

SHEAR STRENGTH OF CASTELLATED BEAM WITH AND WITHOUT STIFFENERS USING FEA (ANSYS 14)

B.ANUPRIYA^{#1}Dr.K.JAGADEESAN^{#2}

Department of Civil Engineering
Arasu Engineering College, Kumbakonam, Tamilnadu, India.

¹anupriyarajavignesh@gmail.com

Department of Civil Engineering
SonaCollegeof Technology, Salem, Tamilnadu, India.

²jaganmoorthi24@gmail.com

Abstract- This paper is focused on the investigation behavior of shear strength of castellated beam with and without stiffeners. Castellated beams are steel beams with web openings and they gain its advantage due to its increased depth of section without any additional weight. However one consequence is the presence of web opening which leads to various local effects like shear and deformation.

In this paper steel I section ISMB 150 and ISMB 200 is selected and castellated beams are fabricated such that depth of the beam is 1.5 times greater than the original depth. The beam is analysed using Finite Element Analysis (ANSYS 14). Two point loads is applied and stress distribution is studied. Stress concentration increases at the hole corners along the shear zone and at load application point. Deflection of the beam with and without stiffeners is studied. And stiffeners are introduced diagonally on the web opening along the shear zone, and in the other case stiffeners are provided on the solid portion of the web along the shear zone.

From the results obtained from ANSYS14 it is concluded that shear strength of castellated beam can be improved by providing diagonal stiffeners along the web opening. Also it is concluded that stiffeners provided on the opening of the web is more effective than stiffeners provided on the solid portion of the web

Key word: Castellated beam, Shear Strength, Diagonal stiffeners, vertical stiffeners, Tension field action, Pratt truss

I. INTRODUCTION

Steel structure building are becoming more and more popular due to their many advantages such as the better satisfaction with the flexible architectural, durability, strength, design, low inclusive cost and environmental protect as steel is manufacture to precise and uniform shapes.

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 limitations on maximum allowable deflections, the high strength properties of structural steel cannot always be utilized to best advantage. As a result several new methods have been aimed at increasing the stiffness of steel members without any increase in weight of the steel required. Castellated beams were one of these solutions. Castellated beams are fabricated from wide flange I-beams.

The web of the section is cut by flame along the horizontal x-x axis along a "Zigzag" pattern as shown in the Fig. 1. The two halves are then welded together to produce a beam of greater depth with hexagonal opening in the web. The resulting beam has a larger section modulus and greater bending rigidity than the original section without an increase in weight. However, the presence of the holes in the web will change the structural behavior of the beam from that of plain webbed beams. Experimental tests on castellated beams have shown that beam slenderness, castellation parameters and the loading type are the main parameters which dictate the strength and modes of failure of these beams.



Fig.1. Zigzag Flame Cutting – Castellated Beam

A. Application of Castellated Beam

Castellated beam are used as structural members in multistory buildings, commercial, industrial and also in portal frames [6].Fig. 2, Fig. 3, Fig. 4& Fig. 5 shows the various application of castellated beam.



Fig.2



Fig.3



Fig.4



Fig.5

B. Limitations of Castellated Beam

A casted beam has some limitations also, stress concentration occurs near the perforations and the shear carrying capacity is reduced. Stress concentration may be reduced by making perforations near the neutral axis where the stress are small making the cut in a zig- zag way[6]. The shear carrying capacity can be increased by stiffening the web at points of concentrated loads and reactions.The major disadvantage of casted beam is the introduction of an opening in the web of the beam alters the stress distribution within the member and also influences its collapse behaviour. These openings decrease the stiffness of the beams resulting in larger deflection[5].

II. LITERATURE REVIEW

These are some of the conclusions from various literature reviews about castellated beam,

- As the depth of opening increases, stress concentrations increases at the hole corners (Vierendeel effect) and at load application point. By taking corrective measures, i.e. by rounding hole corners, providing reinforcement at critical section, providing plate below point load, etc. the serviceability performance of castellated beams can be improved in practice[1].
- As size of beam is increasing, deflection of beam is decreasing. As the web opening move towards the center of beam, stress goes on decreasing and hence deflection is reduced [2]. Hence from this [2] paper if stiffeners are provided along the shear zone, stress can be controlled and shear deformation can be minimized.
- Increase in web post width (e), result in increase of predicted buckling load to yielding mechanism load. As the web thickness t_w increases, the corresponding predicted buckling load and yielding mechanism load increases [4].
- As the web thickness increases, the corresponding predicted buckling load and yielding mechanism load increases. As web post width decreases, the corresponding predicted buckling load and yielding mechanism load increases due to the decrease in area of web openings[5].
- Various terms are used to discuss the castellated beam Fig. 6 illustrate the terms.

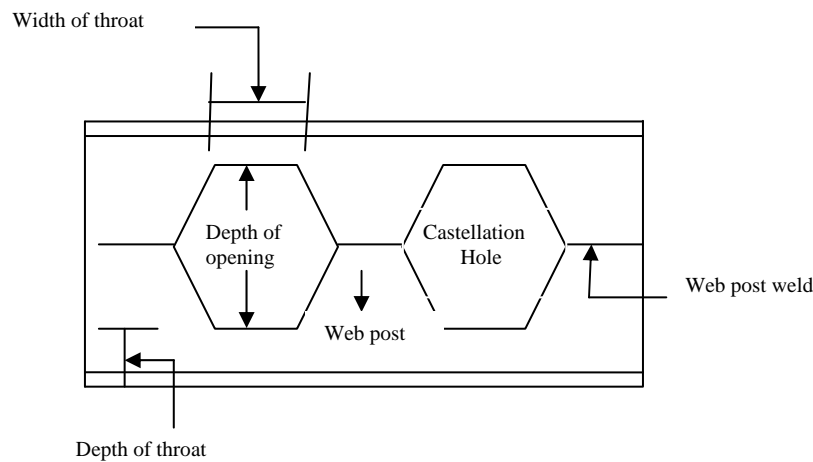


Fig.6. Terminology

- Hence from the various literature reviews it is observed that failure occurs as the depth of the opening increases and also due to the stress concentration across the holes. It can be reduced by taking corrective measures like providing stiffeners.
- And stiffeners may be provided along the shear zone so that stresses can be reduced and deflection can be controlled and shear failure can be minimized.

III. FAILURE MODES OF CASTELLATED BEAM

Kerdal&Nethercot1984., determined there are a number of possible failure modes for castellated beams, which are as follows[7],[9]

- Vierendeel Mechanism: This occurs due to excessive deformation across one of the openings in the web and formation of hinges in the corners of the castellation.
- Lateral Torsional Buckling of the web: This is caused by large shear at the welded joints.
- Rupture of welded joints in the web: This arises due to excessive horizontal shear at the welded joint in the web.
- Lateral Torsional buckling of the overall beam: Castellated beam undergo lateral torsional buckling of the whole span.
- Plastic Hinge Formation: This mode of failure occurs when lateral torsional buckling is prevented. Areas of plasticity are formed in the top and bottom flanges caused by a combination of stresses due to primary flexure and vierendeel action. The hinges may form away from point of maximum bending moment due to the presence of shear and axial forces.
- Web buckling: This is caused by heavy loading and short span of the beam. This may be avoided at a support by filling the first castellation by welding a plate in the hole.

IV. OBJECTIVE OF THE RESEARCH WORK

The main focus of the research work is to study the effect of introducing stiffeners along the shear zone where stress concentration is more so that deflection is minimized and shear failure is controlled. The study is carried out using Finite Element Analysis (ANSYS 14).

V. INVESTIGATION OF CASTELLATED BEAM

- ISMB 150 and ISMB 200 are selected for fabricating castellated beams. The castellated beams were fabricated such that depth of the beam is 1.5 times the original depths IC 225 and IC 300 respectively with an angle of cut 45°.

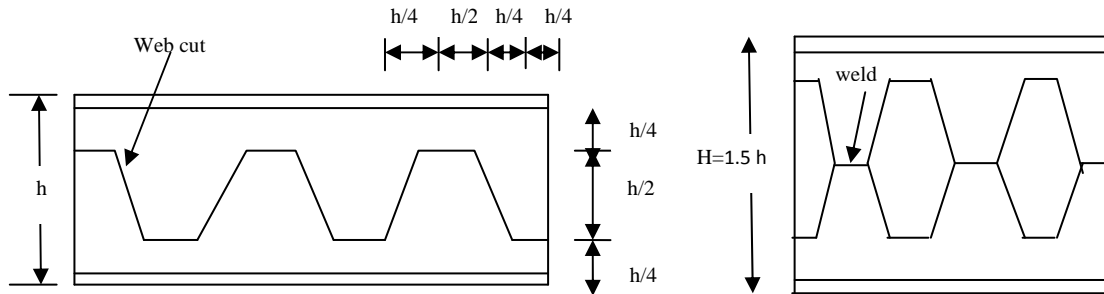


Fig.7. Mathematical Expression

- Select the depth of the stem of the T section at the minimum cross section should not be less than ¼ of the original beam section. Fig. 7 illustrate the expression [5]
- Fig. 8 explains marking layout of I section ISMB 150. (a) shows the details of ISMB 150, (b) shows the marking details of the beam and (c) shows the castellated beam with an increased depth (225 mm from 150 mm) as IC 225.

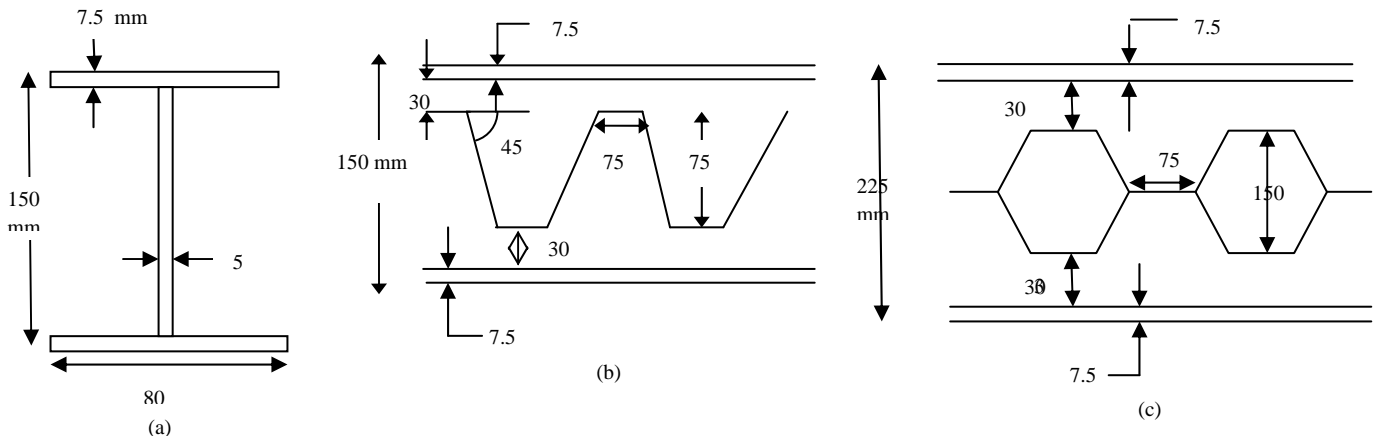


Fig. 8. Marking layout of I section (ISMB 150)

VI. THEORITICAL CALCULATION

These are the following steps followed for designing the castellated beam.

- The moment of resistance of the castellated section which is the product of the resultant tensile or compressive force and the distance between centroids of T section is calculated by
 - $M_R = A \sigma_{at} d$
- The spacing of the castellated beam should not exceed the spacing determined by the equation which is calculated by,
 - $S = \frac{P'}{W/L}$ Where,
 - S= center to center distance between castellated beams
 - P'= Net load carrying capacity in N
 - W= Design load in N/m²

L= Span of the beam in m
- Stiffeners are designed at the supports and below the concentrated loads.
- The beam is checked in shear. the average shear at the end is calculated from

$$\tau_{va} = \frac{R}{d't} < 0.4fy$$

Where

- R= end reaction in N
- d'= depth of the stem of T – section
- t= thickness of the stem

5. The maximum combined local bending stress and direct stress in the T Segment is also worked out and should be less than the permissible bending stress.
6. The maximum deflection of the T- section is at the mid span and is due to the net load carrying capacity and local effects which is calculated by,

$$\delta = \delta_1 + \delta_2 < \frac{L}{325}$$

Where

- δ_1 - Deflection due to net load carrying capacity
- δ_2 - Deflection due to local effects

VII. DISTRIBUTION OF STRESS IN A I SECTION

Fig. 9 shows the nature of shear distribution in an I beam. Fig. 10 shows the bending stress distribution of an I Section [7].

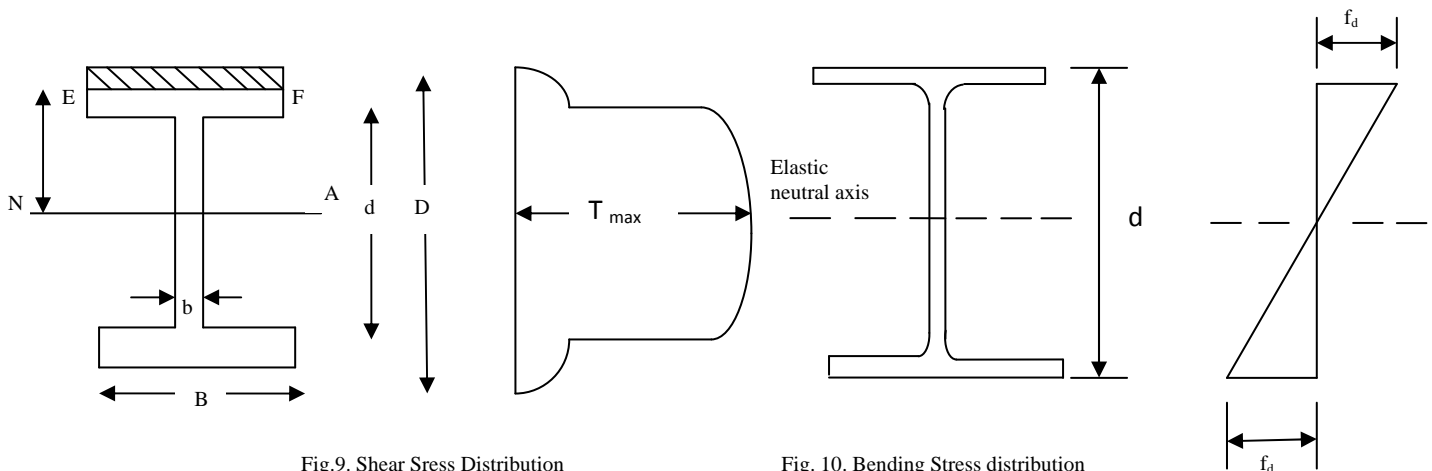


Fig.9. Shear Sress Distribution

Fig. 10. Bending Stress distribution

- From the comparison of the shear and flexureal stress distributions, it may be observed that the flanges carry a major portion of the flexural load , whereas the web carries most of the shear load.
- The primary modes of failure of the beam are by yeilding of the tension flange and buckling of the compression flange. The compression flange buckling can take place in various ways, such as vertical buckling into the web, flange local buckling, or lateral torsional buckling.
- That is at high shear locations, normally near the supports and neutral axis, the principal planes would be inclined to the longitudianl axis of the member.
- Along the principal planes, the principal stresses would be diagonal tension and diagonal compression causes the web to buckle in a direction perpendicular to its action.
- This problem can be solved by reducing the depth to thickness ratio of the web and we can also provide web stiffeners that would develop tension field action to resist diagonal compression[7].

VIII. TENSION FIELD ACTION AND THE EQUIVALENT N- TRUSS

- Fig. 11(a) shows the tension field action. As the web begins to buckle, the web loses its ability to resist thediagonal compression.The diagonal compression is then transferred to the transverse stiffeners and the flanges.
- The web resists only the diagonal tension and this behaviour of the web is called tension field action.
- The behaviour is very similar to a pratt truss, in which the vertical members carry compression and the tension is carried by the diagonal[7].

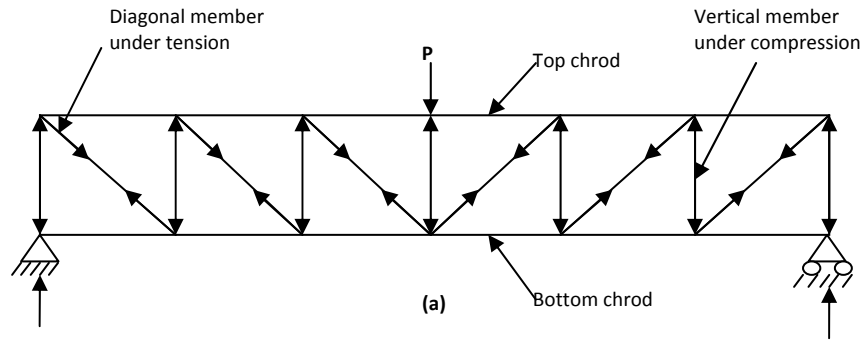


Fig.11. Tension field action and the equivalent N-truss

IX. FORMULATION OF RESEARCH OBJECTIVE

Fig. 12 shows the interruption of tension field by web holes[7]. From the concept of tension field action and pratt truss, stiffeners are introduced on the web. Two types of stiffeners are introduced

1. Diagonal stiffeners on the web opening along the shear zone
2. Vertical stiffeners on the solid portion of the web along the shear zone.

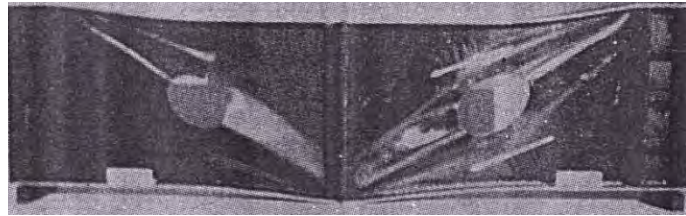


Fig.12. Interruption of tension field by web holes

X. FINITE ELEMENT ANALYSIS

In this paper, a three dimensional (3D) finite element model is developed using ANSYS-14 for IC 225 and IC 300. Various finite element models and von mises stresses are developed. Stress concentration of the beam is studied. Stress concentration is more near the opening leading to shear failure. Hence the webs are stiffened by providing stiffeners on either side of the beam along the shear zone to reduce the stress concentration and to reduce the shear deformation. Stiffeners are provided on opening of the web and also on the solid portion of the web.

In order to study the effect of stiffeners along shear zone the following three cases are considered.

Case (I)

Without stiffeners (**WOS**) along the shear zone.

Case (II)

With Diagonal Stiffeners (**WDS**) on the web opening along the shear zone.

Case (III)

With vertical Stiffeners (**WVS**) on the solid web along the shear zone.

Fig.13 shows the shear force diagram and stiffeners details. Fig a shows the first case with out stiffeners (**WOS**), Fig b shows the second case with diagonal stiffeners (**WDS**), Fig c shows the third case with vertical stiffeners (**WVS**) of castellated beam along the shear zone.

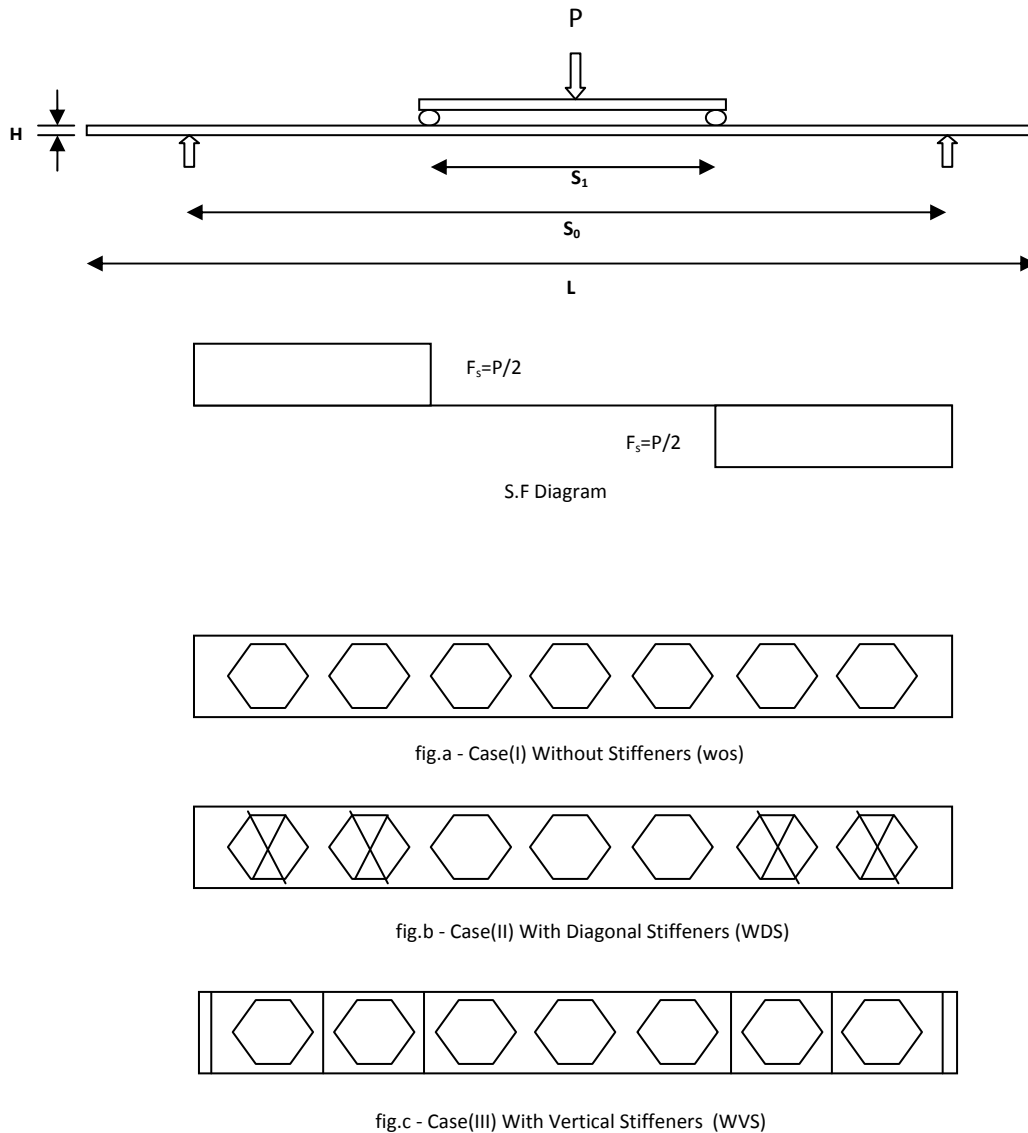


Fig.13. S.F Diagram and Stiffeners Details

The details of the specimens are given in Table 1 and Table 2

TABLE I
Specimen Type I (IC 225)

Specimen detail	Length (m)	Thickness of flange t_f (mm)	Thickness of the web t_w (mm)	Breath of the web b_w (mm)	Height of the web opening HW (mm)	Length of stiffener (mm)	Width of stiffener (mm)	Thickness of Stiffener (mm)
WOS 225	3.2	7.5	5	80	150	-	-	-
WDS 225	3.2	7.5	5	80	150	190	15	5
WVS 225	3.2	7.5	5	80	150	200	20	5

TABLE II
Specimen Type II (IC 300)

Specimen detail	Length (m)	Thickness of flange t_f (mm)	Thickness of the web t_w (mm)	Breadth of the web b_w (mm)	Height of the web opening HW (mm)	Length of stiffener (mm)	Width of stiffener (mm)	Thickness of Stiffener (mm)
WOS 300	3.2	10	6	100	200	-	-	-
WDS 300	3.2	10	6	100	200	260	20	6
WVS 300	3.2	10	6	100	200	260	30	6

A. Assumptions made in the Analysis

The following assumptions are adopted for analysis. Density of steel, young's modulus of steel, poissonratio, yield strength and plastic strain are the basic parameters of the section. All dimensions are in meter.

1. Yield strength (f_y) = 2.5×10^8 N/m²
2. Young's modulus = 2×10^{11} N/m²
3. Poisson's ratio = 0.3
4. Density of Steel = 7830 kg/m³
5. Plastic Strain = 0

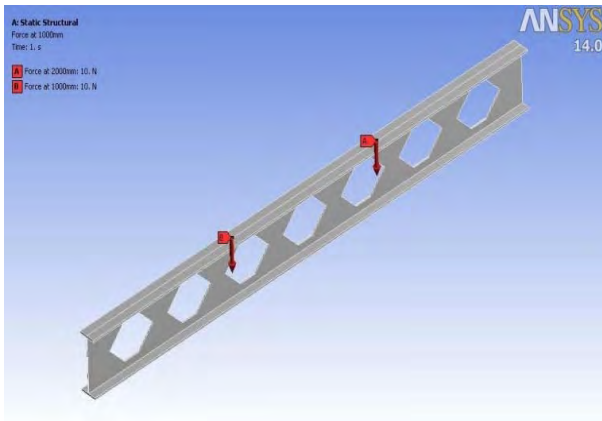


Fig.14 Load application of CB without Stiffeners (WOS 300)

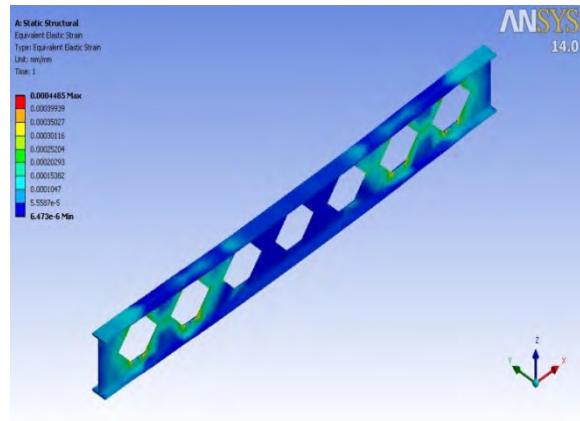


Fig. 15 Stress distribution of CB along the shear zone

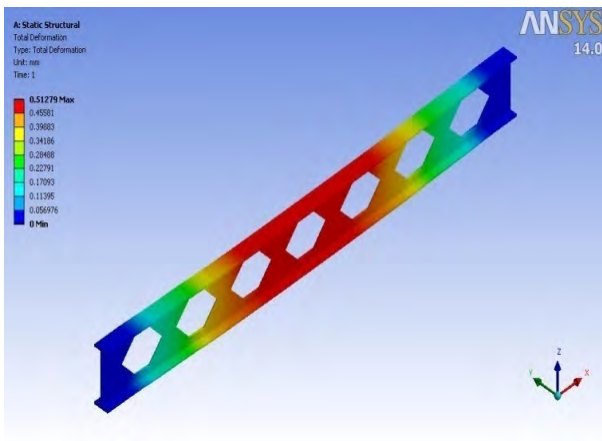


Fig.16 Deflection of CB Without Stiffeners (WOS 300)

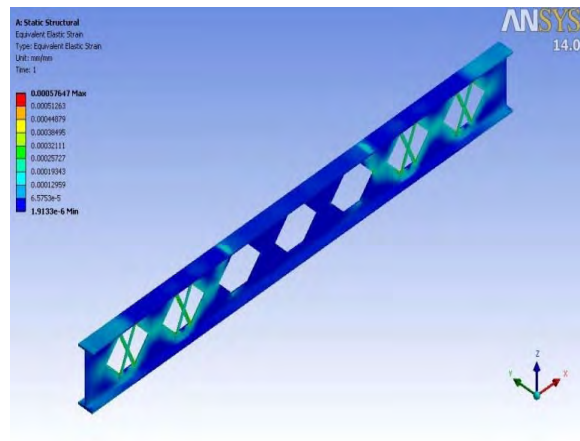


Fig. 17 CB With Diagonal Stiffeners (WDS 300)

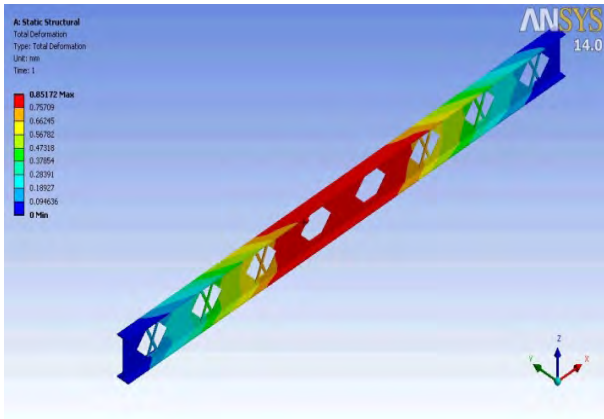


Fig. 18 Deflection of CB with Diagonal Stiffeners (WDS 225)

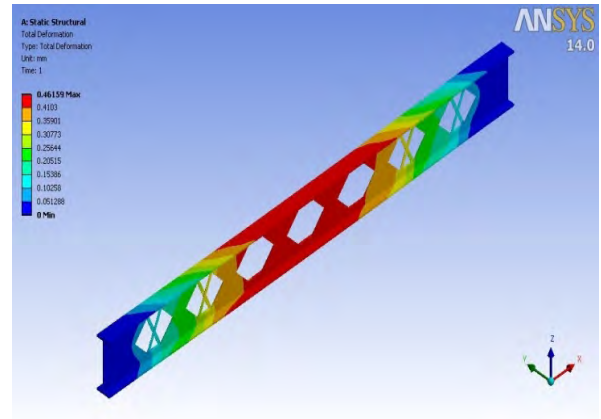


Fig. 19 Deflection of CB with Diagonal Stiffeners (WDS 300)

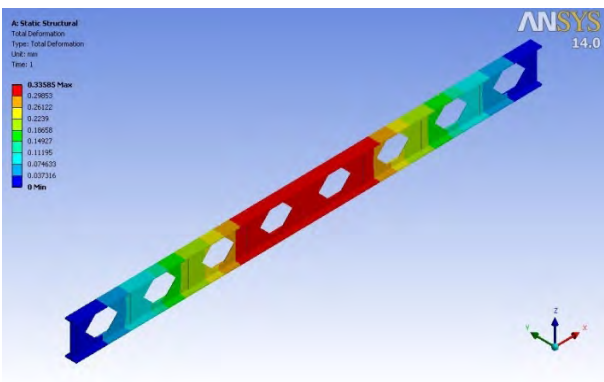


Fig. 20 CB with Vertical Stiffeners (WVS 225)

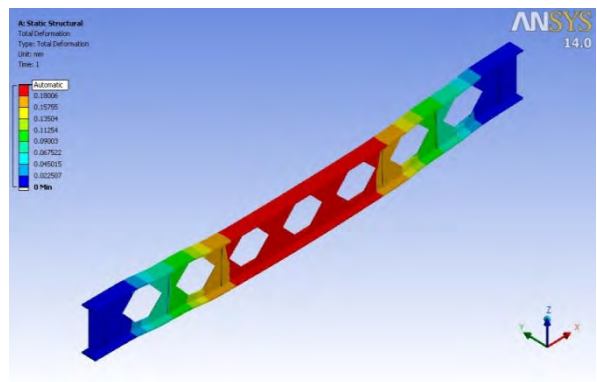


Fig. 21 Deflection of CB with Vertical Stiffeners (WVS 300)

XI. RESULTS AND DISCUSSION

TABLE III
Comparison of load Vs deflection between WOS 225 , WDS 225 & WVS 225

Sl.No	Load (kN)	WOS 225 Deflection (mm)	WDS 225 Deflection (mm)	WVS 225 Deflection (mm)
1.	10	1.28	0.96	1.6
2.	20	2.55	1.93	3.17
3.	30	3.83	2.89	4.77
4.	40	5.10	3.85	6.35
5.	50	6.38	4.82	7.94
6.	60	7.65	5.78	9.52
7.	70	8.93	6.74	11.12
8.	80	10.21	7.70	12.72
9.	90	11.48	8.67	14.29
10.	100	12.76	9.63	15.89

Allowable Deflection = $L/325 = 3200/325 = 9.84\text{mm}$

TABLE IV
 Comparison of load Vs deflection between WOS 300 , WDS 300 & WVS 300

Sl.No	Load (kN)	WOS 300 Deflection (mm)	WDS 300 Deflection (mm)	WVS 300 Deflection (mm)
1.	10	0.57	0.46	0.68
2.	20	1.15	0.92	1.38
3.	30	1.72	1.38	2.06
4.	40	2.29	1.85	2.73
5.	50	2.87	2.31	3.43
6.	60	3.44	2.77	4.11
7.	70	4.01	3.23	4.79
8.	80	4.59	3.69	5.49
9.	90	5.16	4.15	6.17
10.	100	5.73	4.62	6.84
11.	110	6.31	5.08	7.54
12.	120	6.88	5.54	8.22
13.	130	7.46	6.00	8.92
14.	140	8.03	6.46	9.6
15.	150	8.60	6.92	10.28
16.	160	9.18	7.39	10.97
17.	170	9.75	7.85	11.65

Table III and Table IV show the comparison of load Vs deflection of castellated beam between WOS , WDS [10]& WVS for IC 225 and IC 300 respectively.

Fig. 22 and Fig. 23 shows the graph between Load Vs Deflection for all the three cases.

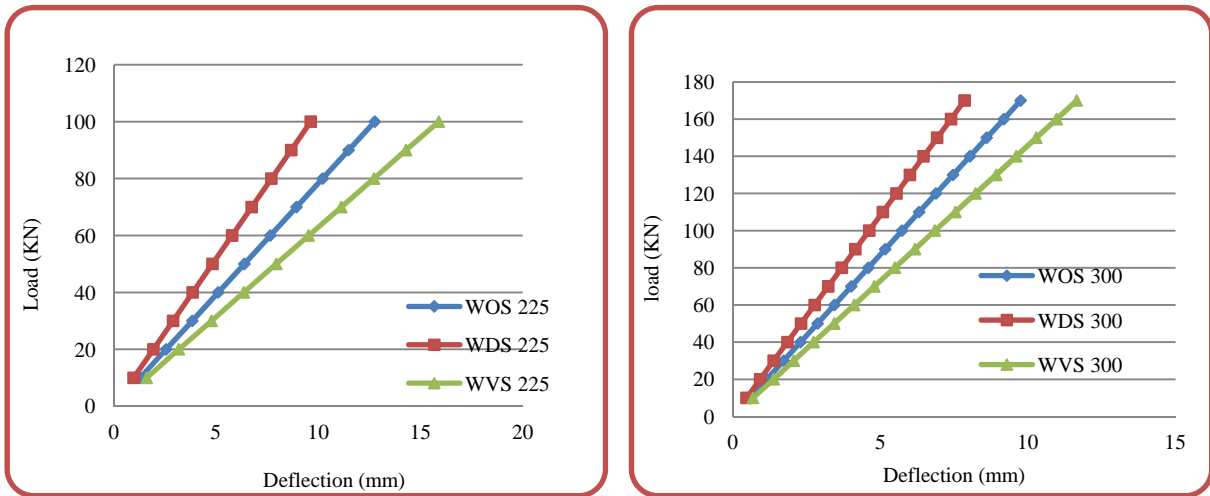


Fig. 22 Comparison Between WOS , WDS & WVS (IC 225)

Fig. 23 Comparison Between WOS, WDS & WVS (IC 300)

For the first case with out stiffeners (WOS), when load is applied over the beam, stresses are distributed across the holes of the corners and deflection of the beam increases. In the second case, the castellated beam with diagonal stiffener yield lesser deflection because of the truss action is takes through diagonal stiffener. In the shear span that is between load and support point the shear is dominating and hence forces flows through diagonal stiffener. The shear force causes diagonal tension and compression in the web and hence the diagonal stiffeners are provided in the direction of diagonal tension and diagonal compression for the smooth flow of shear forces.

In the third case with vertical stiffeners (WVS), when the stiffeners are provided on the solid portion of the web on either side along the shear zone, stress concentration along the holes increases and web panel starts to buckle leading to higher deflection. Which infers that when solid portion of the web is stiffened, shear strength across the holes decreases which leads to higher deflection because, stresses across the opening are higher than the solid portion. When the web holes are stiffened deflection is reduced and when the solid portion of the web is stiffened, strength across the holes are reduced and deflection of the beam increases.

Also it is clear that when diagonal stiffeners are provided the deflection is with in the allowable limit.

XII. THEORITICAL PROOF

The webs, when they are inadequate to carry the load are made strong and stable by the provision of a wide variety of stiffeners.

A. Diagonal Stiffeners along the web opening

When the castellated beam is subjected to vertical shear , complementary shear stresses are developed to satisfy equilibrium of the beam. As a consequence, the beam develops diagonal tension and diagonal compression. Consider a small element in equilibrium inside the solid portion of the web subjected to a shear stress τ (Fig. 24).

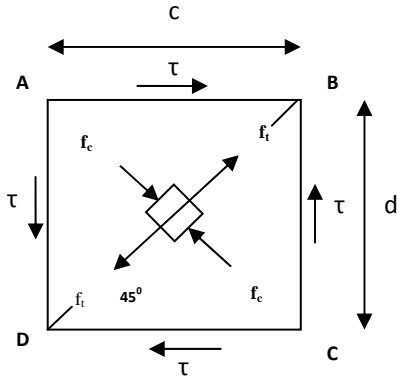
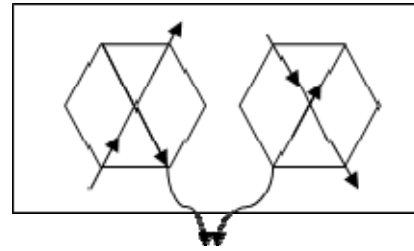


Fig. 24. Shear Panel



Shear force flows through the diagonal embers

Fig. 25. Shear force through diagonal members (Truss Action)

The element is subjected to principal compression along the direction AC and principal tension along the direction BD. As the applied loading is gradually increased, tin turn will increase and the beam will buckle along the direction of the compressive diagonal AC. The beam can not take further increase in compressive stress.

To over come this, diagonal stiffeners are introduced on the web opening where shear is dominating and hence forces flows through diagonal stiffener (Fig-25). The shear force causes diagonal tension and compression in the web and hence the diagonal stiffeners are provided in the direction of diagonal tension and diagonal compression for the smooth flow of shear forces.The behaviour is very similar to a pratt truss, in which the vertical members carry compression and the tension is carried by the diagonal

B. Vertical stiffeneres along the solid portion of the web

Fig. 26shows the tension field action in a panel. As the web begins to buckle, the web loses its ability to resist the diagonal compression. The diagonal compression is then transferred to the transverse stiffeners and the flanges. The vertical component of the diagonal compression is supported by the stiffeners and the flanges resist the horizontal component. The web resist only the diagonal tension and this behaviour of the web is called tension field action.

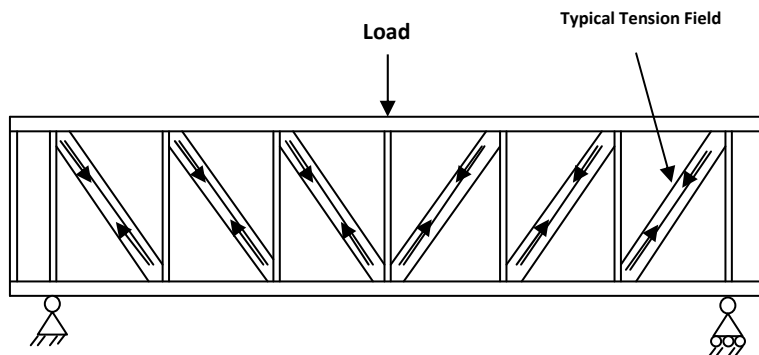


Fig.26 Strut and Tie action in the Truss members

The contribution of tension field action is realized only after the web starts to buckle. The main purpose of these stiffeners is to provide stiffeners to the web rather to resist the applied loads.

The shear capacity of the web has two components, Strength before the onset of the buckling and strength after buckling. As the shear load is increased on a stiffened web panel, the web panel buckles (Fig. 27) which leads to higher deflection.

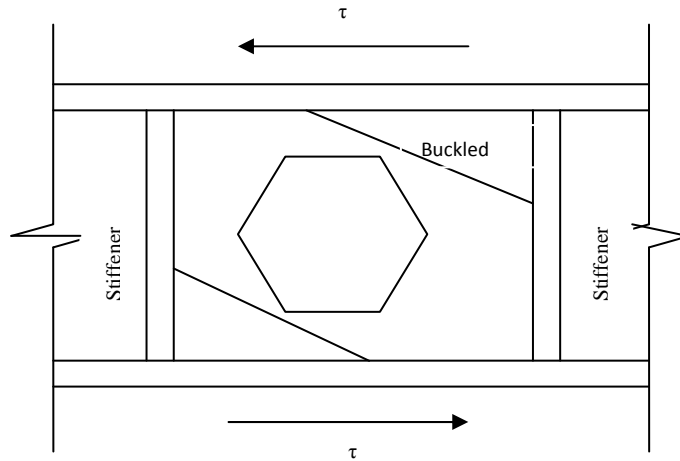


Fig. 27. Buckled panel

XIII. FUTURE WORK

From the research work, Shear strength of the castellated beam can be improved by providing diagonal stiffeners on the web opening along the shear zone.

Vertical stiffeners will be effective if it is provided on the opening of the web along with diagonal stiffeners (i.e.) When the vertical stiffeners, if provided on the opening of the web along with the diagonal stiffeners deflection can be still be reduced and shear failure can be further be reduced.

CONCLUSION

From the results obtained from ANSYS 14, it was observed that stresses are distributed across the web opening along the shear zone and shear failure is more near the holes than in the solid web of the castellated beam.

When vertical stiffeners are provided on the solid portion of the web, shear across the holes does not have any path to flow and hence shear strength across the holes decreases, so web starts to buckle leading to higher deflection. When stiffeners are provided diagonally in the direction of diagonal tension and diagonal compression (strut and tie action), as shown in figure 24, 25 and 26, truss action takes complete along the diagonal members in the open web find smooth flow for the shear forces leading to lesser deflection

Hence shear stiffeners provided on the opening of the web is effective than the solid portion. Also shear strength of castellated beam can be improved by introducing shear stiffeners (Diagonal Stiffeners) on the web opening along the shear zone.

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