	1.67	40	66.8	47.622	0.71
5	1.67 X 50	1.67	50	83.5	48.112	0.58

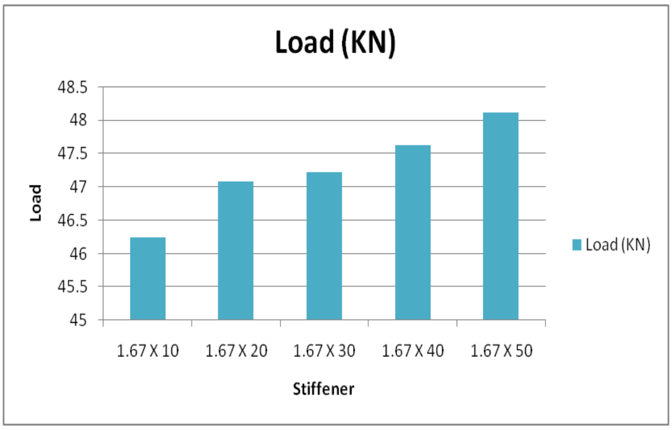

Fig. 14: Result for load carrying capacity of model with stiffener (1.67mm)

Table 7: Result for load carrying capacity of model with stiffener (2 mm)

Hexagonal Opening With Steel Stiffener						
S. no	**Names**	**Thickness (mm)**	**Width (mm)**	**Area (mm²)**	**Load (KN)**	**Ratio of load to area in percentage**
1	2 X 10	2	10	20	46.309	2.32
2	2 X 20	2	20	40	46.838	1.17
3	2 X 30	2	30	60	47.404	0.79
4	2 X 40	2	40	80	47.89	0.60
5	2 X 50	2	50	100	48.447	0.48

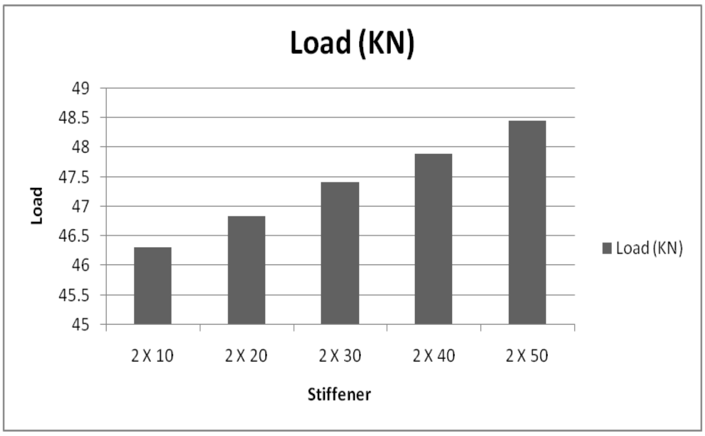

Fig. 15: Result for the load carrying capacity of the model with stiffener (2mm)

5.2 Experimental results for hexagonal opening with and without coupled stiffener

The models of the castellated beam with and without Coupled stiffeners were experimentally analysed. The results give experimental results of the castellated beam with and without Coupled stiffener. For the experimental results perform optimized section are selected from the analysis results. Each individual element behaves as the supporting member for distributing stress equally along with the web post.

(a) Experimental results of without stiffener

Table 8: Experimental results of without stiffener

Description	Load	Deflection
Without Stiffener	5	0.37
	10	0.5
	15	0.81
	20	1.06
	25	1.37
	30	1.74
	35	2.14

	40	2.65
	45	3.43
	50	5.00
	55	9.89
	60	11.64

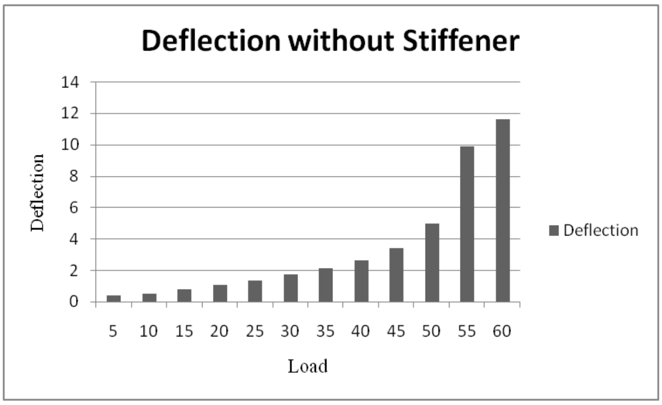

Fig. 16: Experimental results of without stiffener

(b) Experimental results of with FRP stiffener

Table 9: Experimental results of with FRP stiffener

Description	Load	Deflection
With FRP Stiffener	5	0.21
	10	0.41
	15	0.65
	20	0.89
	25	1.17
	30	1.49
	35	1.78
	40	2.21
	45	2.78
	50	3.47
	55	5.11
	60	6.58

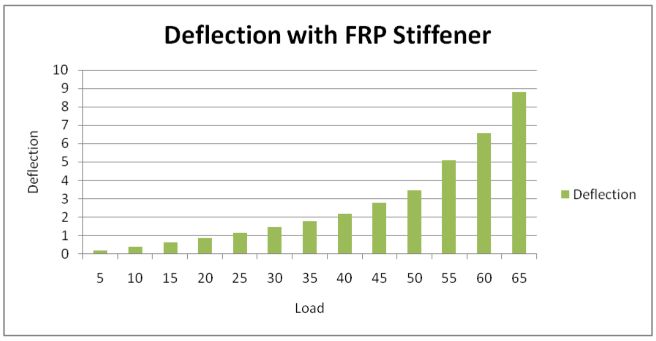

Fig. 17: Experimental results of with FRP stiffener

6. CONCLUSION

Study and optimization of the castellated beam with the coupled Stiffener are done by many researchers. From the research gap, we can frame a conclusion that the study of the behavior of the castellated beam with stiffener is not yet unspoken. But on the other hand over the day by day use of the castellated beam is increasing extensively and demand for good performance of the beam beneath point loading is increasing. This will also give rise to a new area of optimizing the design of stiffener. From the review of literature following conclusions can be drawn:

- Analysis and design of a castellated beam need to be carried out by using stiffeners in the transverse direction and also along the edge of openings in order to minimize web post buckling.
- Optimization of castellated beams with stiffeners by varying the parameters namely, size and positions in the web portion is necessary.

Following conclusions can be drawn from the study so far carried out in respect of behavioural study of optimized castellated beam provided with stiffeners at different locations and using ABAQUS Software.

(a) From the analysis and design (Euro Code guidelines) of a castellated I beam provided with stiffeners in transverse stiffeners, it is concluded that the load carrying capacity of the beam with transverse stiffeners is found to be more as compared to the other transverse stiffeners.

(b) The analytical results giving load carrying capacities of castellated beams provided with various stiffeners under two point loading is found to be almost similar to that of the result obtained in the research paper using software and a percentage variation in load carrying capacity is found to be approximately between 5.21%. Hence, it can be concluded that the results of ABACUS are validated with the results obtained by using the software in a research paper.

(c) The behavior of optimized castellated beams, provided with stiffeners in transverse, has been studied in respect of load carrying capacity and reduction of local buckling. The variation in load carrying capacities as obtained by software analysis is as given below:
- The load carrying capacity of castellated beams with a hexagonal opening provided with transverse FRP and steel stiffeners in between openings is found to be more than the beam without stiffener. The maximum load area ration for the optimization FRP coupled stiffener was noted to be 4.60.

(d) From the experimental performance the following points are concluded below:
- The castellated beam without coupled stiffener in which maximum load carrying is 60 KN and deflection of the section is 11.64mm. The Deflection is more for the without any stiffener provided to section as well as load carrying capacity is less.
- The castellated beam with FRP coupled stiffener in which maximum load carrying is 65 KN and deflection of the section is 8.79mm.
- The castellated beam with FRP (Glass) coupled stiffener in which maximum load carrying is 64.25 KN and deflection of the section is 8.61mm.
- The castellated beam with Steel coupled stiffener in which maximum load carrying is 69 KN and deflection of the section is 8.04mm.

From the above points the shows that the load carrying capacity of without stiffener is less as compared to the provided stiffener section. And Deflection is more for the without stiffener. There for with stiffener sections are better performance as compare to without stiffener is proved that from the results

7. FUTURE SCOPE

- It is recommended to extend the study to understand the behaviour of castellated beams in respect to flexural buckling under a point load and study the remedial measure to avoid stress concentration.
- It is also recommended to study the effect of torsional buckling of the castellated beam with and without stiffeners.
- Also, the load carrying capacity of the castellated beam with diagonal stiffeners can be investigated considering different shapes of opening.

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