Towards Low-Carbon Steel Design: Evaluating Castellated Beams for Embodied Carbon Reduction

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ABSTRACT

The construction industry is facing increasing pressure to reduce the embodied carbon, particularly in structural steel systems, which contributes significantly to the global Greenhouse Gas (GHG) emissions. As a potential solution, castellated beams offer enhanced structural efficiency through web openings that increase stiffness while reducing the material usage. This study investigated the application of castellated beams as secondary structural members and evaluated their Embodied Carbon (*EC*) performance in comparison with that of conventional I-beams. A simply supported beam with a 12 m span was analyzed under typical floor loads. The structural performance was assessed based on the strength and deflection criteria using the American Institute of Steel Construction (AISC) design provisions, whereas the *EC* was calculated using a cradle-to-gate approach. The results demonstrate that the castellated beam (CB18×14) meets all the structural requirements and exhibits superior deflection performance compared to the conventional W14×22 I-beam. Moreover, the castellated beam achieved a 27% reduction in *EC* per linear foot, highlighting its potential as a sustainable alternative to steel-framed buildings. These findings emphasize the dual benefits of castellated beams in enhancing the structural performance and reducing the environmental impact in secondary beam applications.

Keywords-castellated beam; embodied carbon; steel structures; built environment; sustainable construction; UN SDG 13; climate action

I. INTRODUCTION

The urgency of transitioning towards sustainable practices in the construction sector has been widely recognized [1-5]. Among the materials used in modern construction, steel stands out for its high environmental impact primarily because of the carbon-intensive nature of conventional steelmaking technologies. Globally, the steel industry is responsible for approximately 8% of the total GHG emissions [6], making it a significant contributor to the climate change and a target for decarbonization.

While the technological advancements have led to substantial improvements, such as a 60% reduction in the carbon intensity of UK steel production since 1960 and 20% since 1990 [7], the path to net zero remains challenging. These gains highlight not only the potential, but also the ongoing need for design-based strategies that reduce the environmental burden of the steel structures. As emphasized in [8], an optimum structural design can play a pivotal role in minimizing the *EC* through material efficiency and structural performance optimization.

Several studies have extensively explored optimal design strategies for the steel structures, focusing on enhancing the structural efficiency and minimizing the material use [9-12]. These investigations emphasized the importance of geometric and material optimization, addressing parameters, such as member sizing, cross-sectional shape, and overall structural configuration. The goal was to develop design solutions that achieve maximum performance with minimal resource consumption, thereby contributing to more sustainable and cost-effective steel-construction practices.

In this context, a promising strategy is the application of castellated beams, that is, steel beams modified with web openings that increase the moment of inertia of the section without a proportional increase in the material use. These beams have gained attention in structural design owing to their enhanced stiffness-to-weight ratio and their ability to accommodate service routes without additional structural depth [13-17]. Consequently, castellated beams are widely adopted in secondary framing systems, where the repetition and material efficiency are critical factors. Developments in optimization techniques, such as the charged system search algorithm, have been employed to minimize the material usage and cost of the castellated beams with hexagonal and circular openings [13]. Moreover, the structural and economic efficiencies of castellated beams are highly sensitive to design parameters and project-specific requirements, which can influence their overall performance [18]. Despite these challenges, castellated beams remain a compelling alternative to conventional I-beams, particularly when both the structural performance and environmental impact are considered.

Although numerous studies have explored the structural performance and economic efficiency of castellated beams, limited attention has been paid to their environmental implications, particularly in terms of the embodied carbon. Most existing research emphasizes the mechanical behavior, load-bearing capacity, and optimization of the geometric parameters. However, the sustainability aspect, especially in the context of cradle-to-gate carbon emissions, remains underexplored. Moreover, despite the widespread use of castellated beams in secondary framing systems, a comparative analysis of the carbon footprint of conventional I-beams in real design scenarios is lacking.

In response to this gap, the primary objective of this study is to evaluate the *EC* of castellated beams used as secondary structural elements and to compare the results with those of conventional I-section beams designed for the same loading and span conditions. By focusing on the cradle-to-gate life cycle stages, this study aims to quantify the material savings and potential carbon reduction benefits offered by the castellated beam systems. These findings are expected to inform sustainable structural design practices and contribute to the decarbonization of steel-intensive construction projects.

II. METHODOLOGY

This work investigated the structural and environmental performance of castellated beams in secondary framing applications by evaluating their *EC* and comparing it with conventional I-beam sections. A typical secondary beam configuration was considered to reflect the practical design scenarios commonly encountered in steel-frame buildings.

A simply supported secondary beam with a span of 12 m, as shown in Figure 1, was selected for analysis. The beam was modeled as a non-composite castellated steel section, supported at both ends, and assumed to be fully laterally braced along its length by the floor system, thereby eliminating the concerns related to lateral-torsional buckling. The beam was subjected to uniformly distributed loads as follows:

- Superimposed dead load: 1.2 kN/m^2,
- Live load: 1 kN/m^2,
- Self-weight: Automatically considered based on the cross-sectional properties of each beam type.

These loading conditions represent the typical design values for the floor systems in commercial buildings. The structural analysis was carried out using two standard load combinations: 1.2D + 1.6L for strength checks, and D + L for deflection evaluation, in accordance with the AISC design provisions [19].

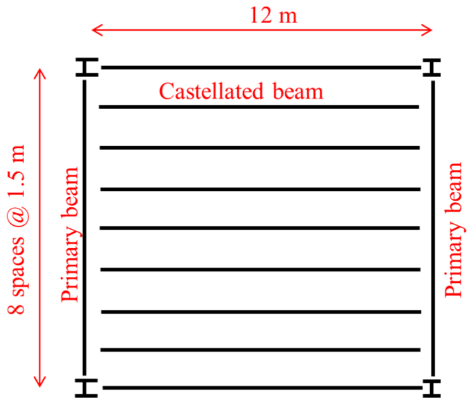

Fig. 1. Floor plan.

Both the castellated and conventional I-beams were designed using ASTM A992 steel [19], a standard structural steel grade commonly used in building construction. The material properties considered were:

- Yield strength (F_y): 345 MPa
- Ultimate tensile strength (F_u): 450 MPa
- Modulus of elasticity (E): 200,000 MPa

The analysis was performed using analytical expressions in accordance with the AISC Steel Manual [20, 21]. The strength and deflection criteria were evaluated to ensure compliance with the standard design requirements.

The design of the castellated beams requires comprehensive analysis of multiple limit states to ensure both safety and performance. One critical aspect is the evaluation of the axial and flexural strengths of the tee sections formed by the cut web, as these components bear the primary bending stresses across the beam. The interaction between the flexural and axial forces in the tee sections is governed by:

For $P_r/P_c \geq 0.2$

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{vr}}{M_c}\right) \leq 1.0 \qquad (1)$$

For $P_r/P_c < 0.2$

$$\frac{P_r}{2P_c} + \left(\frac{M_{vr}}{M_c}\right) \leq 1.0 \qquad (2)$$

where P_r is the axial force, P_c is the compressive strength capacity, M_{vr} is the required flexural strength of the tee, and M_c is the available flexural strength.

Additionally, the web post buckling, a localized failure mode influenced by the spacing and shape of openings, must be carefully assessed because excessive buckling can lead to a sudden loss of the load-carrying capacity. The required flexural strength (M_{rh}) of the web post is given by:

$$M_{rh} = V_{rh} h_{tee} \qquad (3)$$

where h_{tee} is the height of the tee section, which is the distance over which the shear force acts. The available flexural strength of the web post (M_p) can be expressed as:

$$M_p = 0.25 t_w (e + 2b)^2 F_y \qquad (4)$$

where t_w is the web thickness, e is the tee section length, and b is the horizontal length.

Horizontal and vertical shear forces present another crucial limit state because of the presence of web openings: the shear distribution is altered, and stress concentrations may occur at the edges of the openings, thus increasing the risk of shear-induced failure. The available horizontal shear strength of the web post (V_{ch}) is expressed as:

$$V_{ch} = 0.6 F_y e t_w \qquad (5)$$

The available vertical shear strength was calculated for the net and gross sections. The available vertical shear strength for the net section (V_{cvn}) is calculated as:

$$V_{cvn} = 0.6 F_y \left(d_{t-top} + d_{t-bot}\right) t_w C_{v2} \qquad (6)$$

Similarly, the available vertical shear strength for the gross section (V_{cvg}) is calculated as:

$$V_{cvg} = 0.6 F_y d_g t_w C_{v1} \qquad (7)$$

The coefficients C_{v1} and C_{v2} depend on the geometry of the castellated beam, specifically the size and shape of the openings and the relative size of the web post.

A conventional I-section with equivalent span and loading conditions was used as a benchmark for comparison. Both beams were designed to satisfy the strength and serviceability (deflection) criteria for a given load combination. The section modulus, moment of inertia, and resulting deflection were calculated for both cases. The *EC* of each beam type was calculated using a cradle-to-gate approach, focusing on life-cycle stages A1–A3, as defined in the BS EN 15978 standard [22]. The total *EC* was determined using:

$$EC = \sum Q \times CF \qquad (8)$$

where Q represents the quantity of the material used (kg), and CF denotes the Carbon Factor (kgCO₂e/kg). A CF of 1.9 kgCO₂e/kg was adopted for structural steel based on a comprehensive inventory of the carbon and energy emissions developed using the circular ecology approach [23]. The carbon contribution of each beam was calculated based on its weight per unit length. Special attention was given to the material reduction achieved through the castellated design, and its corresponding impact on *EC* was quantified to highlight the potential for carbon savings compared with the conventional solid-web I-section.

III. RESULTS AND DISCUSSION

The design of the castellated beams involves the evaluation of several critical limit states to ensure structural safety and performance. Key considerations include the axial and flexural capacities of the tee sections formed by the web openings, which resist most of the bending stresses. The local web post buckling must also be assessed, because it is influenced by the opening geometry and spacing, potentially leading to a sudden loss of strength. Additionally, the horizontal and vertical shear forces require careful analysis because of the altered stress distribution and increased concentration around the openings, which may increase the risk of shear failure. The castellated beam used in this study was derived from a standard W12x14 I-section, which was transformed into a CB18x24 section. This configuration reflects a typical geometry used in practice, providing increased depth and improved moment of inertia while maintaining the material efficiency. The final profile and web opening layout are shown in Figure 2.

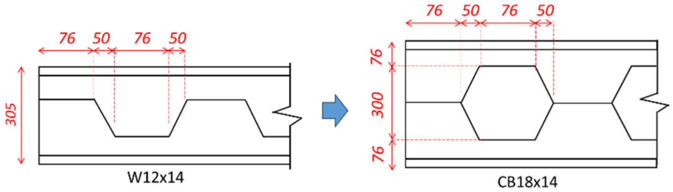

Fig. 2. Castellated beam configuration (units in mm).

The structural performance of the castellated beam was evaluated by examining the critical failure mechanisms and comparing the corresponding design strengths with the applied demands, as summarized in Table I. The results demonstrated satisfactory strength under all evaluated limit states, with capacities exceeding the applied demands. The most critical condition, flexural-torsional buckling, showed a utilization ratio of approximately 72%, indicating adequate lateral stability. The flexural strength of the tee sections formed by the web openings was also sufficient, with only 24% of the capacity utilized. Both the horizontal and vertical shear demands were significantly below their respective capacities, with utilization ratios of 26% and 17%, respectively. These results confirm that the castellated beam configuration provides safe and efficient performance for secondary beam applications under the given loading conditions.

The conventional I-beam exhibited adequate structural capacity under the applied loads, with both flexural and shear strengths exceeding the corresponding demands, as listed in Table II. The flexural strength of the section was 88 kNm, slightly above the applied moment demand of 86 kNm, resulting in a high utilization ratio of approximately 98.5%, which indicates that the section was nearly fully utilized in bending. In contrast, the shear demand was relatively low at 29 kN compared to the available shear strength of 286 kN, reflecting a utilization ratio of only 9%. These results confirm that the conventional I-beam is structurally sufficient, but the high flexural utilization suggests a limited reserve capacity in bending, in contrast to the more balanced performance observed in the castellated beam design.

TABLE I. CASTELLATED BEAM DESIGN

Failure mechanism	Strength	Demand
Flexural torsional buckling (kN)	288	208
Flexural strength of tee (kNm)	2.5	0.6
Horizontal shear (kN)	80	22
Vertical shear (kN)	160	28

TABLE II. CONVENTIONAL I-BEAM DESIGN

Failure mechanism	Strength	Demand
Flexural strength (kNm)	88	86
Shear strength (kN)	286	29

Although both the castellated and conventional I-beams satisfied the strength requirements under the applied loads, the deflection behavior revealed a critical difference in performance, as depicted in Table III. In this study, the deflection limit was governed by L/180, where L is the span length, resulting in a maximum allowable deflection of 66 mm. The castellated beam exhibited a midspan deflection of 65 mm, which remained within the allowable limit, thereby complying with the serviceability criteria. In contrast, the conventional I-beam exhibited a deflection of 133 mm, which significantly exceeded the L/180 limit of 66 mm. This indicates that despite satisfying the strength requirements, the conventional section fails to meet the serviceability limits, making deflection control the governing design criterion. The enhanced stiffness provided by the increased depth of the castellated section effectively limits the deflection, offering a structurally and serviceably superior solution for secondary beam applications in long-span floor systems.

To address the serviceability failure observed in the conventional I-beam, further analysis was conducted to identify an appropriate I-section that satisfied both the strength and deflection criteria. The revised evaluation indicated that the W14 × 22 section provides sufficient flexural and shear strength while maintaining the deflection within acceptable limits, as illustrated in Table III. This adjustment highlights the need for careful consideration of the serviceability constraints during the design process, particularly for longer spans. It also reinforces the benefits of using castellated beams, which offer enhanced stiffness without a significant increase in material usage, hence potentially reducing the environmental impact associated with upscaling conventional sections.

TABLE III. BEAM DEFLECTION

Beam	Deflection (mm)	Limit (mm)
Castellated beam	65	66
W12x14 I-section	133	66
W14x22 I-section	62	66

The *EC* analysis compares the castellated beam CB18×24 with the conventional W14×22 I-beam, as both sections satisfy the strength and deflection criteria established in the structural design phase. Although the castellated beam was derived from a W12×14 section, the original section was found to be insufficient in serviceability, exceeding the allowable deflection limit under the given loading and span. Therefore, the W14×22 section was adopted as the appropriate benchmark for the *EC* comparison, as it was the minimum conventional I-section that satisfied both structural performance requirements.

The results revealed a significant difference in the environmental impact between the two beam types. The castellated beam produced approximately 27% less *EC* than the W14×22 I-beam, with total values of approximately 43 kgCO₂e and 68 kgCO₂e, respectively (Figure 3). This reduction is primarily attributed to the reduction in the steel mass achieved through the introduction of web openings, which increases the beam depth and stiffness without proportionally increasing the material consumption. These findings are consistent with the broader trends in the literature supporting material-efficient structural systems. For instance, authors in [24, 25] demonstrated that castellated and cellular beams could achieve notable improvements in the structural performance through geometric optimization. However, their studies did not quantify the *EC* savings associated with such designs. In contrast, the present study provides a quantitative evaluation of the environmental impact and shows that the castellated beams not only maintain structural adequacy, but also result in substantial *EC* savings, offering a dual benefit.

Compared to earlier works reporting cost savings of around 10–20% [11, 13], the current study exhibits 27% reduction in *EC* and further reinforces the sustainability potential of the castellated beams. This positions the castellated beams as compelling alternative to conventional I-beams, particularly in secondary framing systems, where repetition amplifies both the environmental and economic impacts.

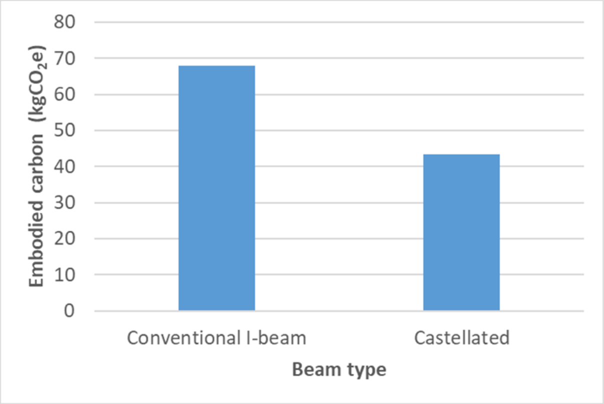

Fig. 3. *EC* calculations.

IV. CONCLUSIONS

This study investigated the application of castellated beams as secondary structural members with a focus on the structural performance and Embodied Carbon *(EC)* efficiency. A comparative analysis was conducted between a castellated beam (CB18x14) and a conventional I-beam (W14x22), both of which were designed to satisfy the same loading and span conditions.

The results confirmed that the castellated beam satisfied all strength and serviceability requirements, with adequate reserve capacity across the flexural, shear, and buckling limit states. In contrast, although the initially selected conventional I-beam (W12x14) satisfied the strength criteria, it failed to satisfy the deflection limits. This necessitated the use of a larger section (W14 × 22), which resulted in an increased material usage.

The deflection analysis demonstrated the superior stiffness of the castellated beam, with the deflection remaining within allowable limits, whereas the conventional beam exceeded the serviceability criteria until it was upscaled. Notably, the *EC* assessment revealed that the castellated beam had approximately 27% lower *EC* per linear foot than the W14 × 22 I-beam. This reduction is attributed to the material efficiency achieved through the web opening configuration, which reduces the steel mass while maintaining the structural adequacy.

This study integrated the evaluation of *EC* and the structural performance of castellated beams using a realistic design scenario for secondary framing systems. By quantifying the environmental benefits alongside the mechanical adequacy, this study offers new insights into the potential of castellated beams to support low-carbon structural designs. These findings contribute to sustainable construction practices and highlight the need for further research on the optimization of opening geometries and broader design applications.

Although the findings of this study demonstrate the structural and environmental advantages of the castellated beams for secondary framing applications, it is important to acknowledge certain limitations. The analysis was restricted to a single span length and a specific loading scenario, and the castellated beam design was based on a fixed opening configuration without variations in the geometric parameters. Therefore, the conclusions should be interpreted within the context of this case-specific evaluation. Future research should incorporate sensitivity or parametric analyses to explore how variations in the opening geometry, such as hole size, spacing, and shape, affect both the structural performance and embodied carbon. Additionally, expanding the study to cover a broader range of spans and loading conditions would further enhance the generalizability and practical relevance of the findings for sustainable steel designs.

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DATA AVAILABILITY

https://zenodo.org/records/14954743

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