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Finite Element Analysis of Composite Beams and Columns with Castellated Members

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Abstract— Nowadays castellated beams and columns are widely used in a variety of geometries suitable for various structures. Castellated members are made from hotrolled steel I sections by increasing the depth and creating openings in the web. This is achievedby cutting the web in a definite pattern and thenrejoining thetwo halves by welding together. The new section with holes will gain the advantages due to its increased depth and section modulus than the original section. The strength to weight ratio of the section is increased without additional usage of steel. But there are number of failure modes for the castellated members.Application of partial and full encasement of concrete can avoid failure mechanisms and increase yield moment capacity. This paper presents finite element analysis of composite beams and columns with castellated members of full height web openings. Numerical analysis on composite beams and columns was carried out through ANSYS16.1 software. In this paper, different shapes of web openings namely rectangular, hexagonal and elliptical were considered in partially and fully encased with concrete.Obtained results showed that the elliptical web opening is efficient for the better behaviour.

Index Terms—Ansys 16.1, Composite beams and columns with castellated members, Different shapes of web openings, Finite element analysis, Partial and full encasement of concrete.

1 Introduction

Steel I-section can be modified to strengthen the section by increasing the depth and creating openings in the web. This is achieved by flame cutting a single rolled I section in a definite pattern and then rejoining the segmentsafter offsetting one portion so that the high points of the cut comes into contact to form a section with a number of regular openings in its web. The new section with holes will have a depth at least 50% more and its section modulus is increased by 2.25 times than the original section. Such beams are more resistant to bending, as the section modulus is increased. The strength to weight ratio of the beam is increased without additional usage of steel. In the case of castellated column due to the increase in width of column the radius of gyration of column increase and the slenderness ratio of column get reduce. Due to this effect the buckling load carrying capacity of column increases.They are light, strong, and cheap. Castellated members were used in many varieties of structures like garages, parking lots, steel frames and industrial buildings.Use of castellated beam and column had become very popular and they haveunique sets of advantages dependent on particular construction needs.

Castellated section has some limitations also. They are less fire resistance compared to the plate girders and the need of reinforcement when a beam is subjected to the heavy loads.Presence of web openings in castellated sections, leads to different types of failuressuch as Vierendeel collapse mechanism, buckling of a web post, flexural failure, lateral torsional buckling andrupture at welded joints. Stress concentration occurs near the perforations. Hence to reduce the stress concentration and to increase the strength steel encased in concrete method can be used. Steel encased in concrete method is used to avoid steel from buckling and that can be used for beams and columns. There are two types of encased method namely partially encased and fully encased. In partially encased method only the web is covered with the concrete. In fully encased method the whole steel section is covered with concrete so that the top and bottom flanges are not in the outermost position. Application of partial and full encasement can avoid failure mechanisms and increases yield moment capacity.

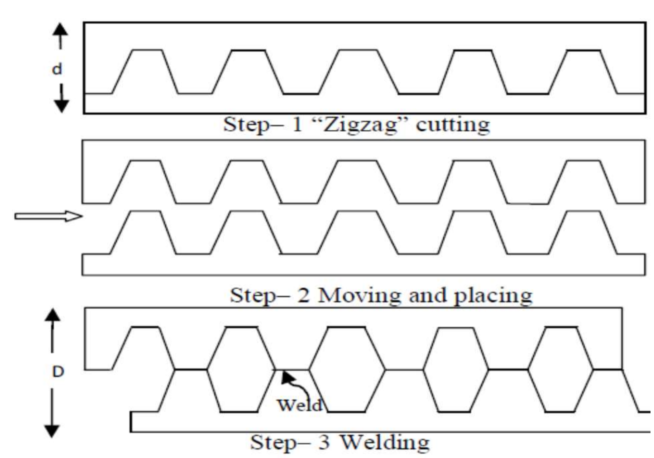

Fig. 1. Steps in the castellation process

2 OBJECTIVES

The main purpose of this analysis is to study thebehaviour of composite beams and columns with castellated members.In this work, studying the behavior of castellated steel beams and columns with different shapes of full height web penings namely rectangular, hexagonal and elliptical in partially and fully encased condition.

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3 LITERATURE REVIEW

T.C.H.Liu and K.F. Chung, (2003) conducted a study of "Steel beams with large web opening of various shape and size: finite element investigation".The analysis reveals that the most important parameter in assessing the structural behaviour of the perforated sections is the critical opening length. The opening depth controls the shear and the moment resistances of a perforated section. In general, plastic hinges are always formed at both ends of the tee-sections above and below the web openings at failure. All steel beams with large web openings of various shapes behave similarly under a wide range of applied moments and shear forces.

Khaled Sawy, Amr Sweedan and Mohamed I.Martini(2009) conducted a study on "Major-axis elastic buckling of axially loaded castellated steel columns".Numerical analysis of castellated columns was done to determine the critical elastic buckling load and the associated mode of failure of such castellated columns. Column is axially loaded with concentrated loads applied at its ends. Results indicate that columns with bigger castellation size are associated with higher values for the buckling modification factor. As such these columns experience higher reduction in their buckling capacity due to the encountered reduction in the shear stiffness.

Konstantinos Daniel Tsavdaridis and Cedric D'Mello(2011) investigated about "Web bucklingstudy of the behaviour and strength of perforatedsteelbeamswithdifferentnovel web openingshapes".Investigated the failure mode and load strength of the web-post between two adjacent web openings.(ANSYS). Failure of the specimens occurs under the combined action of shear and moment. In general, when novel elliptical web openings are considered, the critical openings length is narrower and hence the Vierendeel capacity is high and it concludes that the vertical shear capacities increase as the web-post width is increased, and conversely slightly decreased when they are subjected to high Vierendeel bending forces.

Konstantinos Daniel Tsavdaridis and Cedric D'Mello (2012) carried out a study on "Optimisation of novel elliptically based web opening shapes of perforated steel beams". Studied the behaviour of beam with different novel web opening shapes to optimise the web opening shapes of beams that are subjected to high shear forces. The stresses in the vicinity of the web openings were affected by both angle of inclination (θ) and radius (R). Deflections of the perforated beams are only affected by radius (R). Beams with vertical and inclined classic elliptical web openings behave more effectively compared to beams with circular and hexagonal web openings, mainly in terms of stress distribution and local deflection.

Wei-bin Yuan, Boksun Kim and Long yuan Li (2014)studied about "Buckling of axially loaded castellated steel columns". Presented a new analytical solution for calculating the critical buckling load of simply supported castellated columns when they buckles about the major axis. This analytical solution takes into account the influence of web shear deformations on the buckling of castellated columns. The influence of web shear deformations on the critical buckling loads is increased with the cross-sectional area of a tee section and the depth of web opening and decreased with the length and the web thickness of the column.

Peijun Wang, Qijie Ma and Xudong Wang (2014) conducted a study of "Investigation on Vierendeel mechanism failure of castellated steel beams with fillet corner web openings".Vierendeel failure of castellated steel beams with fillet corner web openings was investigated by finite element analysis. Authors suggested that fillet radius which equals to a quarter of the opening height as the best choice. With the increase in the opening length, the vertical shear capacity of the perforated member decreases also due to the increase in the local Vierendeel bending moment. The unit member with fillet corner opening has a higher load carrying capacity compared with those with hexagonal, rectangular openings, but lower than that with circular opening.

Delphine Sonck and Jan Belis, (2016)conducted a study on "Lateraltorsionalbucklingresistance of castellatedbeams (ABAQUS) ". The Lateraltorsionalbuckling behaviour of symmetric castellated steel beam loaded by a constant bending moment was investigated numerically. Three tested castellated steel beams were made from a parent section of height 160mm with steel of f_y 275 Mpa. Different length of beam considered were 3.09 m, 3.99 m & 6.09 m. In the numerical model, the flanges and the web were modelled by quadratic shell elements. All the beams failed because of lateral-torsional buckling. The failure loads were the largest for the shortest specimens. A preliminary design approach was also proposed.

M. Najafi and Y.C.Wang (2017) carried out a study on "Behaviour and design of steel members with web openings under combined bending, shear and compression". Investigated how an additional axial compression affects the Vierendeel failure mechanism on beams. When there is no axial load, clearly defined plastic hinges form at the corners. As the compressive axial load increases, yielding moves towards the centreline of the openings. Under either pure compression or pure bending, the maximum axial or bending capacities of the beams were limited by buckling of the compressive tee-section. Based on the results of numerical simulations, this paper had proposed an analytical method to calculate the capacity of steel members at the location of openings.

Richard Frans, Herman Parung, Desi Sandy and Surianti-Tonapa (2017) presented an investigation on "Numerical modelling of hexagonal castellated beam under monotonic loading". Evaluated the performance of beam by considering the parameters opening angle and spacing between openings. Three variations in angles (50^0, 60^0& 70^0) with different opening spacing (6mm, 9mm & 12mm) for hexagonal shapes were analysed. Best result was at a spacing 6mm and an angle of 60^0, with load at yield is 78.4812 KN and deflection at yield is 0.7867 mm.

Iman Satyarno, Djoko Sulistyo, Dina Heldita and A. Talodaci Corte (2017) performed an experimental study on "Full height rectangular opening castellated steel beam partially encased in reinforced mortar".Analysis was done with full height rectangular opening castellated steel beam without encasing and with partially encasing using reinforced mortar.

Short span beams were used to study the shear failure mechanism and long span beams to study flexural failure mechanism. On the application of partially reinforced mortar encasing in the long span beam can avoid the vierendeel mechanism and increase the yield moment capacity around 3.5 times of original steel section yield moment.

4 VALIDATION

Ansys workbench 16.1 software was used for the validation and it was done with the full height rectangular opening castellated steel beam made from the parent section which has height 150mm, width of flange 75mm, flange thickness 7mm, web thickness 5mm and yield strength 278MPa. In full height rectangular opening castellated steel beams the vertical and horizontal cutting pattern made with the width of hole in the web to be 130mm, the depth of hole as 264mm and the total height of castellated steel beam 278mm or almost as twice as its original height 150mm. Total length of the beam was taken as 2990mm.Two point loading method was used in beam and which were supported by hinge at one end and roller at other end. The maximum load value obtained after analysis was compared with the journal values.

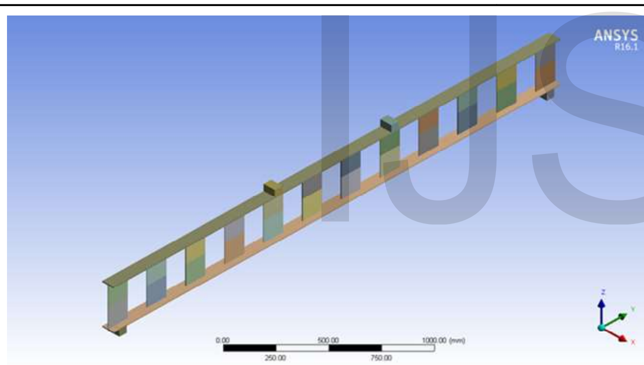

Fig. 2.Castellated steel beam with full height rectangular opening used in validation

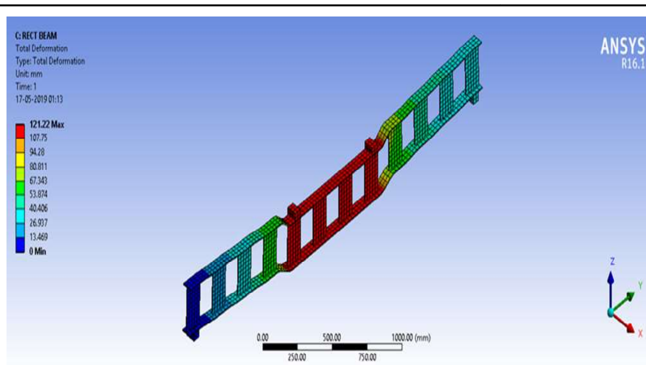

Fig. 3.Total deformation diagram of castellated beam with full height rectangular opening

TABLE 1
RESULTS COMPARISON

Results	Maximum load ((kN)
From FEA	22.359
From journal	24.5
Percentage difference	8.74%

5FINITE ELEMENT ANALYSIS

A non-linear static analysis was done inansys workbench 16.1 software for castellated beams and columns. The same material and geometrical parameters of I section in the validation process was used for finite element analysis of beams. Two more shapes of full height web openings other than the rectangular namely, hexagonal and elliptical were considered in the case of beams and columns. By keeping the opening area as constantfull height rectangular, full height hexagonal and full height elliptical opening beams and columns were analysed. In case of columns end condition was one end fixed and other end pinned.Axial loading was used and the column length was 2990 mm as in beam. So the study includes finite element analysis of:

1. Castellated beams with full height web openings
2. Partially encased castellated beams with full height web openings
3. Fully encased castellated beams with full height web openings
4. Castellated columns with full height web openings
5. Partially encased castellated columns with full height web openings
6. Fully encased castellated columns with full height web openings

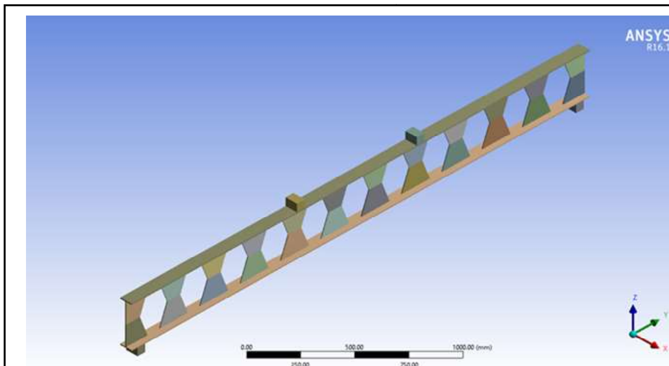

Fig. 4.Castellated steel beam with full height hexagonal opening

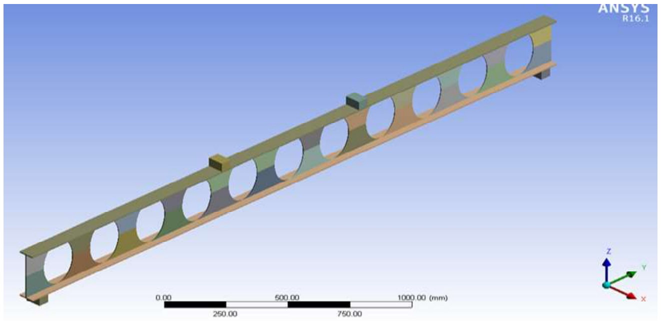

Fig. 5.Castellated steel beam with full height elliptical opening

Steel encased in concrete method is used to avoid steel from buckling.In partially encased method only the web is covered with the concrete. In fully encased method the whole steel section is covered with concrete so that the top and bottom flanges are not in the outermost position. Concrete was provided in 25mm thickness above the flanges to make full encasement. M 25 concrete was used for the encasement. Steel was modelled with the element SOLID 186, three dimensional 20-node element having 3 degrees of freedom at each node and the concrete with the element SOLID 65, three dimensional 8 node element having 3 degrees of freedom at each node.

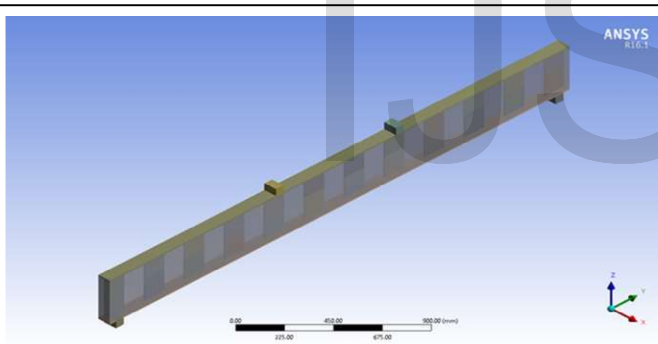

Fig. 6.Model of partially encased full height rectangular opening castellated beam

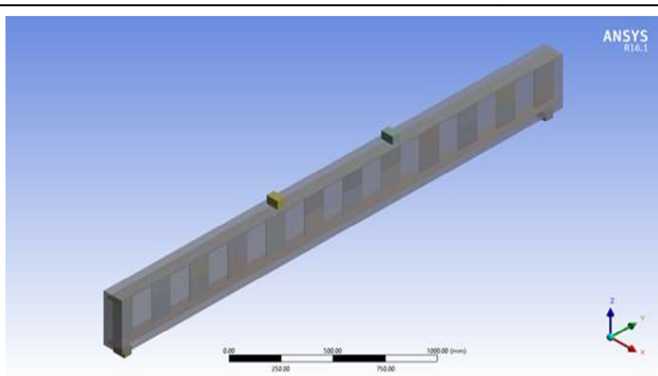

Fig. 7.Model of fully encased full height rectangular opening castellated beam

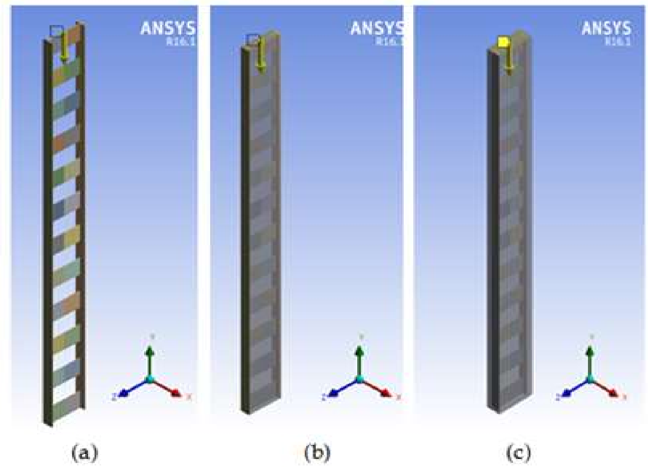

Fig. 8.(a) Model of full height rectangular opening castellated column (b) partially encased condition (c) fully encased condition

6 RESULTS AND DISCUSSION

The nonlinear static analysis was done for full height web opening castellated steel beams and columns, partially encased and fully encased with three different shapes of openings.In case of castellated beam with full height web openings, elliptical opening showed maximum load carrying capacity and 45.85 percentage of increase in load carrying capacity than rectangular opening beam. Hexagonal opening showed 22.9 percentage of increase in load carrying capacity than rectangular opening beam.

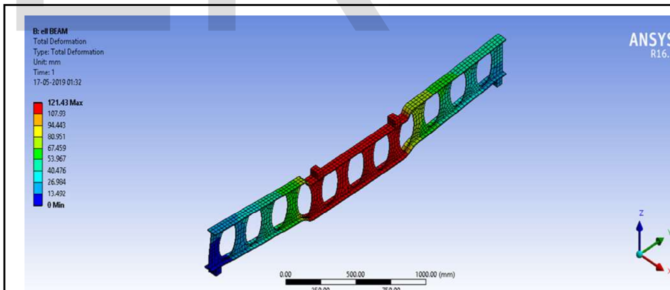

Fig. 9.Total deformation of castellated beam with full height elliptical opening

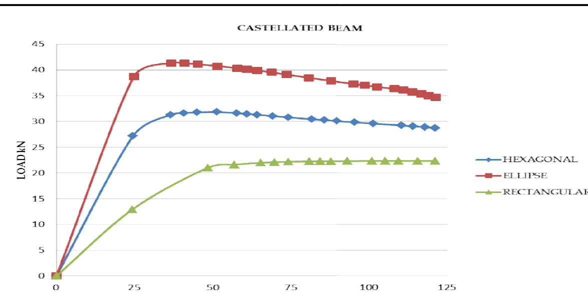

Fig. 10.Load deflection curve comparing the three shape of openings in castellated beams with full height web openings

In case of partially encased castellated beams, the three shapes of full height web opening were compared and the elliptical shape of opening was the better one which showed 19.19 percentage of increase in load carrying capacity than rectangular opening beam. Hexagonal opening showed 7.56 percentage of increase in load carrying capacity than rectangular opening beam.

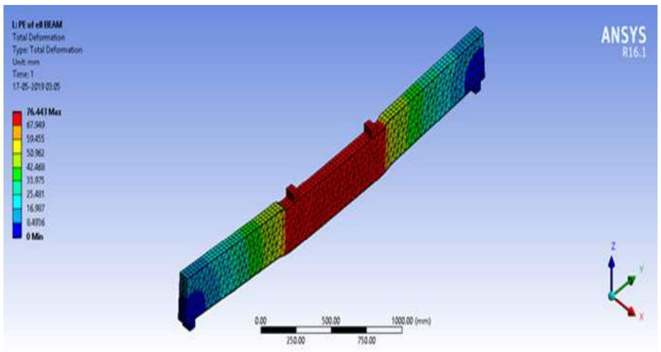

Fig. 11.Total deformation of castellated beam with full height elliptical opening in partially encased condition

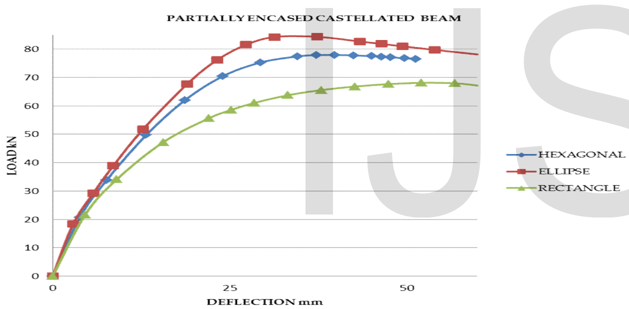

Fig. 12.Load deflection curve comparing the three shape of openings in castellated beams with full height web openings in partially encased condition

In case of fully encased castellated beam, elliptical shape of opening showed maximum load carrying capacity. Elliptical opening showed 1.53 percentage of increase in load carrying capacity than rectangular opening beam. Hexagonal opening showed only 1.23 percentage of increase in load carrying capacity than rectangular opening beam.

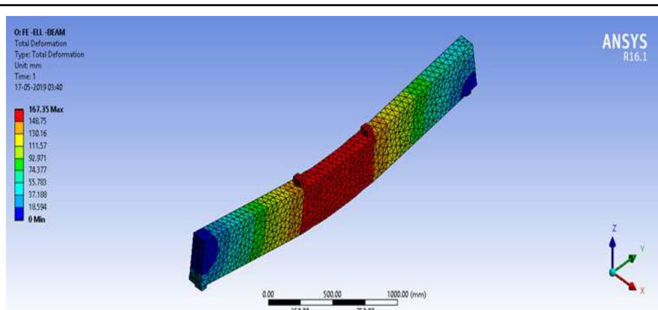

Fig. 13.Total deformation of fully encsed castellated beam with full height elliptical opening

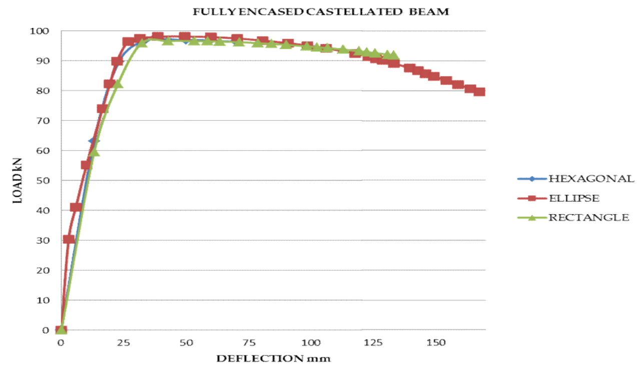

Fig. 14.Load deflection curve comparing the three shape of openings in castellated beams with full height web openings in fully encased condition

In case of castellated columns elliptical opening was better in all conditions. In castellated columns, elliptical opening showed 8.12 percentage of increase in load carrying capacity than hexagonal opening column. Rectangular opening showed 6.18 percentage of increase in load carrying capacity than hexagonal opening column. In case of partially encased castellated column, elliptical opening showed 4.52 percentage of increase in load carrying capacity than rectangular opening column. Hexagonal opening showed 1.21 percentage of increase in load carrying capacity than rectangular opening column. In case of fully encased castellated column, elliptical opening showed 2.58 percentage of increase in load carrying capacity than rectangular opening column. Hexagonal opening showed only 0.64 percentage of increase in load carrying capacity than rectangular opening column.

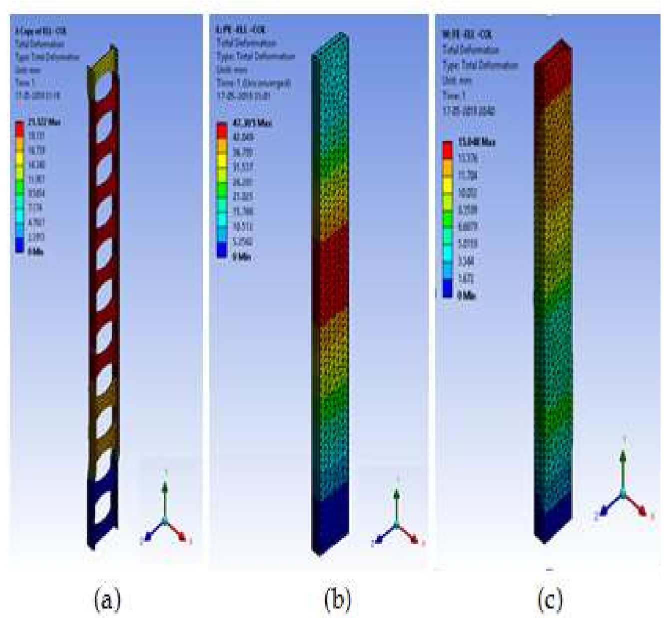

Fig. 15.(a) Total deformation of full height elliptical opening castellated column (b) partially encased condition (c) fully encased condition

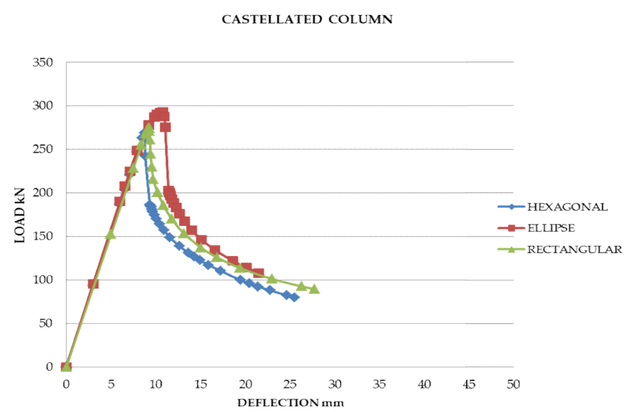

Fig. 16.Load deflection curve comparing the three shape of openings in castellated columns with full height web openings

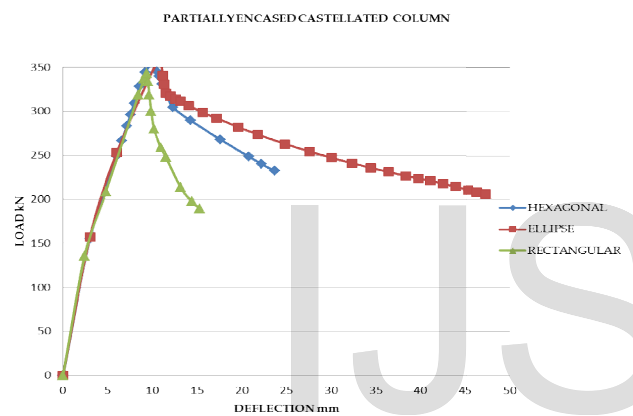

Fig. 17.Load deflection curve comparing the three shape of openings in castellated columns with full height web openings in partially encased condition

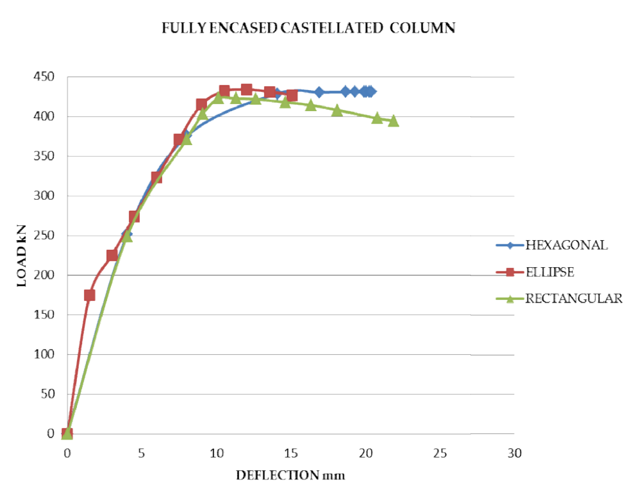

Fig. 18.Load deflection curve comparing the three shape of openings in castellated columns with full height web openings in fully encased condition

TABLE 1
RESULTS COMPARISON

	Model	Shape of web opening	Maximum load (kN)
Castellated steel beam	Without encasement	Elliptical	41.292
		Hexagonal	31.833
		Rectangular	22.359
	Partially encased	Elliptical	84.294
		Hexagonal	77.919
		Rectangular	68.112
	Fully encased	Elliptical	98.181
		Hexagonal	96.966
		Rectangular	96.682
Castellated steel column	Without encasement	Elliptical	292.79
		Hexagonal	269
		Rectangular	274.67
	Partially encased	Elliptical	359
		Hexagonal	354.64
		Rectangular	342.79
	Fully encased	Elliptical	433.77
		Hexagonal	430.98
		Rectangular	422.6

7 CONCLUSION

Castellated members were developed as structural channels to increase the depth and strength without adding additional material and weight.Such beams are more resistant to bending, as the section modulus is increased. Castellated column has more buckling load carrying capacity. Both castellated beam and column has advantageous applications in structural engineering.

In this paper, castellated steel beams and columns with full height web openings were considered. In castellated members stress concentration increases at hole corners and at load application point. Elliptical shape of web opening shows better performance in both castellated beams and columns.

To reduce the stress concentration and to increase the strength, steel encased in concrete method can be used. Both composite beams and columns with partial encasement and full encasement were analysed. Both the methods improved the load carrying capacity of the member. Elliptical shape of web opening showd more load carrying capacity in both partially encased and fully encsed condition. From the analysis it can conclude that elliptical shape of web opening is more suitable for the better behaviour of castellted members.

REFERENCES

[1] T.C.H.Liu and K.F. Chung, “Steel beams with large web opening of various shape and size: finite element investigation” *Journal of constructional steel research*, pp. 1159-1176, 2003

[2] Khaled Sawy, Amr Sweedan and Mohamed I.Martini, "Major-axis elastic buckling of axially loaded castellated steel columns" *Journal of thin walled structures,* pp. 1295–1304, 2009

[3] Konstantinos Daniel Tsavdaridis and Cedric D'Mello, "Web buckling study of the behaviour and strength of perforated steel beams with different novel web opening shapes" *'Journal of constructional steel research,* pp. 1605-1620, 2011

[4] Konstantinos Daniel Tsavdaridis and Cedric D'Mello, "Optimisation of novel elliptically-based web opening shapes of perforated steel beams" *'Journal of constructional steel research,* pp. 1605-1620, 2012

[5] Wei-bin Yuan, Boksun Kim and Long yuan Li, "Buckling of axially loaded castellated steel columns" *Journal of constructional steel research,* pp. 40-45, 2014

[6] Peijun Wang, Qijie Ma and Xudong Wang, "Investigation on Vierendeel mechanism failure of castellated steel beams with fillet corner web openings" Journal of engineering structures, pp. 44-51, 2014

[7] Delphine Sonck and Jan Belis, "Lateral torsional buckling resistance of castellated beams" Journal of Structural Engineering, pp. 1-9, 2016

[8] M. Najafi and Y.C.Wang, "Behaviour and design of steel members with web openings under combined bending, shear and compression" Journal of constructional steel research, pp. 197-206, 2017

[9] Richard Frans, Herman Parung, Desi Sandy and SuriantiTonapa, "Numerical modelling of hexagonal castellated beam under monotonic loading" Journal of sustainable civil engineering structures and construction materials, pp. 781-788, 2017

[10] Iman Satyarno, Djoko Sulistyo, Dina Heldita and A. Talodaci Corte, "Full height rectangular opening castellated steel beam partially encased in reinforced mortar" Journal of sustainable civil engineering structures and construction materials, pp. 176-184, 2017