Structural Performance of Double castellated Steel Beams with Innovative Opening Configuration

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ABSTRACT

This research delves into the structural performance of castellated steel beams featuring expanded webs, emphasizing how design variables, such as the number of openings and cutting angle, affect the load capacity, deflection, and stiffness. Castellated beams are engineered to improve the strength-to-weight ratio of the standard I-beams by cutting and reconstructing the web into hexagonal, rectangular, or circular openings. This configuration not only boosts the beam load capacity and minimizes weight, but also maintains or enhances stiffness, rendering it well-suited for long-span structures. In the present study, seven beam specimens were tested under one-point load conditions, including six castellated beams. The key findings demonstrate that reducing the number of openings significantly increases the load capacity and reduces deflection. The castellated beams outperformed RB-S by up to 68.9% in the load-carrying capacity at Service Limit Deflection (SLD). Additionally, the study examined the influence of cutting angles (58°, 52°, and 45°) on the beam performance, concluding that a 52° angle provided the best balance between strength and stiffness. The results underscore the importance of optimizing castellated beam designs for large-scale construction applications, where balancing weight reduction, structural integrity, and serviceability is crucial.

Keywords-castellated beams; vierendeel mechanisms; web post-buckling; number of openings

I. INTRODUCTION

The development of automated manufacturing techniques, particularly Computer Numerical Control (CNC), has made it possible to produce castellated and cellular beams cost-effectively. These beams are strong enough to carry more loads and span longer distances between supports with reliable bending moments. However, introducing openings in the web may result in a drop in beam stiffness, which may increase the deflections and stress concentrations [1]. Many studies have investigated different opening shapes [2-7], providing worthy information regarding how the geometry of these openings affects the integrity and performance of the beams. Numerous other studies [8-12] have examined the effects of the beam characteristics and built-up sections, and effect on their overall stability and load-carrying capability. Additionally, variations in steel types, particularly cold-formed steel [13-17], offer valuable insights into how the steel type influences the beam failure characteristics. Moreover, research has focused on strengthening techniques to minimize all modes of failure, such as stiffeners for beams [18-24]. Stiffeners strengthen critical areas of a portion of the bent to reduce possible buckling or local failures. There has also been a focused attention on the composite materials, wherein two or more materials are mixed to obtain a combination of certain superior properties, which are considered to improve the performance of a beam [24-34]. Composite materials enhance the beam mechanical strength and stiffness, making them suitable for applications where traditional materials fall short.

Despite the extensive research into various castellated beam configurations, the unique configuration of double castellated beams is not explicitly addressed in the literature. This study aims to close this gap by providing outstanding knowledge about the structural performance of double castellated beams. In prior studies, the openings, sections, types of steel, and strengthening techniques have contributed greatly to a consolidated understanding of the beam behavior and have provided appropriate design guidelines for the beam structures and structural elements. This study aims to examine the behavior of double castellated beams, focusing on the effects of the opening spacing, the number of openings, and cutting angles. The former focuses on the configurations of double castellated beams and understanding their structural performance considerations, including load deflection, load-bearing capacity, and modes of failure. Also, this study explores the scope for optimization in the beam design to facilitate their practical applications in construction.

II. EXPERIMENTAL WORK

Two ordinary hot-rolled steel beams (IPE160) were manufactured by being cut into specific configurations. Each corresponding part of the first beam is swapped for the second one's counterpart, as shown in Figure 1. This results in a unique configuration known as a double castellated beam, a detailed analysis of which is presented in this paper.

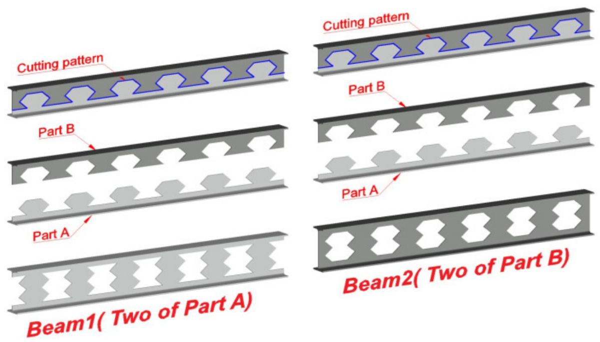

Fig. 1. Fabrication of castellated steel beam with new pattern.

A. IPE Steel Beam

A standard IPE160 was used in this study to construct the beam with an expanded open-web. The details of its characteristics are provided in Tables I and II.

TABLE I. IPE160 SECTION CHARACTERISTICS

G (kg/m)	h (mm)	*tf* (mm)	*tw* (mm)	R (mm)	A (cm^2)	I (cm^4)	*Sx* (cm^3)	*Zx* (cm^3)
15.8	160	7.4	5	65.8	20.1	869	108.6	124

TABLE II. IPE160 MECHANICAL CHARACTERISTICS

Component	Thickness (mm)	Yield stress (MPa)	Ultimate tensile strength (MPa)	Elongation percentage (%)
Flange	7.4	266.2	391.1	30
Web	5	279.4	410.3	28
Plate	5.5	271.7	398.8	28

B. Tested Specimens

One solid beam without openings, RB-S, is used as a reference beam, six beams have been manufactured from IPE steel beams with a double castellated opening, DCB58°-8, DCB58°-14, DCB58°-6, DCB52°-8, DCB45°-8, and NCB58°-8, with the latter being a traditional castellated beam. One-point loads were applied to the seven beams over a total length of 2870 mm and a clear span of 2670 mm. Figures 2-7 and Table III present detailed descriptions of the beams analyzed in this study.

TABLE III. DETAILS OF STEEL BEAM SPECIMENS

Sp.No.	b (mm)	e (mm)	Dg (mm)	S (mm)	Angle for cutting (Θ°)	No. of openings
RB-S	NA	NA	160	NA	NA	0
NCB58°-8	50	80	240	260	58°	8
DCB58°-8	25	80	240	240	58°	8
DCB58°-14	25	50	240	150	58°	14
DCB58°-6	25	100	240	300	58°	6
DCB52°-8	31	80	240	240	52°	8
DCB45°-8	40	80	240	240	45°	8

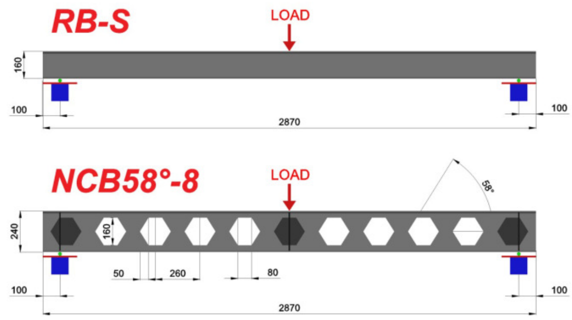

Fig. 2. Dimensions of RB-S and NCB58°-8.

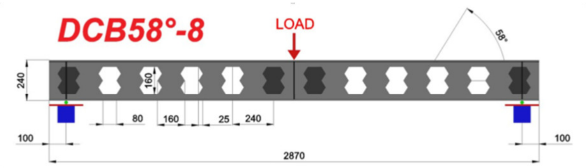

Fig. 3. Dimensions of DCB58°-8.

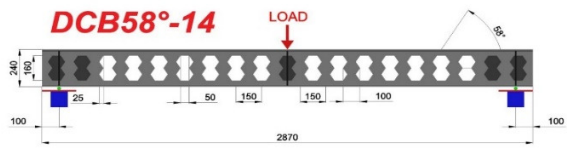

Fig. 4. Dimensions of DCB58°-14.

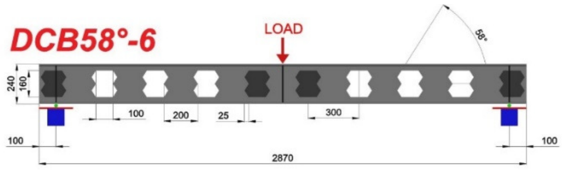

Fig. 5. Dimensions of DCB58°-6.

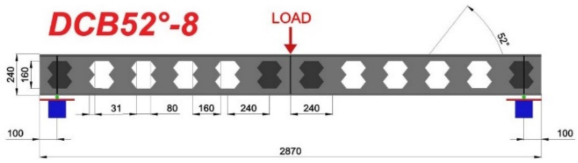

Fig. 6. Dimensions of DCB52°-8.

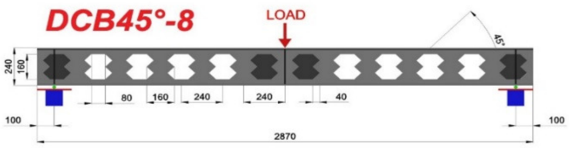

Fig. 7. Dimensions of the beam DCB45°-8.

C. Fabricating of Castellated Steel Beam with New Opening

The web section was cut in a new zigzag pattern along its centerline using a CNC plasma-cutting machine aimed at producing steel beam specimens with open-expanded webs. This cutting produced two halves labeled as parts A and B. The two edges of part A were then welded together to form a castellated beam with a zigzag opening, while those of part B were welded to create a castellated beam featuring double openings. As shown in Figure 8, a 3 mm thick welding was employed to join the two parts, forming a castellated section of steel. Vertical bearing stiffeners with 8 mm thickness were also welded to the web at the supports and concentrated point loads.

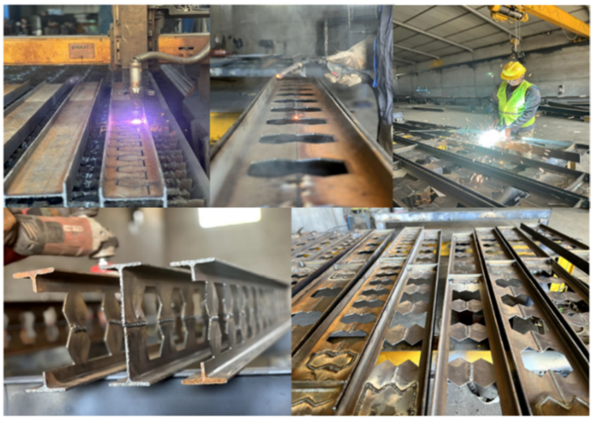

Fig. 8. Process of manufacturing castellated steel beams.

D. Test Setup

The beams were tested in the structure laboratory of the Civil Engineering Department of Baghdad University. The testing procedure involved applying static load through the utilization of a hydraulic jack and a load cell with a capacity of 50 tons. The load gradually increased until the beams reached the point of failure. During the testing, various measurements were recorded, including strains and the deflection at the center of the beam. A single concentrated load was applied at the center of each beam, as depicted in Figure 9.

III. TEST RESULTS AND DISCUSSION

All beam specimens were tested for failure using a machine that applied a one-point load at the beam's center. The same loading conditions were applied to all beams, and the performance of the beams with openings was compared to that of the solid control beam. An 11 mm deflection, corresponding to the Serviceability Limit of L/240, was used as a reference.

A. Load-Deflection Curves

1) Number of Opening Effect on Castellated Steel Beams

Three castellated beam specimens with different numbers of openings (14, 8, and 6) were evaluated along with RB-S, which did not have any openings. All beams were constructed using the IPE 160 section, with a consistent opening cutting angle. The influence of the number of openings on the load-carrying capacity and deflection was carefully analyzed.

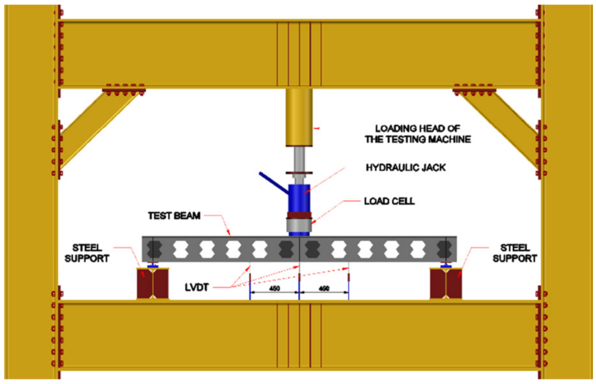

Fig. 9. Profile of the test setup.

a) Ultimate Load Capacity

RB-S reached a peak load-carrying capacity of 54.4 kN before failure, while the load-carrying capabilities of DCB58°-14, DCB58°-8, and DCB58°-6 exhibited an enhancement of 37%, 33%, and 51%, respectively. This demonstrates that the number of openings affects the structural strength of castellated beams, with fewer openings resulting in a greater increase in the ultimate load capacity.

b) Service Limit Deflection

At the SLD of 11mm, the castellated beams showed significant improvements in the load-carrying capacity compared to RB-S. Specifically, the load-carrying capacities of DCB58°-14, DCB58°-8, and DCB58°-6 increased by 49.6%, 40.8%, and 68.9%, respectively. This indicates that the castellated beams can significantly outperform the solid beams under service loads as the number of openings decreases.

c) Mid-Span Deflection

On the point of ultimate load, the mid-span deflection of the castellated beams was considerably reduced compared to RB-S, meaning that the deflection of DCB58°-14, DCB58°-8, and DCB58°-6 decreased by 53.9%, 50.8%, and 59.7%, respectively. This reduction in deflection signifies the greater stiffness of the castellated beams with a smaller number of openings. For the tested steel beams, the web post weld was equal to 2e, with "e" being the horizontal length of the web cut. From the test, it became clear that the greater the area of the web post welds is, the higher is the load-carrying capacity of the beam, versus some deflection. Additionally, the area of the web post and several openings highly influence the behavior of the steel beams, especially in SLD, which is pronounced at 11 mm. Fewer openings combined with larger web post weld areas allow for greater load-carrying capacity with less deflection.

2) Effect of Cutting Angle

The impact of the cutting angles (58°, 52°, and 45°) on the castellated steel beams was analyzed, with the opening spacing having been fixed at 80 mm. The double castellated beams were compared to an RB-S and a traditional castellated beam (NCB58°-8) to evaluate the effect of the cutting angles on the load-carrying capacity and deflection.

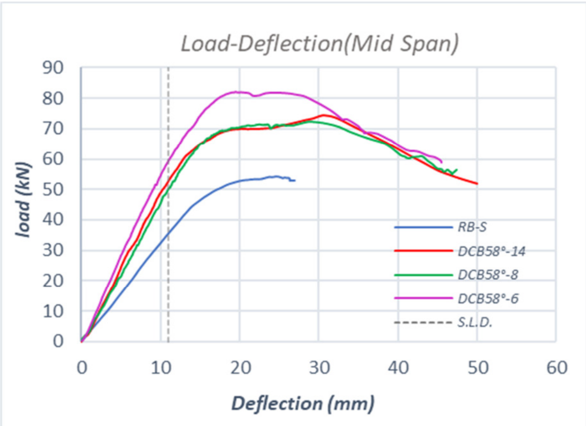

Fig. 10. Load–mid-span deflection curves of RB-S, DCB58°-14, DCB58°-8, and DCB58°-6.

a) Ultimate Load Capacity

The results indicated a significant impact of the cutting angles on the load-carrying capacity of the tested beams. The load-bearing capacity of DCB58°-8, DCB52°-8, and DCB45°-8 exceeded that of RB-S. The ultimate load percentage increases were 33% for DCB58°-8, 48.5% for DCB52°-8, and 36.7% for DCB45°-8. Under the same parameters and conditions, outlined in Table III, the DCB58°-8 showed an 8% increase in the ultimate load capacity compared to NCB58°-8.

b) Service Limit Deflection

At the SLD of 11mm, the load-carrying capacity of the castellated beams improved drastically over that of RB-S. That is, the load-carrying capacity of DCB58°-8, DCB52°-8, and DCB45°-8 is 40.8%, 52.4%, and 45.1% higher than that of the RB-S, respectively. This confirms that the 52° angle (DCB52°-8) performs best under service load conditions.

c) Mid-Span Deflection

Compared to RB-S, at ultimate load, the mid-span deflection of the castellated beams is likely reduced. The deflection of DCB58°-8, DCB52°-8, and DCB45°-8 amounted to a reduction of 50.8%, 55.2%, and 52.6%, respectively. The beam with a 52° cutting angle (DCB52°-8) displayed the least deflection, suggesting enhanced stiffness and stability. The results demonstrate that the cutting angle is a critical influencing factor for the structural performance of castellated steel beams. The optimal angle range for the double castellated beam differs from that of NCB58°-8 (58°-62°), with the former consistently exhibiting superior performance across all cases. Of the three studied angles, 52° catered to the best balance between the increased load capacity and reduced deflection, hence being the most optimal one concerning strength and stiffness. This study presents the particular importance for optimizing the cutting angle to enhance castellated steel beams' performance, especially when the openings are kept unchanged. The load-deflection curve is listed in Figures 10 and 11.

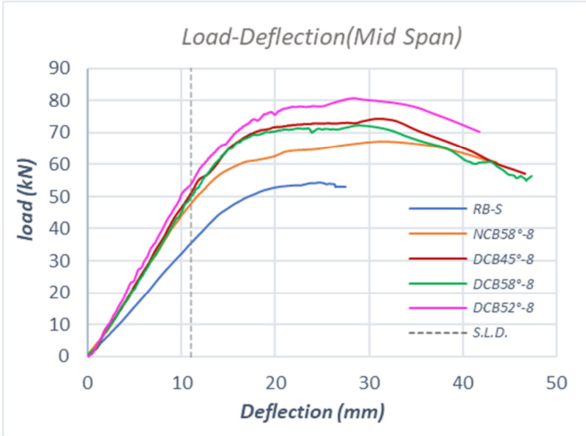

Fig. 11. Load–mid-span deflection curves of RB-S, NCB58°-8, DCB58°-8, DCB52°-8, and DCB45°-8.

B. Modes of Failure

As shown in Figures 12-17 and Table IV, various failure modes were observed across all tested beams. Flexural failure was identified as the primary mode in RB-S, characterized by excessive deflection under the applied load. This led to material yielding in tension at the bottom flange and compression at the top flange. DCB58°-14 and DCB45°-8 predominantly exhibited global flexural failure with web post-buckling, having been caused by the stress concentrations near the openings. NCB58°-8, DCB58°-8, DCB58°-6, and DCB52°-8 demonstrated flexural failure combined with a Vierendeel mechanism. This behavior was attributed to the formation of plastic hinges at specific angles around the web openings. Under high bending moments, these openings experienced localized bending and significant stress concentrations along their edges. In addition, RB-S, DCB58°-6, and DCB52°-8 exhibited lateral-torsional buckling during advanced loading stages. At this stage, the compression flange buckled laterally, causing the beam to twist, and resulting in lateral displacement and rotation. This deformation extended to the web and tension flange due to the interaction between the beam components. These observations are consistent with the findings of [16, 34], where the Vierendeel mechanism and flexural failure were also identified as key failure modes in the beams with web openings. These studies highlight the significant impact of geometric discontinuities on the failure mechanisms.

TABLE IV. ULTIMATE LOAD AND FAILURE MODE OF TESTED STEEL BEAMS

Se. No.	Pu (kN)	Pu/Pu, ref (%)	Failure mode
RB-S	54.4	100	Flexural
NCB58°-8	67.2	123.5	Vierendeel mechanism
DCB58°-8	72.4	133.1	Flexural and Vierendeel mechanism
DCB58°-14	74.5	136.95	Flexural and Web post-buckling
DCB58°-6	82.3	151.28	Flexural and Vierendeel mechanism
DCB52°-8	80.8	148.53	Vierendeel mechanism
DCB45°-8	74.4	136.76	Web post-buckling with steel rupture

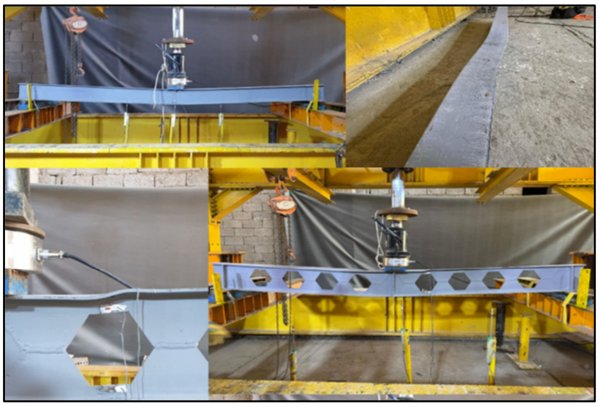

Fig. 12. Mode of failure for RB-S and NCB58°-8.

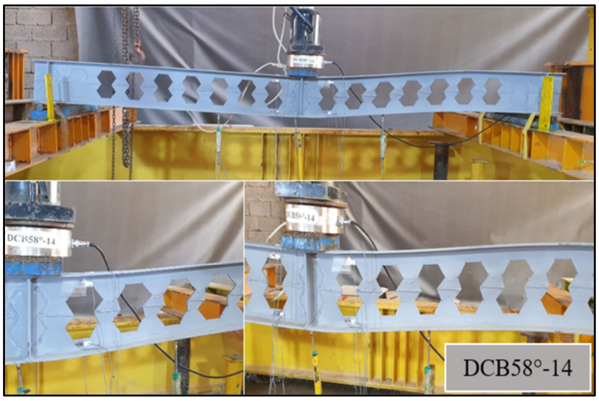

Fig. 13. Mode of failure for DCB58°-14.

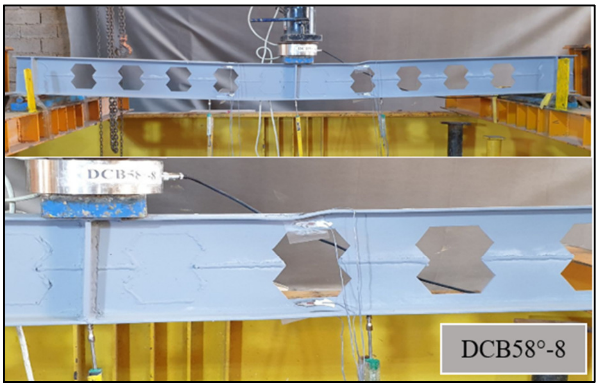

Fig. 14. Mode of failure for DCB58°-8.

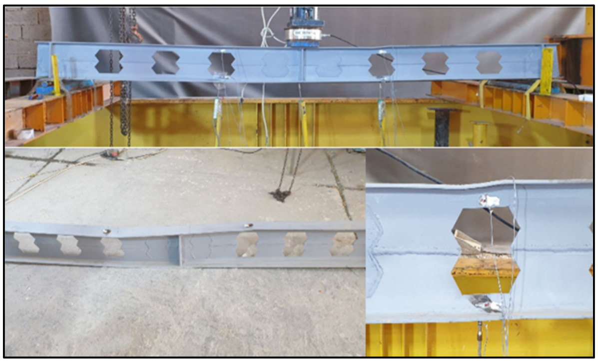

Fig. 15. Mode of failure for DCB58°-6.

Fig. 16. Mode of failure for CB45°-8.

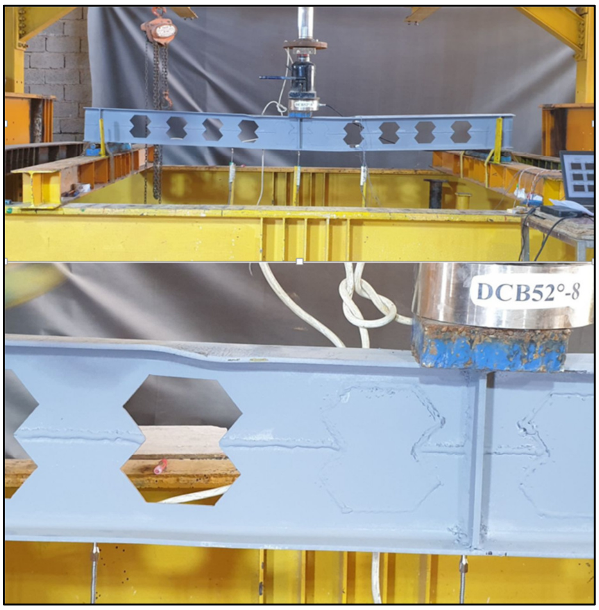

Fig. 17. Mode of failure for DCB52°-8.

IV. CONCLUSIONS

This study presents an innovative configuration of castellated steel beams involving double castellated openings. It provides essential insights for optimizing the structural performance of beams with differing numbers of openings and cutting angles to improve their strength and stiffness. Based on the results of the experimental work, the following conclusions were reached:

- Double castellated steel beams are a novel type of castellated steel beam that exhibits promising strength properties and performance. This can be attributed to the utilization of advanced manufacturing and configuration techniques.

- Decreasing the number of holes in castellated steel beams significantly enhances their structural performance. Beams with fewer openings exhibited an increase in the ultimate load capacity of up to 51% and a reduction in the mid-span deflection by as much as 59.7%. This indicates that fewer openings result in both greater strength and increased stiffness.
- Having varied the cutting angle (58°, 52°, and 45°) while having kept the number of openings constant significantly affected the beam structural behavior. Beams with a 52° cutting angle demonstrated the best performance, with an increased load-carrying capacity and a reduced deflection, making them the most efficient configuration in strength and stiffness.
- All tested castellated beams demonstrated improved performance over the solid reference beam, RB-S, under service limit conditions, with an increase in the load carrying capacity ranging from 40.8% to 68.9%, depending on the number of openings and cutting angle.
- The double castellated beams achieved an 8% increase in the ultimate load capacity compared to the normal castellated beam, offering greater strength, stiffness, and reduced deflection.
- The double castellated beams benefited from fewer openings and an optimal cutting angle of 52°. These factors improve the load capacity, reduce deflection, and minimize the risk of failure, making them effective in applications that require both strength and flexibility.
- Various failure modes were observed, with flexural failure and the Vierendeel mechanism being the most common. Web-post buckling occurred in beams with more openings or under high shear stresses, highlighting the influence of geometric discontinuities on the failure behavior.

Overall, this study's findings indicate that double castellated beams have the potential to be utilized in future works due to their beneficial features and the aesthetic appearance of their structure. Furthermore, the outcomes of this study can assist in establishing design guidelines for the most effective utilization of double castellated beams in structural engineering.

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