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Study on Behaviour of Castellated Beams with Externally Prestressed Condition

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Abstract

Castellated beams offer a balance between structural efficiency and architectural aesthetics. They provide opportunities for creativity, innovation, and sustainability in construction projects, making them valuable components in the fields of engineering and architecture. Engineers and architects often use castellated beams to achieve both structural and aesthetic goals in their designs. In structural aspect, the behaviour of castellated beam serves less than the service provided by solid beam. Though this of obvious, the improvement of behaviour of castellated beam should be concentrated. Here an attempt has been made experimentally to use external prestressing to enhance castellated beam behaviour. Four beams are fabricated and tested. The castellated beam with prestress behaves extremely good in all aspects can be noted from the results. Finite element analysis is also attempted for the experimental beams and discussed in this paper.

Keywords: Castellated Beam, Prestress, Finite element analysis

1. Introduction

Castellated beams, also known as "castle beams" or "castellated steel beams," are a type of structural beam commonly used in building construction. These beams are characterized by a unique pattern of evenly spaced openings, resembling the battlements of a castle, hence the name. The process of creating castellated beams involves taking a standard wide-flange steel beam and cutting a series of evenly spaced slots or openings along its web (the vertical portion of the beam). These slots are typically made using a computer-controlled cutting process, such as plasma cutting or laser cutting as shown in Fig. 1.

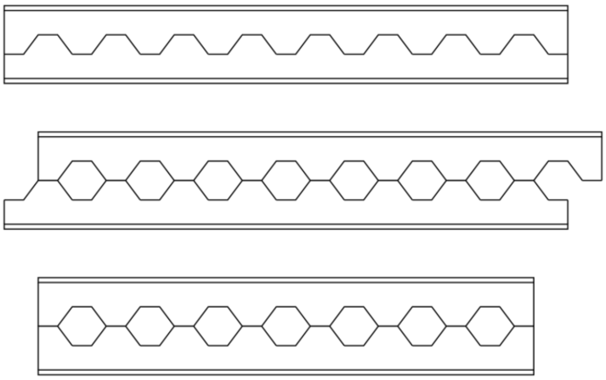


Fig. 1 Schematic Representation of process of a castellated beam

(**Source:** https://en.wikipedia.org/wiki/Castellated_beam)

As per AISC[1], the failure of castellated beams are primarily due to Compactness and Local buckling, Overall beam flexural Strength, Vierendeel bending of Tees, Web post buckling, Axial tension or compression, horizontal shear, Vertical Shear and Lateral Torsional Buckling. Both lateral torsional instability and formation of flexural mechanism may occur simultaneously as a failure mode and predicting failure loads are established considering both failure mode by Kedral et al[2]. The behaviour of normal and high strength castellated beams under combined lateral torsional and distortional buckling modes are studies by Ellobody[3]. Lateral torsional buckling can be avoided by properly spaced and designed lateral bracings[4]. Distortional buckling mode of failure is also a significant factor to be considered[5]. To control lateral torsional buckling of the beams, elastically bracing of the beams works well [6]. The beams stiffened around castellation as star pattern better performance. Also, instead all castellation, stiffeners only at end castellation performs satisfactory [7]. Usually castellation are in hexagonal in shape. Apart from hexagonal, some studies has been carried out using circle and octagonal shape as well [8]. Apart from LTB (lateral torsional buckling), local buckling also possible major failure mode in these beams [9]. Opening i.e. castellation in various eccentricities has minimal research work done and is also major part to evaluate in this area [10].

Many non-linear finite element analyses is also seen to have done by researchers around globe in castellated beams using platforms such as ANSYS, ABACUS etc[11][12][13][14]. Many experimental works has been carried out in this castellated beam by Research and Development swinden laboratories on 1957[15] and 1958[16], Toprac et al. (1959)[17], Kolosowski, J. (1964)[18], Sherbourne (1965)[19], Sherbourne (1966)[20], Bazile et al. (1968)[21], Hosain et al. (1973)[22], Galambos et al. (1975)[23], Kerdal et al.(1982)[24], Okubo et al. (1985)[25], Zaarour et al. (1995)[26], Redwood et al. (1998)[27], Zirakian et al. (2006)[28]. All these works has been reviewed before accordingly the geometry of the beam has been fixed for this experimental work.

2. Research Significance

Lot of advantages and disadvantages has been seen in castellated beams. In view to improve the strength of the castellated beams, the idea of prestressing the castellated beam has been considered. Not much study has been carried out in this area. This drove us to do the test and study in this aspect.

3. Experimental Study

The beamsare fabricated in factory and tested in Structural Engineering Laboratory, Sona College of Technology, Salem, Tamilnadu, India. Four full scale specimens has been planned and tested in laboratory. First beam is control beam with no castellation. it has been designated as B indicating Beams. Second beam is with hexagonal castellation and designated as B+C indicating beam with castellation. Third beam is castellated beam with stiffeners and designated as B+C+S indicating beam with castellation with stiffeners. Last beam is castellated beam strengthened with stiffeners along with external prestressing. This is designated as B+C+S+P indicating beam with castellation with stiffeners with prestressing. Lot of studies performed around globe in castellated beams. The different notations are used to denote various parameters in castellated beams by the codes and researchers. The following notations demonstrated Fig. 2 is adopted in this study.

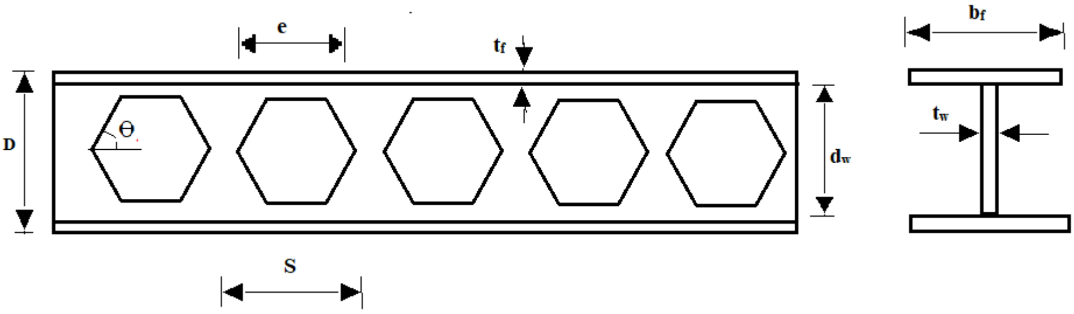
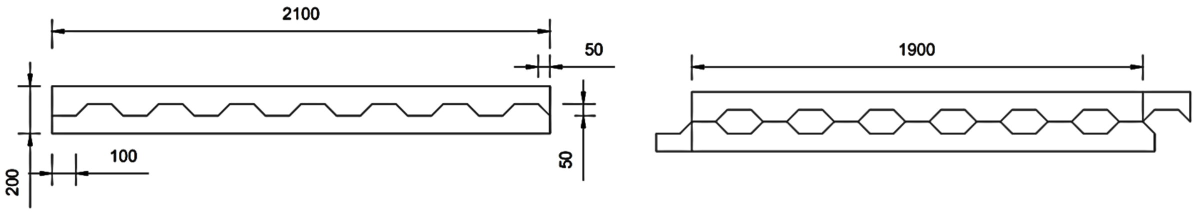


Fig. 2 Notations of parameters in Castellated Beams

3.1 Geometry of the Specimen

The experiment series includes four full scaled beams as indicated in previous section. The length of the beam is taken as 1.9 m for all beams. The web depth of the control beam is 200 mm while for all other three beams are 250 mm. This increased depth is due to castellation. All four specimenshave same material size and quantity. This means that there is no extra material is used to increase the depth from 200 mm to 250 mm. This is shown in Fig. 3.



(a) Web Laser Cutting (b) Castellation

Fig.3 Web Portion of Castellated beams

The thickness of the specimens is taken as 4 mm. This is arrived on the basis of Table 2 page 18 of IS800:2007. The limiting width to thickness of web of I section is 84ξ for the section behaves in plastic. The geometric dimensions of the tested beams are illustrated in Table 1.

Table 1Geometric Detail of Experimental Specimens

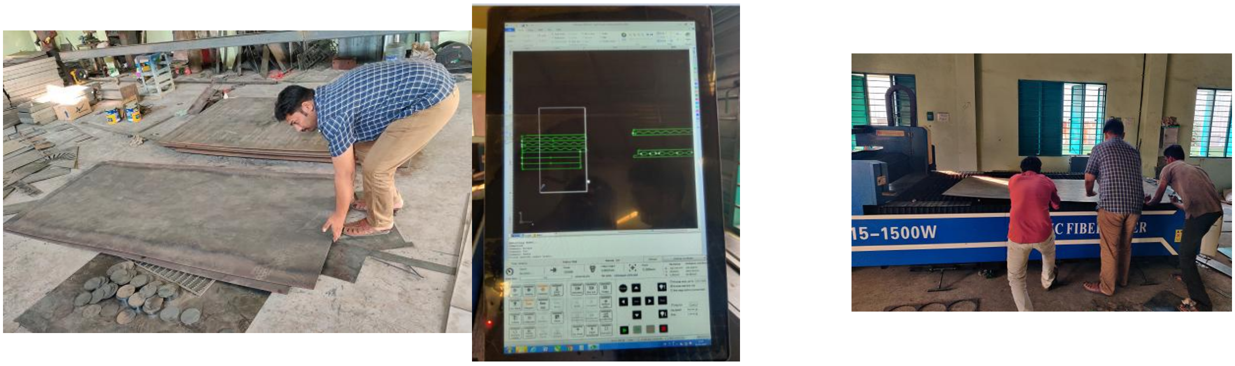
S. No.	ID	fy (MPa)	D (mm)	b_f (mm)	t_w(mm)	t_f (mm)	S (mm)	e (mm)	*SS (mm)	**PS Depth (mm)	PS Force (kN)	L (m)
1	B	250	208	100	4	4	0	0	0	0	0	1.9
2	B+C	250	258	100	4	4	300	200	0	0	0	1.9
3	B+C+S	250	258	100	4	4	300	200	300	0	0	1.9
4	B+C+S+P	250	258	100	4	4	300	200	300	158	15	1.9

***SS – Stiffener Spacing**

****PS - Prestress**

3.2 Specimen Fabrication

The process of fabrication of castellated beams includes material selection, design of beams, CNC Cutting, alignment, welding, Grinding. As mentioned, 4 mm thick steel plates have been chosen for fabrication of castellated beams. The castellation pattern is typically created using Computer Numerical Control (CNC) cutting. After cut, the plate is flattened to ensure all the castellation are aligned properly. Welding is done for connections at the cut edges of the castellated beam. The flanges are also welded fully with this castellated web portion. The beam fabrication process is shown in Fig. 4.



(a) Steel Plate (b) Drawing Feed in CNC (c) Plate placement in CNC

(d) CNC Laser Cutting (e) Positioning (f) Welding

(g) Hole for Prestress Strand (h) Castellated Beam (i) With Stiffeners

Fig. 4 Preparation of Castellated beam

The fourth specimen B+C+S+P is an externally prestressed beam which is the prime interest for this study. This prestress is done with the help of Utracon Structural System. The prestress strand size is 12.7 mm. The straight prestress profile has been chosen and accordingly the strands are inserted through the hole in the stiffener as seen in Fig. 4(g). These prestress strands are positioned and properly cut at the ends. The prestress force has been given at the ends and all the process are shown in the Fig. 5.

(a) Strand Insertion (b) Strand Cutting (c) Anchorage End Block

(d) Prestressing (e) Prestress Monitoring (f) Finished Prestress Beam

Fig. 5 Process of External Prestressing

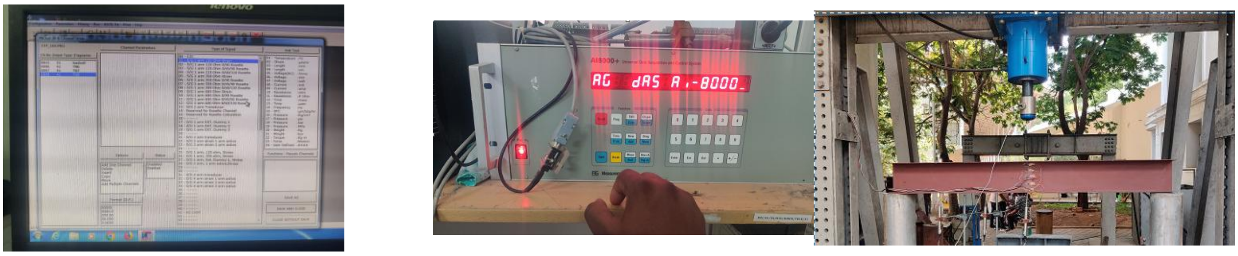
3.3 Test Setup

The testing of beams is done using 50 ton capacity reaction frame in Sona College of Technology in Salem, Tamilnadu, India. The four beams are tested for its flexural behaviour. All the beams are fitted with 5 strain gauges at the centre of the beam along its depth as shown in Fig. 6. The strain gauges are Foil type 120 ohm resistance with grid length 5 mm.

(a) Surface Preparation (b) Strain Gauge Placement

Fig. 6 Strain Gauge Installation

Beam is made simply supported and two point loading is given to study the flexural behaviour. The shear span is fixed about 450 mm and span of beam fixed about 1800 mm.It has been used 25 ton capacity hydraulic jack which is fixed and tightened sufficiently to avoid any movement of the jack. Two points loading is given with the help of a spreader steel beam under the jack. This is shown in Fig. 7. The loading has been applied with the rate of 0.2 kN/s. The reading has been taken until the load drops after reaching the peak load. Three LVDT has been fixed for reading the deflection of the beam. 16 Channel DAQ (Data Acquisition System) has been used for recording the testing data. Prosoft software is used to read the data acquisition.



(a) Prosoft Software (b) DAQ Device (c) B

(d) B+C (e) B+C+S (f) B+C+S+P

Fig. 7Experimental Setup

4. Experimental Results

A series of four beams has been tested to investigate its bending characteristics. The results include load-deflection response, failure pattern, strength, ductility, lateral stiffness and energy dissipation.

4.1 Load-Displacement Response

The entire beam test series is tested with four points loading with a/d ratio as 2.25. As per Kani's Valley, the influence of shear span to depth ratio has major role in flexure behaviour as shown in Fig. 8. This drove us to test with less a/d ratio. Hence the shear span is fixed at 450 mm which gives a/d ratio as 2.25.

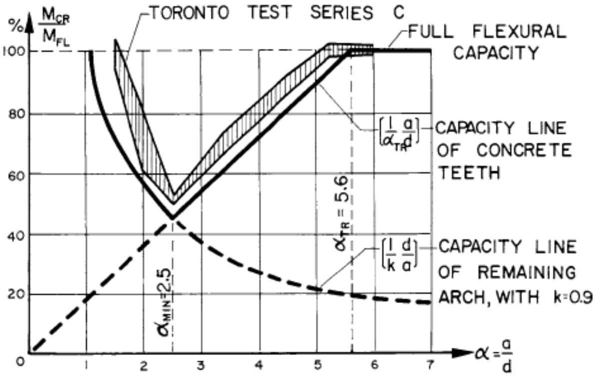


Fig.8Kani's Valley

As the beams are not laterally restrained, the lateral torsional buckling mode failure is initially expected. But the beam is loaded with low a/d ratio. All the four beams exhibited lateral torsional buckling failure as seen in Fig. 9. The vertical displacement is very less with high for prestress beam about 15 mm.

(a) B (b) B+C

(c) B+C+S (d) B+C+S+P

Fig. 9 Beam Failure

All the beams except last failed by lateral torsional buckling. Last beam i.e. prestressed beam failed by both lateral torsional buckling and bending mode. This is clearly seen from Fig. 9. This is happened due to the presence of direct stress along cross section due to the prestress. LTB failure happens due to no lateral support and also in function of length of the beam. This has been largely influenced by prestress and strength has been enhanced in massive extent. The load – displacementplot i.e vertical deflection taken with help of LVDT at centre is shown in Fig. 10.

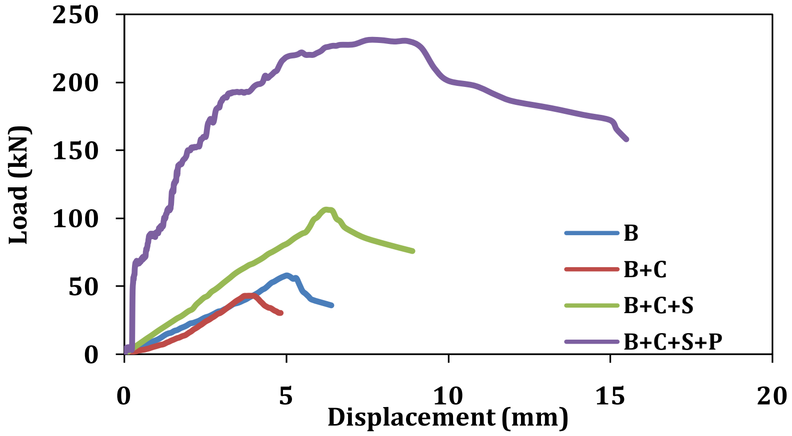


Fig. 10 Load – Displacement Plot

4.2 EEEP Curve

The analysis is performedbased on Equivalent Energy Elastic Plastic Curve (EEEP Curve) principle. This EEEP curve is a perfectly elastic-plastic representation of the actual response of the specimen. This bilinear EEEP curve is plotted such that it equals the area under the load-deflection curve until failure i.e. the energy dissipation capacity is equal. Fig. 11shows the various points of interest used to derive the EEEP curve.

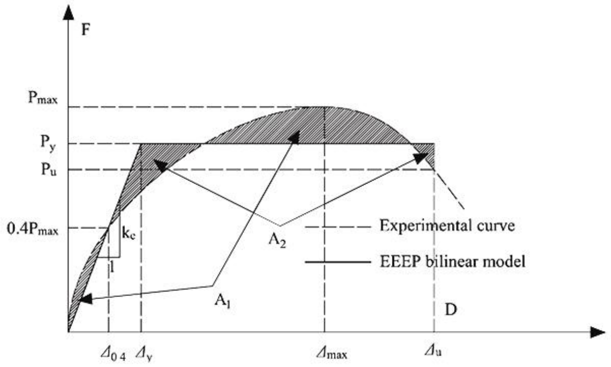


Fig. 11EEEP Curve

The salient features of the EEEP bilinear curve are,

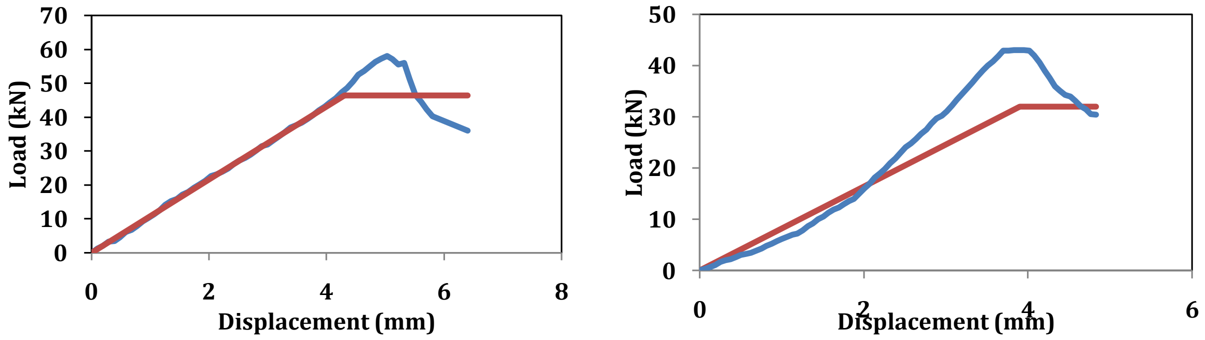
k_e – Secant Stiffness at the point corresponding to 40% of the maximum load

P_y – Yield strength as per EEEP curve

Δ_y – Yield Displacement corresponds to P_y

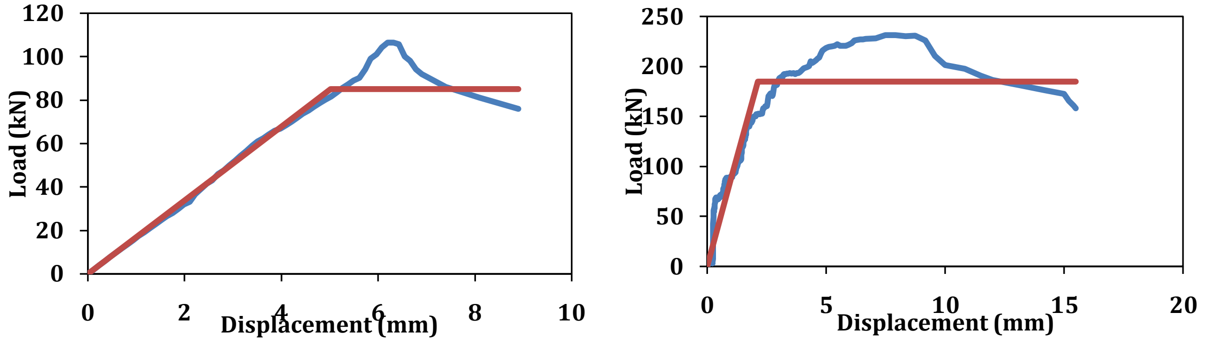
Δ_u – Ultimate displacement which corresponds $0.8P_{max}$ at post peak

The area (energy) under the backbone curve was then calculated up to the post-peak displacement that corresponds to the EEEP curve up to the lateral displacementΔ_u. The slope of inclined portion of the EEEP curve corresponds to the Secant Stiffness at 40% of the maximum load in backbone curve. A horizontal line depicting the plastic portion of the EEEP curve was then positioned so that the area bounded by the EEEP curve and the back bone are equal. Thus the value of yield strength and yield displacement is calculated. The EEEP curves for our specimen are shown in Fig. 12.



(a) B

(b) B+C



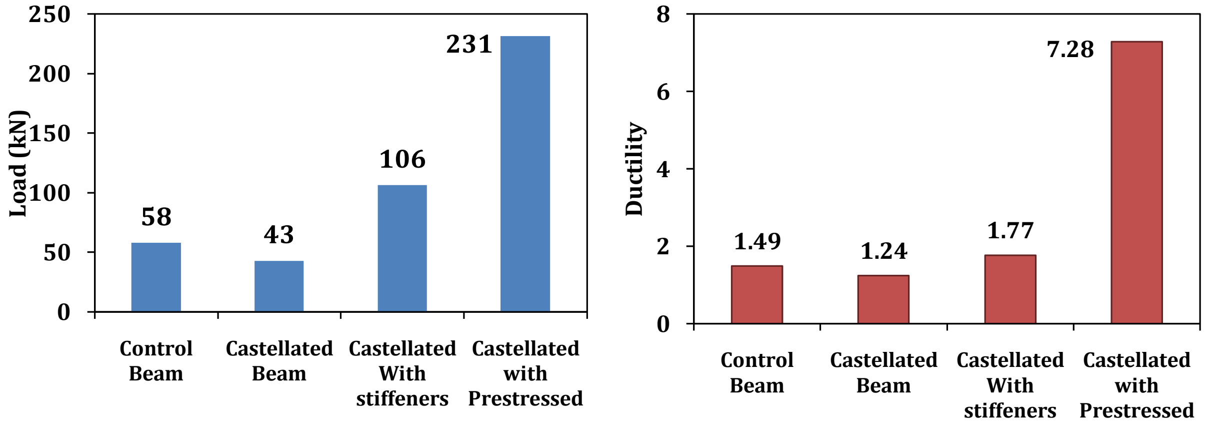
(c) B+C+S

(d) B+C+S+P

Fig. 12EEEP Curves

4.3 Ultimate Load and Ductility Index

The Peak load is high for prestressed beam. This is about four times than that of control beam. Also it can be seen that the peak strength of castellated beam has fall about 25% than control beam.There is 82% increase in Strength in case of beam with stiffeners as seen in Fig. 13.Ductility is defined by the degree to which a material can sustain plastic deformation.The ductility index is calculated from the ratio of ultimate displacement to the yield displacement. This is calculated based on the values from EEEP curve. The prestress beam has ductility about 4.8 times higher. This is due to the failure of control beam inLTB mode.



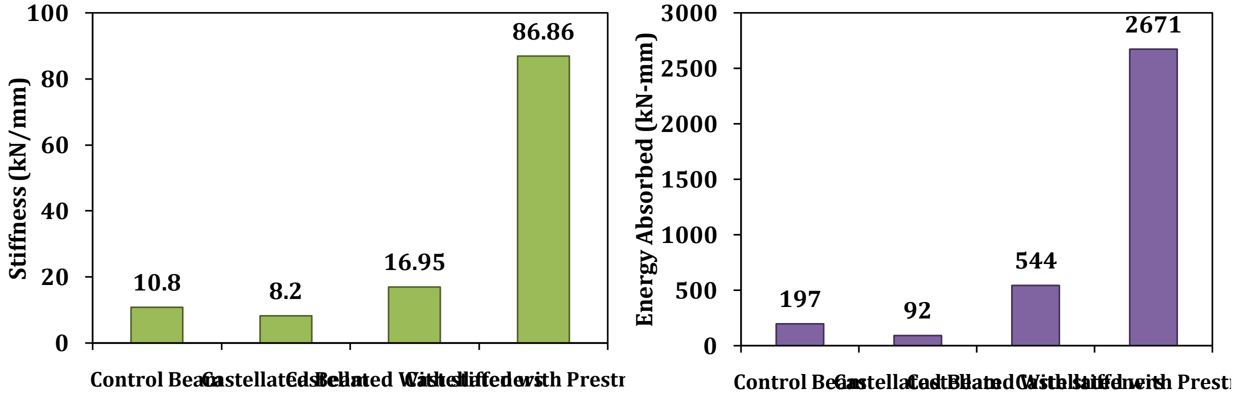
(a) Peak Strength

(b) Ductility Index

Fig. 13Peak Strength and Ductility of Beams

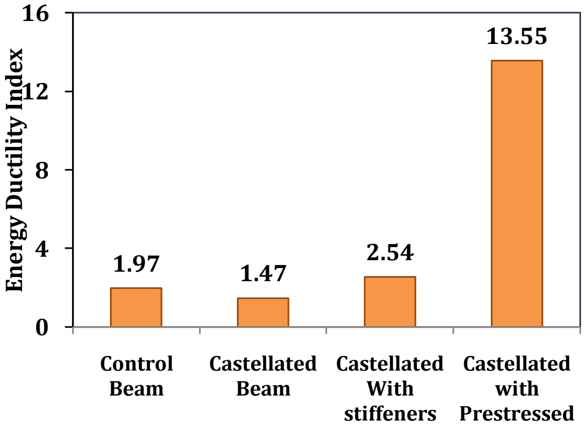
4.4 Stiffness and Energy Absorption

Stiffness is the extent to which an object resists deformation in response to an applied load[29]. The secant stiffness has been calculated corresponding to the ultimate load in the EEEP curve.It can be seen from the Fig. 14. That the stiffness for prestress beam has been increased about 8in comparison with control beam. The energy absorption capacity has found using Equivalent Energy Elastic Plastic Curve (EEEP Curve). The energy absorbed has been seen about 13 times and energy ductility index about 6.8 times increase for prestress beam in compared with control beam.



(a) Stiffness Index

(b) Energy Absorbed



(c) Energy Ductility

Fig. 14Stiffness and Energy of Beams

4.5 Result Comparison

The detailed flexural analysis has been performed and the results are tabulated in Table 2. The prestress beam seems to have performed in greater extent. This is due to the failure modes of the beams.

Table 2 Result Comparison

	ID	Peak Load (kN)	Ductility	Stiffness (kN/m)	Energy absorbed (kN-m)	Energy Ductility Index
Control Beam	B	58	1.49	10.8	197	1.97
Castellated Beam	B+C	43	1.24	8.2	92	1.47
Castellated With stiffeners	B+C+S	106	1.77	16.95	544	2.54
Castellated with Prestressed	B+C+S+P	231	7.28	86.86	2671	13.55

Lateral torsional behaviour of the beams played a vital role in the results. The prestress force contributes the direct force along the cross section of the beam. This controls the LTB failure of the beam and in turn results in this massive variation in output as shown in Fig. 15. It can be seen that the better performance order in almost all analytical parameters are in ascending, Castellated beam, control beam, castellated beam with stiffeners and castellated beam with stiffeners with prestress. Load carrying capacity of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 74%, 183% and 399% respectively. Ductility of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 83%, 119% and 489% respectively. Stiffness of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 76%, 157% and 804% respectively. Energy absorbed of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 47%, 276% and 1356% respectively. Energy ductility index of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 75%, 129% and 688% respectively.

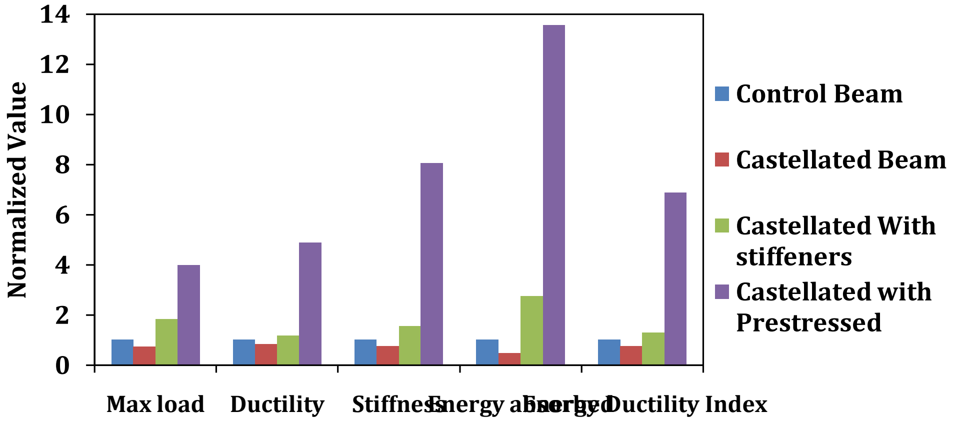


Fig. 15Result Comparison

5. Finite Element Modelling

Experiments provide the real behaviour of the structure but arecostly and time overwhelming. Development of sophisticated tools for analysis like the finite element analysis programme, it is potential to model and analyse the complicated structure. Finite element analysis (FEA) is widely used to analyse many structural components, as it is much faster than the experimental method and is very cost effective. In the present study the finite element package ANSYS 23 is used for modelling.

5.1 Element type Used

Three elements are adopted for modelling castellated beams. They are SHELL 281, PRETS179 and Solid 185 elements. Eight noded Shell elements is used for modelling beam, eight noded solid element is for modelling loading blocks and two noded link element for modelling prestress strands. It can be observed that the link is 1D element; shell is 2D element and solid is 3D element.

5.2 Material Property

All steel materials are assumed to exhibit elasto-plastic response with identical properties in tension and compression. The input material properties are enlisted in Table 3.

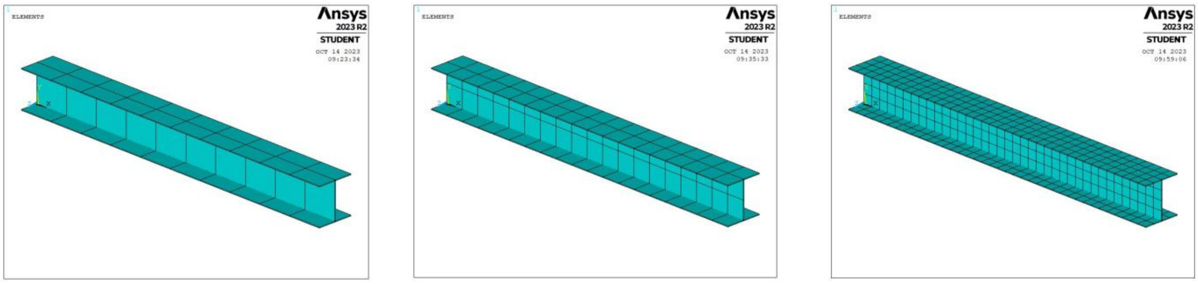
Table 3 Material Properties (in N, mm)

S. No.	Element Type	Component	Material Properties	
1	PRETS179	Prestress Strand	Linear Isotropic	
			Ex	200000
			PRXY	0.3

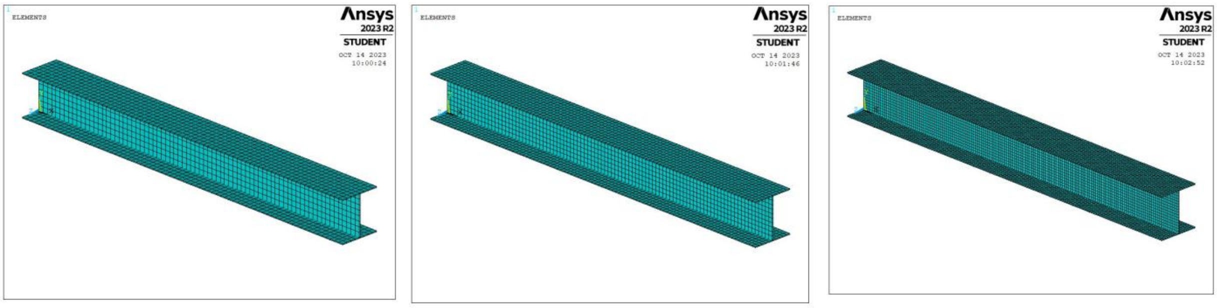
			Bilinear Isotropic	
			Yield Stress	1860
			Tangent Modulus	0
2	SHELL281	Beam	Linear Isotropic	
			Ex	200000
			PRXY	0.3
			Bilinear Isotropic	
			Yield Stress	250
			Tangent Modulus	0
3	SOLID185	Steel Loading Plate	Linear Isotropic	
			Ex	200000
			PRXY	0.3
			Bilinear Isotropic	
			Yield Stress	500
			Tangent Modulus	0

5.3 Mesh Convergence Study

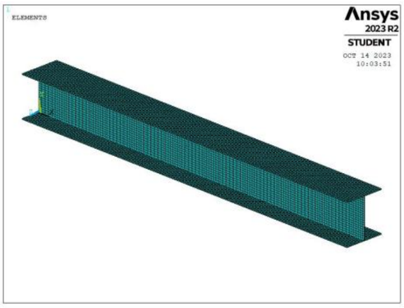
The mesh convergence study is executed to find the suitable mesh size of each element in the numerical model. Here, this study is performed using shell model in steel beam. Six beams of dimensions 1900 mm x 200 mm x 4 mm thick are modelled in ANSYS 23.0 with increasing number of elements 5700, 11400, 22800, 45600, 91200, 114000 corresponding to mesh size 200 mm, 100 mm, 50 mm, 25 mm, 12.5 mm and 10 mm2 respectively using Shell281 element as shown in Fig. 16.



(a) 200 mm Mesh Model (b) 100 mm Mesh Model (c) 50 mm Mesh Model



(d) 25 mm Mesh Model (e) 20 mm Mesh Model (f) 12.5 mm Mesh Model



(g) 10 mm Mesh Model

Fig. 16 Beam Model for Convergence Study

The variation of number of elements to deflection is shown in Fig. 17, describes that the deflection remains nearly constant from 45600 elements to 114000 elements. So, the finite element model consisting of 45600 elements corresponds to mesh size 25 mm is used for this entire study.

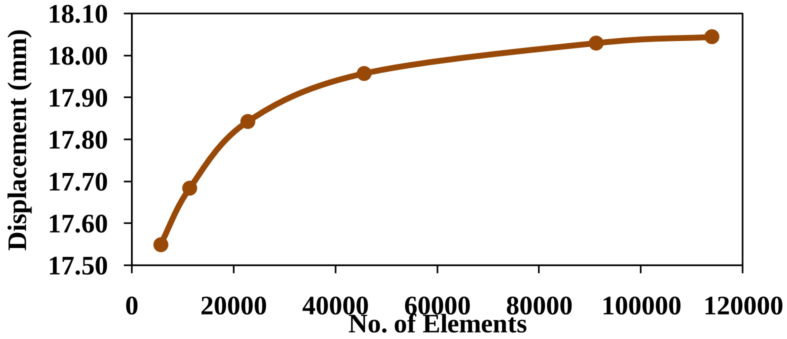
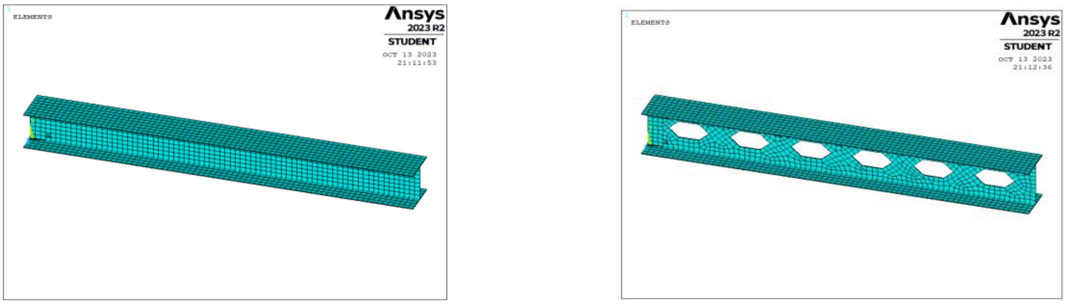


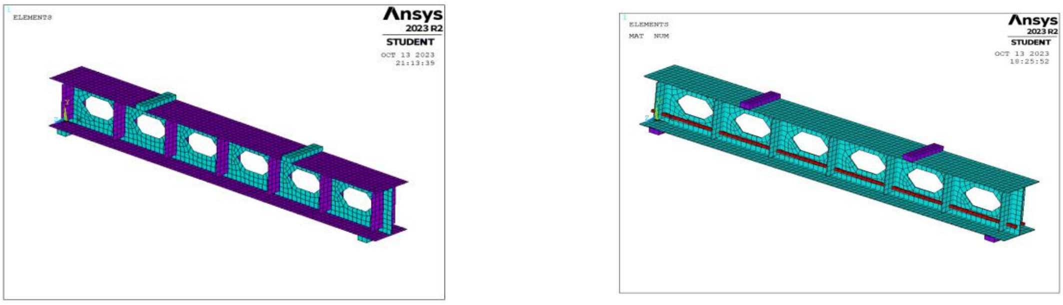
Fig. 17 Mesh Convergence Study

5.4 Modelling and Meshing

As indicated earlier, beam is modelled using SHELL281 element, loading blocks are modelled using SOLID185 and prestressed strands are modelled using LINK180 element. The material models are assigned respectively and meshed with 25 mm mesh size as got from previous section. The model and meshing is shown in Fig. 18.



(a) B Specimen (b) B+C

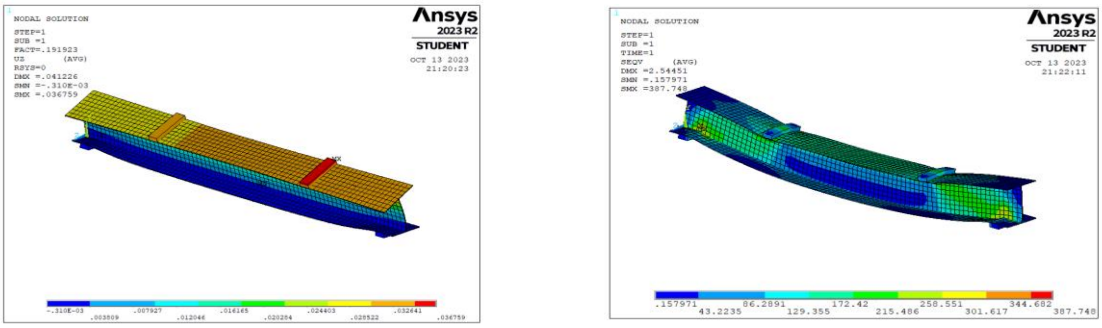


(c) B+C+S (d) B+C+S+P

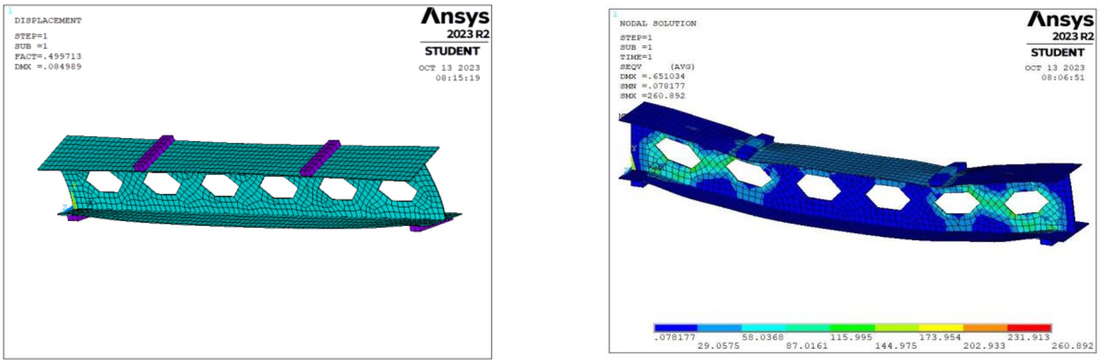
Fig. 18 Meshing

5.5 Results and Discussion

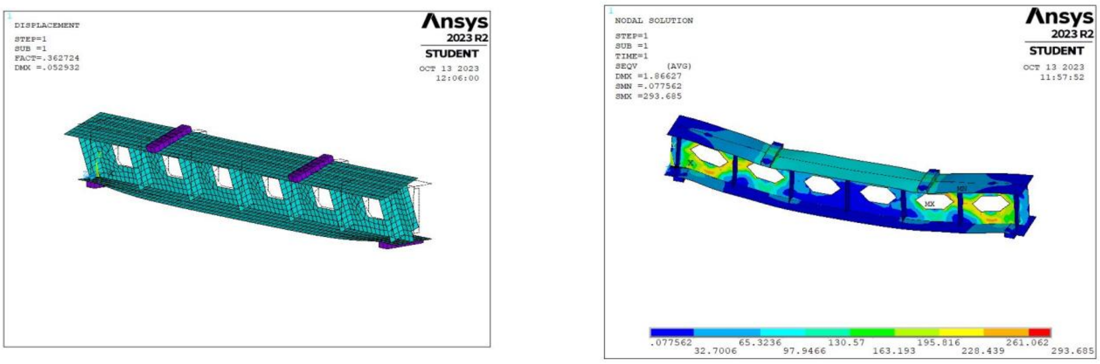
The failure criteria are chosen to be Von Mises stress as the material is steel. The Von Mises stress, often referred to as the Von Mises yield criterion, is a measure of the stress experienced by a material subjected to complex or multi-axial loading conditions. The displacement and von mises stresses of the specimens are shown in Fig. 19.



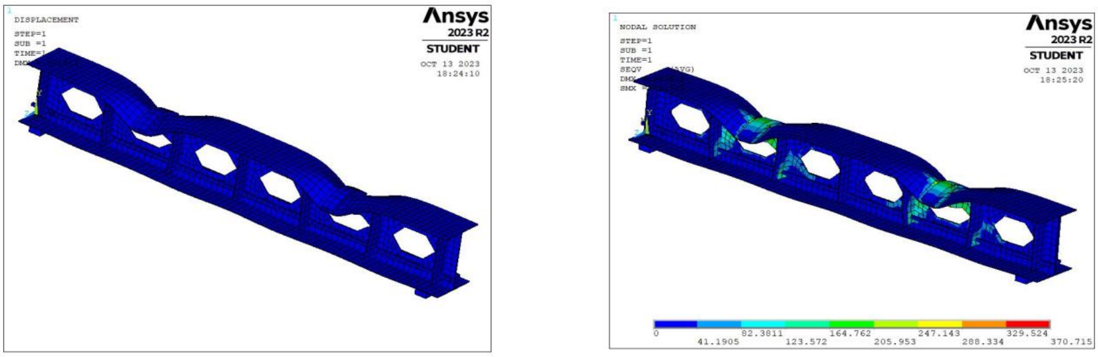
(a) B Specimen Deflection (b) B Specimen Von mises



(c) B+C Specimen Deflection (d) B+C Specimen Von mises



(e) B+C+S Specimen Deflection (f) B+C+S Specimen Von mises



(g) B+C+S+P Specimen Deflection (h) B+C+S+P Specimen Deflection

Fig. 19 Deflection and Von Mises stress

It can be seen that the failure mode of beam with prestress has been completely transformed. The loading flange has been failed instead of LTB or bending. The loading at which this von mises stress has been obtained is taken as failure load and is listed in Table 4.

Table 4 Numerical Analysis Result

	Control Beam	**Castellated Beam**	**Castellated with stiffeners**	**Castellated with Prestressed**
Experimental (kN)	58	43	106	231
Numerical (kN)	54 (1000 N at 54 Nodes)	37.8 (700 N at 54 Nodes)	118.8 (2200 N at 54 Nodes)	205.2 (3800 N at 54 Nodes)

6. Conclusion

The behaviour of prestressed beams with and without prestress has been studied in this work. The experimental and numerical analysis has been done. The major inferences from this study are as follows.

- Failure modes of the beams are combined effect of bending and lateral torsional buckling. Except prestressed beam, LTB failure mode hand rises over bending.
- Load carrying capacity of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 74%, 183% and 399% respectively.
- Ductility of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 83%, 119% and 489% respectively.
- Stiffness of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 76%, 157% and 804% respectively.
- Energy absorbed of the castellated beam, castellated beam with stiffeners and castellated beam with stiffener with prestress beams with respect to control are about 47%, 276% and 1356% respectively.
- A finite element study result well agrees with experimental results.

In nutshell, the use of prestress over castellated beam enhances the behaviour of the beam in all aspect heavily.

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