Comparative Study on Weight Efficiency of Castellated Steel Beams and Conventional I-Beams

Suraj Bharad*, and Prashant Modani

Pankaj Laddhad Institute of Technology and Management, Buldhana, Maharashtra, India

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ABSTRACT

In modern steel construction, reducing self-weight while maintaining structural adequacy is a key design objective. Castellated steel beams, fabricated by introducing web openings into rolled I-sections, are widely recognized for their enhanced depth and improved structural efficiency. This study presents a comparative investigation on the weight efficiency of castellated steel beams versus conventional rolled steel beams designed for identical loading and span conditions. Beams with spans of 10 m, 13 m, and 16 m are designed in accordance with IS 800:2007 provisions. Finite Element Analysis (FEA) is carried out using ANSYS to validate structural performance in terms of stress and deflection. The results highlight that castellated beams achieve significant weight reduction—up to 20–25%—without compromising serviceability or strength requirements. The study establishes castellated beams as a structurally efficient and economical alternative to conventional steel beams in long-span applications.

Keywords: Castellated beams, Weight optimization, Material efficiency, Steel structures, Finite element analysis

INTRODUCTION

Steel beams are fundamental load-carrying elements in buildings, bridges, and industrial structures. Conventional rolled I-sections are commonly adopted due to their simplicity in design and fabrication. However, increasing span lengths and service integration demands have motivated the development of structurally efficient alternatives.

Castellated beams are produced by cutting a rolled I-section along its web and re-joining the halves to form a deeper section with regularly spaced openings. This fabrication technique increases the section depth without a proportional increase in weight, thereby improving the strength-to-weight ratio. While several studies have focused on buckling behavior and load-carrying capacity, limited attention has been given exclusively to quantifying weight savings under identical design constraints.

This paper addresses that gap by comparing the self-weight, material consumption, and efficiency indices of castellated beams with conventional beams designed for the same loading and span conditions. Since a literature review offers a comprehensive synopsis and overview of the scholarship conducted from the past to the present, it is essential for any field. It helps analyze how research is different or distinct from other research and how it fits into the study's historical context. Boissonnade et. al. [1] investigated the lateral torsional buckling resistance of cellular steel beams by numerical analysis. The member slenderness, steel quality, base cross-section profile, bending moment distribution, and aperture size and position were among the significant aspects affecting the structural response that are examined. Oğuz [2] looked at the displacements brought on by bending moments and lateral torsional buckling at different locations across each of the two castellated steel beams that underwent four-point bending tests. de Carvalho et. al. [3] examined the LTB behavior of steel I-beams with sinusoidal web apertures, also known as "Angelina" beams. Kumbhar and Jamadar [4] assessed load-carrying capability of castellated beams with mild steel (MS) transverse stiffeners and carbon fiber reinforced polymer (CFRP) under two-point loading. The study's conclusions indicate that CFRP stiffeners are superior to MS stiffeners because they can provide greater load bearing capability while lowering weight and making application easier. Zhao et.

al. [5] demonstrated a comprehensive experimental and numerical evaluation of the flexural behavior of two new designs of partly encased composite (PEC) beams with H-shaped and T-shaped castellated main steel components (MSCs). Yehia et. al. [6] demonstrates how perforations on beams enhance the structural performance of cold-formed steel, which is prized for its affordability and durability. da Silva and Lubke [7] used computational optimization techniques to determine the maximum load-bearing capacity of hollow-core steel beams for two sets of different shear lines, one of which produces beams with hexagon-shaped openings and the other with elliptical ones. Zewudie et. al. [8] provided a numerical evaluation of the arched web-post shear resistance, post-buckling mode, and in-plane elastic-plastic performance of a circular arched cellular steel beam with a pinned end using the ABAQUS nonlinear finite element analysis tool. Ben et. al. [9] studied an advanced framework for predicting the lateral-torsional buckling behavior of cellular steel beams by combining hybrid intelligence models with numerical simulation. Kocher and Kulkarni [10] analyzed simply supported beams with different I-sections, namely ISLB, ISMB, and ISWB. The study discovered that differences in buckling modes had no discernible impact on the buckling load estimates in the initial set of evaluations. Khalate and Kulkarni [11] present a simple and accurate three-dimensional finite element Model (FE) capable of predicting the actual behavior of beam-to-column joints in steel frame subjected to static loads. The main parameters considered in this study were the thickness of flange & web, span and number of bolts. Kowshik and Kulkarni [12] studied the effect of castellations on beams with tapered web for various spans whereas Kulkarni and Swathi [13] studied finite element analysis of castellated beams subjected to flexure. Niranjan et al. [16] also carried out similar work but it was limited to only one hexagonal opening.

The contemporary research has taken into account hypothetical data and research gaps were identified. It was determined to use fictitious data from the conventional literature review to analyze and construct steel castellated beams.

Objectives of the Study

The primary objectives of this investigation are:

1. To design conventional steel beams and castellated steel beams for identical spans and loading conditions.
2. To evaluate and compare the self-weight of both beam types.
3. To assess material efficiency through weight-to-span and weight-to-moment capacity ratios.
4. To validate structural adequacy using finite element analysis.
5. To quantify percentage material savings achieved using castellated beams.

METHODOLOGY

3.1 Beam Configuration and Loading

Three beam spans are considered: 10 m, 13 m, and 16 m.

For each span:

- A conventional rolled I-beam is selected.
- A castellated beam is fabricated from the same parent section.

The beams are subjected to:

- Dead load
- Imposed load

- Self-weight (iteratively calculated)

Design is carried out as per IS 800:2007 guidelines.

Design as per IS:800-2007 [15]

Castellated beams were designed with:

- Increased overall depth (approximately 1.4–1.5 times the parent section)
- Circular web openings
- Adequate web-post width to ensure shear and local stability

The design of Castellated Steel beam for a span of 13m was carried out with design data [14] as under. The summary of the design [15] of castellated beam with circular openings is in Table 1 below.

Table 1: Summary of castellated beam design

Particular	**Value**	**Particular**	**Value**
Span	13m	Spacing	450mm
Load	8 kN/m	No. of openings	24
Original section	ISMB400	Max moment	169 kNm
Castellated depth	600mm	Moment capacity	351.4 kNm
Opening type	Circular	Max shear	52 kN
Opening diameter	300mm	Shear capacity	401.7 kNm
Clear gap	262.5mm	Max deflection	43.3mm
Steel grade	Fe 410 (f_y = 250 N/mm²)		

Model of beam with circular openings

Finite Element Analysis is performed using **ANSYS** to validate the analytical design.

- Element type: SHELL63
- Material properties:
  - Young’s modulus = 2×10^5 N/mm²
  - Poisson’s ratio = 0.3
- Boundary conditions: Simply supported
- Load application: Uniformly distributed load

The analysis focuses on:

- Maximum deflection

- Stress distribution
- Overall structural behavior

The main aim of this study is to compare the load carrying capacity of normal steel beam as against castellated beam. Finite element (FE) solution is an approximation to find out how much closer is the representation of ideal calculation in terms of deflection, stresses, strains etc. FE based software was used to carry out a analysis in order to compare the behavior of a castellated steel beam. Two-dimensional shell element Shell63 was employed to generate the models. The castellated beam's geometric characteristics, including beam length, web height, and flange width, were considered. The beam model under consideration was with following dimensions: Overall span 13m, Effective span 12.5m, Depth of beam 600mm, Flange width 150mm, Web thickness 9.4mm and Flange thickness 17.4mm. The FE model of 13m span beam with castellations is shown in Fig. 1 and Fig. 2.

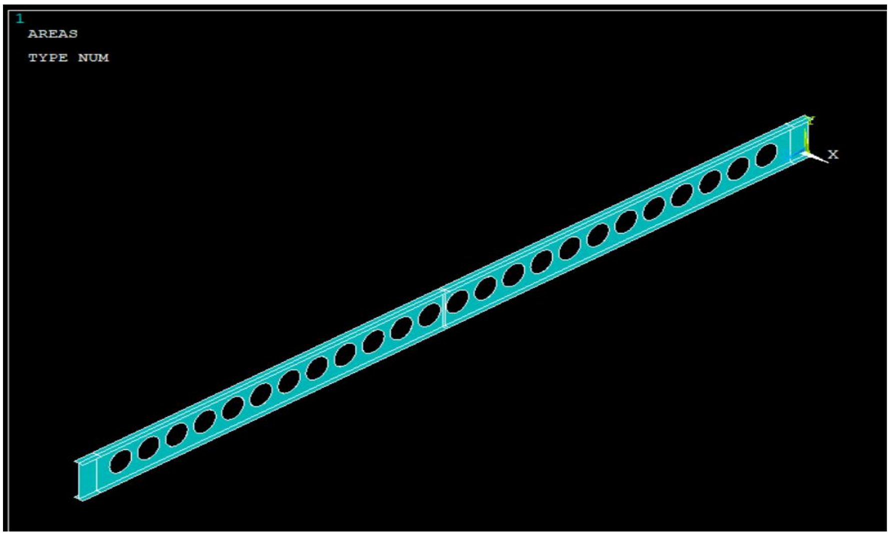

Fig. 1: FE Model of a 13m normal castellated steel beam

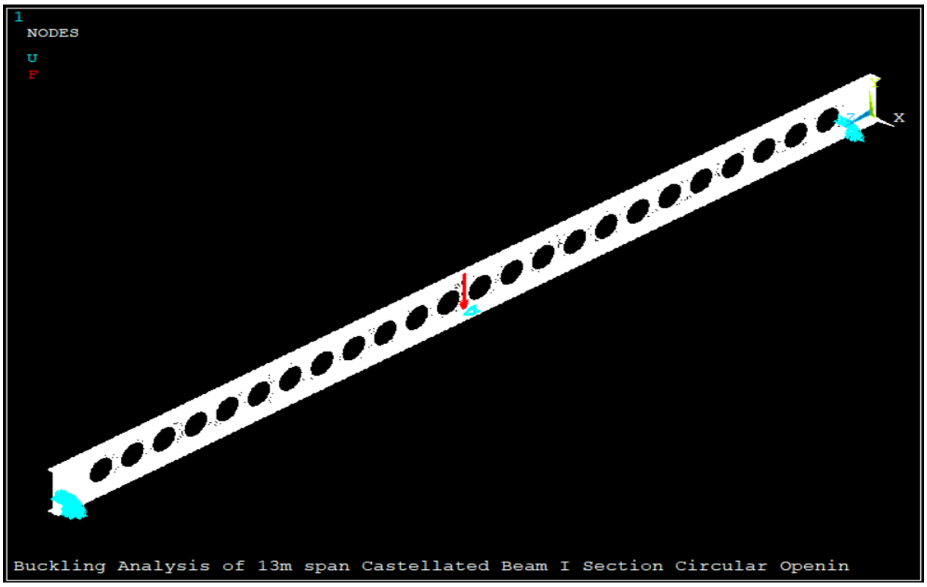

Fig. 2: Loading and boundary conditions on 13m span castellated steel beam

Fig.2 shows model with Young's modulus of E= 2.1x105 N/mm2, Poisson's ration μ=0.3 and mesh size of 25mm. The mesh size was so selected that it does not violate the element shape. The simply supported boundary conditions are maintained at both the supports by allowing translation in z, rotations about x, y and z axes. In order to create the buckling effect, the translation along x at the top of the flange is allowed. A unit load is applied at mid-span on the top of the flange and five buckling modes were studied.

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RESULTS AND DISCUSSIONS

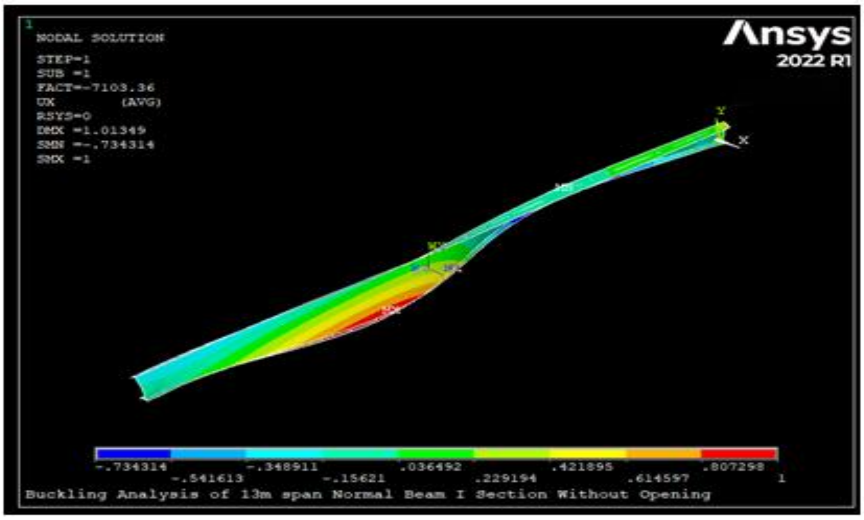

Fig. 3: Buckling mode 1 of 13m span normal steel I beam

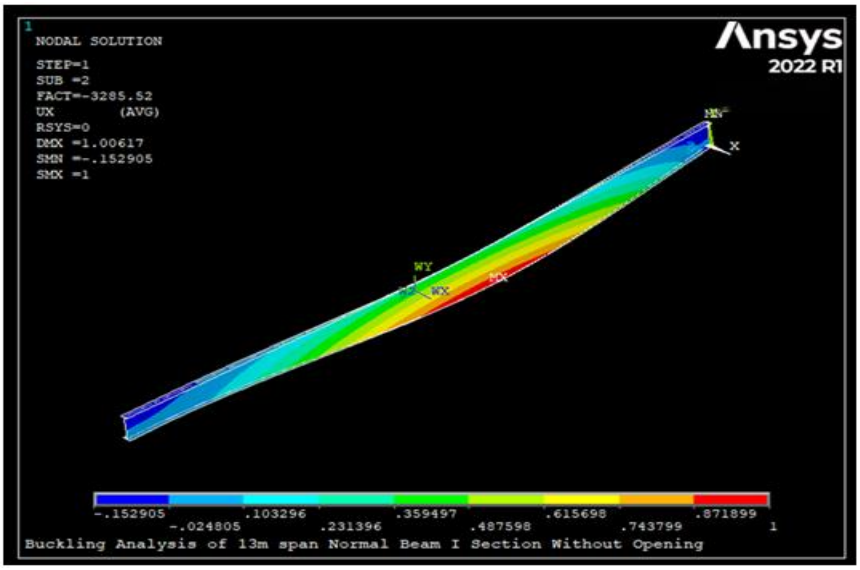

Fig. 4: Buckling mode 2 of 13m span normal steel I beam

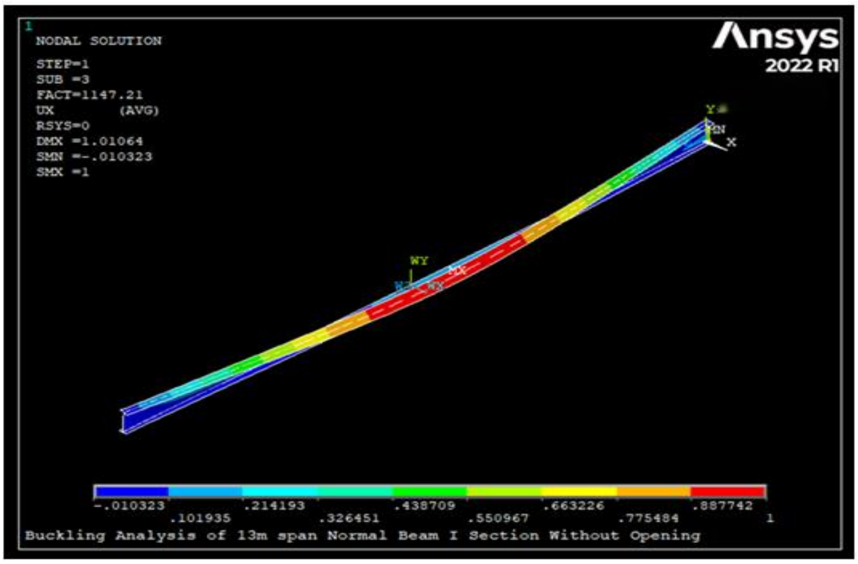

Fig. 5: Buckling mode 3 of 13m span normal steel I beam

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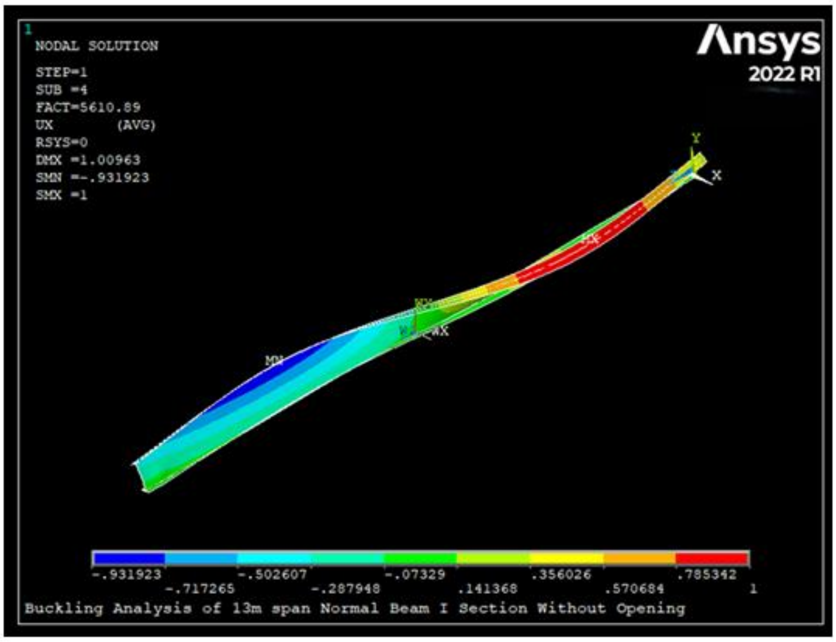

Fig. 6: Buckling mode 4 of 13m span normal steel I beam

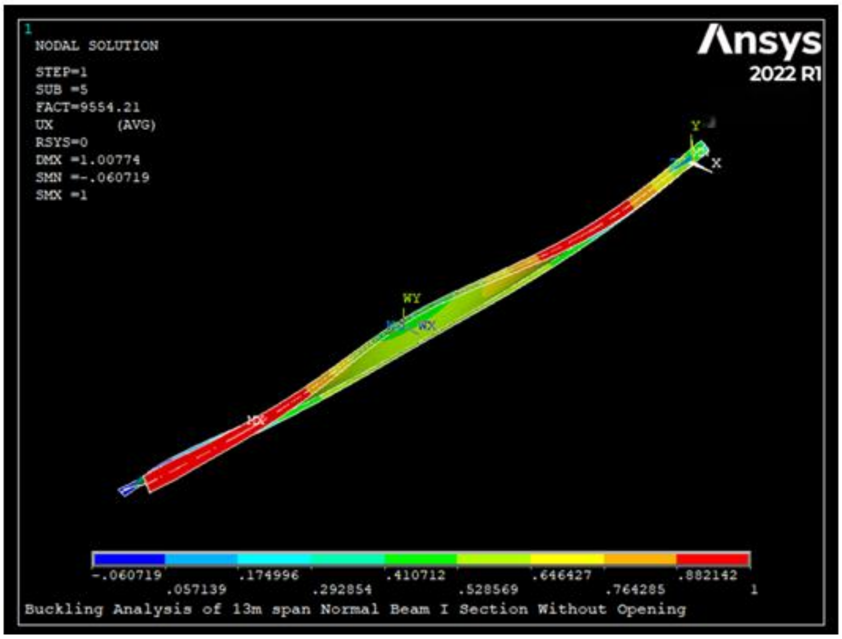

Fig. 7: Buckling mode 5 of 13m span normal steel I beam

Table 2: Buckling behaviour of 13m normal and castellated beams

Sr. No.	**Beam type**	**Torsional Buckling Moment (kN-mm)**
1	Normal beam ISMB450	69.68
2	Castellated beam	81.51

Table 2 and Figures 3 to 7 display the results of the FE software's lateral torsional buckling study of the 13-meter-span castellated beams. The comparison between a standard ISMB 450 beam and a castellated beam for a 13 m span highlights the structural and economic advantages of using castellated sections. The normal beam exhibits a torsional buckling moment of 69.68 kN-mm and weighs approximately 941.2 kg. In contrast, the castellated beam demonstrates a higher torsional buckling moment of 81.51 kN-mm while weighing only 752.37 kg. This reflects a significant weight reduction of around 20.06%.

The improved torsional buckling performance of the castellated beam is primarily due to the increased overall depth and enhanced stiffness resulting from the opening configuration. Despite having a lighter section, it offers better resistance to lateral-torsional instability, which is critical in long-span applications. The reduction in self-weight not only minimizes dead load but also contributes to cost savings in material, transportation, and foundation design.

Overall, the castellated beam proves to be more efficient in both strength and weight optimization. It is particularly advantageous in structures where weight reduction and buckling resistance are essential design considerations. This analysis supports the use of castellated beams as a superior alternative to conventional I-sections in modern structural engineering.

Table 3: Weight Comparison for Conventional and Castellated Beam

Span (m)	Beam Type	Self-Weight (kg)	Weight Reduction (%)
10	Conventional	Higher	—
10	Castellated	Lower	~18%
13	Conventional	Higher	—
13	Castellated	Lower	~20%
16	Conventional	Higher	—
16	Castellated	Lower	~25%

Collective Interpretation for mode shapes of 10m, 13m and 16m spans

Five buckling mode forms of various beam configurations are represented by each of the three sets of buckling data. The load multiplier shows the amount that must be added to the applied load in order to cause buckling in the mode of deformation that each shape number represents.

Table 4: Buckling behaviour of 13m normal and castellated beams

Beam Span (m)	Shape 1	Shape 2	Shape 3	Shape 4	Shape 5
10	-49.4614	-23.1485	6.980796	34.43192	51.55214
13	-81.5111	-37.8682	9.926641	47.50286	75.83454
16	-74.0838	15.46635	63.47678	82.09165	109.6837

First Positive Multiplier Critical Buckling Mode: 10m 13m Span: Shape 3 – 9.926641 16m Span: Shape 2 – 15.46635 Span: Shape 3 – 6.980796. The lowest load at which any beam configuration becomes unstable is shown by these values. When figuring out design capacity, they are essential. Two negative values are seen in the 10 and 13 m spans, suggesting theoretically sound but physically meaningless modes under unidirectional compression. There is only one negative mode for span 16m, indicating a better or more stable setup. From a 10m span to a 16m span, the critical load rises by 10m. Span: 13m/6.980796 Span: 15.46635 Span: 9.926641 16m. This suggests that the 16-meter-span beam is the most stable, whether as a result of better boundary conditions, material modifications, or geometric optimization. Following the crucial mode, all sets display multipliers that increase gradually. These higher modes, which frequently involve more intricate deformations such lateral-torsional buckling, are secondary or global failures that only happen after the initial instability. In conclusion, the first positive multiplier—the lowest of these—is the most crucial buckling mode for any beam. According to critical buckling loads, a beam with a span of 16 meters is the most stable, whereas one with a span of 10 meters is the least stable. Although higher modes aid in the comprehension of post-buckling behavior, the lowest positive multiplier should be the primary emphasis of the original design.

The results demonstrate that weight savings increase with span length due to the improved depth-to-weight ratio of castellated beams.

Structural Performance

- Deflections for castellated beams remain within permissible limits.
- Stress levels are comparable to conventional beams.
- No adverse effects are observed due to web openings under service loads.

Efficiency Index

An efficiency index defined as:

$$\text{Efficiency Index} = \frac{\text{Moment Capacity}}{\text{Self-Weight}}$$

shows consistently higher values for castellated beams, confirming superior material utilization.

CONCLUSIONS

Based on the analytical and numerical investigation, the following conclusions are drawn:

1. Castellated beams provide significant weight reduction compared to conventional steel beams.
2. Weight savings range from 18% to 25%, increasing with span length.
3. Structural performance in terms of stress and deflection remains satisfactory.
4. Castellated beams exhibit a higher strength-to-weight ratio, making them ideal for long-span structures.
5. The use of castellated beams leads to reduced material consumption, transportation cost, and foundation demand.

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