Evaluating the Potential of Tapered Members for Embodied Carbon Reduction in Gable Steel Frames

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ABSTRACT

As part of the global sustainability efforts, the construction industry is facing an increasing pressure to reduce its environmental impact, particularly in terms of Embodied Carbon (EC) emissions. Steel, a critical material in modern construction, contributes significantly to these emissions owing to its carbon-intensive production process. This study investigated the potential of tapered steel members as sustainable alternatives to standard I-beams in gable steel frame structures, focusing on reducing the EC and improving the overall structural efficiency. This study evaluates the structural performance, embodied carbon, and cost implications of tapered members compared to standard I-beams across different span lengths. The results show that the tapered steel members can achieve up to a 22% reduction EC compared to the standard I-beams while also providing higher design efficiency. These benefits became more pronounced as the span width increased. From a cost perspective, the tapered members offer savings for shorter spans; however, for longer spans, the increased fabrication complexity may offset the material and carbon reductions. This study contributes to the growing body of knowledge on sustainable structural design by emphasizing the importance of the material optimization and environmental impact reduction in the construction industry.

Keywords-tapered steel member; embodied carbon; low carbon steel design; built environment; construction sustainability

I. INTRODUCTION

Global warming poses a critical challenge for environmental sustainability, with buildings playing a central role in it, contributing to 36% of the global energy consumption and nearly 40% of the total CO_2 emissions, both directly and indirectly [1]. Therefore, decarbonizing the building sector has become a priority, in alignment with the global and regional climate policies. For instance, Indonesia is committed to have achieved net-zero emissions by 2060 [2]. Similarly, the updated Energy Performance of Buildings Directive emphasizes energy efficiency, mandating that all new buildings be zero-emission by 2030 [3].

Sustainable practices need to be adopted in the construction industry [4-9]. Steelmaking, an integral part of modern economies, poses significant environmental challenges because of its carbon-intensive nature [10]. Steel production contributes approximately 8% of total Greenhouse Gas (GHG) emissions [11], highlighting the need to reevaluate the steel usage in construction to reduce its environmental impact.

In this context, optimal structural design has emerged as a strategy for promoting sustainability in steel constructions [12-

14]. By systematically optimizing the structural layouts and configurations, optimal design minimizes the resource consumption, reduces the energy demand, and lowers the overall environmental impact of the steel structures [15]. Achieving structural efficiency and resource optimization in steel structures has been thoroughly explored [16-18]. Geometric and material optimization have been a focus of research, with particular attention given to member sizing, shape, and configuration to develop sustainable and efficient designs.

Advances in fabrication techniques have facilitated the use of non-uniform (tapered) members in steel frames, enabling significant material savings and economic benefits, particularly for frames and single-story buildings [19]. Tapered members, typically fabricated from welded plates, can be optimized to satisfy the specific stress and stiffness demands [20-22]. However, their design introduces challenges, such as complex stability characteristics and buckling resistance calculations [23-25]. Research has focused on developing efficient numerical methods for the modal and elastic time-history analysis of frames with tapered sections, utilizing non-prismatic elements and exact consistent mass and stiffness matrices. Additionally, a code-free second-order direct analysis was proposed for the stability design of the steel frames with tapered members, eliminating the need for uncertain effective length and independent member buckling checks. These advancements contribute to a better understanding of the tapered member behavior, providing insights for practical structural designs in various applications, including seismic zones [26-28].

Despite the advancements in the design and optimization of the steel structures, research on the application and performance of tapered members remains limited in key areas. Existing studies primarily focus on the economic and structural efficiency of tapered members but often overlook their potential to reduce embodied carbon. Moreover, although numerical methods and stability analyses have advanced, research that integrates the environmental impact of the tapered members with their structural performance is lacking. This gap is particularly pronounced in the context of gable steel frames, where the use of tapered members can offer substantial benefits in terms of material savings and sustainability.

This study aims to address these gaps by investigating the application of tapered members in gable steel frames to reduce the embodied carbon. The former focuses on evaluating the structural and environmental performance of tapered members considering their ability to optimize the material use while maintaining design integrity. By conducting a detailed analysis, this study seeks to provide insights into the dual benefits of tapered members: achieving structural efficiency and minimizing the carbon footprint of the steel frames. It also contributes to the development of sustainable design practices for steel structures.

II. METHODOLOGY

This study evaluated the structural performance, embodied carbon, and cost-effectiveness of gable steel frames with wide-span configurations, focusing on the application of tapered members. To determine the latter's effectiveness, a standard I-beam section is used as a benchmark for comparison. This analysis was conducted within the framework of different wide-span configurations ranging from 10 m to 20 m. The methodology integrates advanced structural analysis, environmental impact assessment, and economic evaluation to provide an understanding of the sustainability and practicality of the design.

Gable steel frames, as shown in Figure 1, were analyzed and designed using the commercial finite element software SAP2000 [29], which is widely recognized for its precision in structural engineering. To ensure consistency with the established practices, gravity loads were determined in accordance with the provisions of ASCE 7-16 [30], covering load combinations and safety factors. The dead loads encompassed the self-weight of the structure along with a superimposed dead load of 0.9 kN/m and a live load of 3.5 kN/m. For the material selection, JIS G 3101 SS400 steel with a yield strength of 245 MPa was used to balance strength, cost efficiency, and sustainability. The structural elements were designed to meet the compactness criteria, ensuring the absence of slender elements that might compromise stability and design compliance.

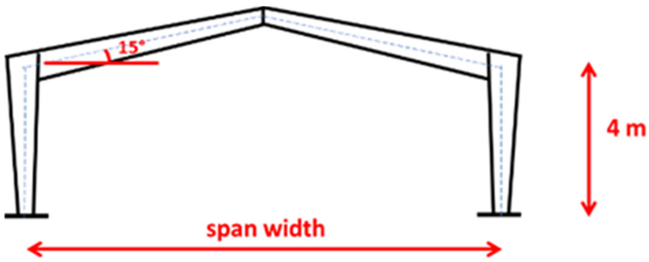

Fig. 1. Gable steel frame model.

The design procedures in this study followed the AISC 360-16 specifications [31]. The adoption of a direct analysis approach in the design method enables a thorough examination of the structural elements. The axial force-bending moment interaction between the columns and beams is expressed by:

When $\frac{P_r}{P_c} \geq 0.2$:

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \quad (1)$$

When $\frac{P_r}{P_c} < 0.2$:

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \quad (2)$$

P_r, P_c, M_r, and M_c represent the required axial, axial, flexural, and flexural strength, respectively. The values of P_r and M_r were obtained from the structural analysis, and the details of the calculation of P_c and M_c can be found in the AISC 360-16 Specification [31].

In this study, tapered members were fabricated by welding steel plates into non-uniform cross-sections. The flange dimensions along the length of the members were constant and the web height varied linearly, as shown in Figure 2. These members were optimized to align with the stress distributions, improve material efficiency, and reduce the overall weight. The unique design of the tapered members ensures that the cross-sectional utilization ratio is maximized, thereby contributing to significant material savings and enhanced sustainability.

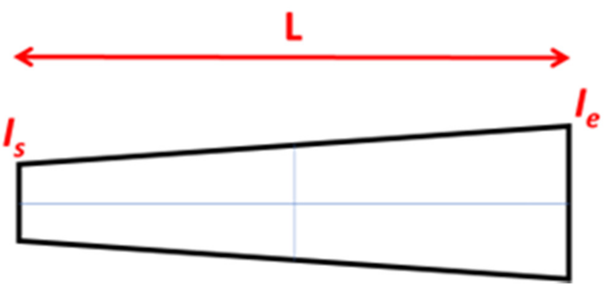

Fig. 2. Longitudinal view of the tapered member at a varying web height.

The EC of both the tapered members and standard I-beams was assessed using a cradle-to-gate framework, encompassing the life cycle stages A1 to A3, as defined in BS EN 15978 []. This includes raw-material extraction, transportation, and manufacturing. The total EC was determined using:

$$EC = \sum(Q_i \times CF) \quad (3)$$

where Q_i is the amount of material and CF is the carbon factor taken as 1.55 kgCO_2e/kg. A carbon factor of 1.5 kgCO_2e/kg for the steel structures was established using the circular ecology approach [33]. The latter aligns with established standards, facilitating a thorough assessment of the carbon footprint associated with the production of steel structures, considering various stages in their life cycle from inception to the production gate.

TABLE I. UNIT COSTS OF THE MATERIALS (1 USD = 16,200 IDR)

Item	Unit rate per kg (IDR)			
	Labor	Equipment	Material	Total
Standard I beam	811	1,507	22,798	25,116
Tapered beam	811	1,507	25,200	27,518

The cost-effectiveness of the designs was evaluated using a comprehensive construction cost analysis tailored to the Indonesian practices. This analysis incorporates the primary cost components of labor, equipment, and material costs, as shown in Table I. The analysis benchmarked the costs of the tapered members against the standard I-beams to determine their economic viability, while ensuring an alignment with the local construction industry norms.

III. RESULTS AND DISCUSSION

The comparative structural designs of the gable steel frames utilizing standard I-beams and tapered members are summarized in Tables II and III, which present the profiles required to ensure structural safety for all investigated span widths. The stress ratios of the members, which indicate the design efficiency, are also included to evaluate the performance of each member type. The stress ratio, which is defined as the ratio of the applied stress to the allowable stress, is a key metric for assessing the effectiveness of the cross section of a structural member.

For the tapered members, the ratios consistently approached the optimal utilization range across the various spans analyzed. The non-uniform cross-sectional profile of the tapered members enables a better alignment with the stress distribution along the member length, thereby optimizing the material usage. This increased efficiency not only reduces the material requirements, but also contributes to significant reductions in the EC and construction costs. On the other hand, the standard I-beams exhibit lower stress ratios, reflecting a less efficient use of the material. This discrepancy can be attributed to the uniform cross-section of the standard I-beam, which may lead to overdesign in regions subjected to lower stress demands.

TABLE II. GABLE STEEL FRAME DESIGN USING STANDARD I-BEAM

Span (m)	Standard I-beam	
	Profile	Stress ratio
10	IWF 250 × 125	0.614
12	IWF 300 × 150	0.614
14	IWF 350 × 175	0.536
16	IWF 350 × 175	0.832
18	IWF 400 × 200	0.608
20	IWF 400 × 200	0.969

The EC results for the gable steel frames presented in Figure 3 reveal notable differences between the standard I-beam designs and the tapered members across varying span widths. For smaller spans (10 m and 12 m), the tapered members exhibited a modest reduction in EC compared to the standard I-beams, with reductions of 5.3% (800 kgCO_2e versus 845 kgCO_2e) and 13% (1016 kgCO_2e versus 1168 kgCO_2e), respectively. These savings can be attributed to the optimized cross-sectional configuration of the tapered members, which reduces the material usage without compromising the structural integrity.

TABLE III. GABLE STEEL FRAMES DESIGN USING TAPERED BEAM

Span (m)	Tapered member		
	Profile at end-*i*	Profile at end-*j*	Stress ratio
10	IWF 250 × 125	IWF 200 × 100	0.667
12	IWF 300 × 150	IWF 200 × 100	0.859
14	IWF 350 × 175	IWF 250 × 125	0.621
16	IWF 350 × 175	IWF 250 × 125	0.957
18	IWF 400 × 200	IWF 300 × 150	0.789
20	IWF 400 × 200	IWF 350 × 175	0.937

As the span width increases, the advantages of the tapered members become more pronounced. For spans of 14 m, 16 m, and 18 m, the tapered members achieved EC reductions of 12.1%, 12.2%, and 14.4%, respectively, compared with their standard I-beam counterparts. These significant reductions highlight the efficiency of the tapered members in accommodating larger structural demands, where material savings are amplified by their ability to align closely with the stress distribution. For the largest span (20 m), the tapered members demonstrated a slightly lower EC (2840 kgCO_2e) than that of the standard I-beam (2949 kgCO_2e). This deviation may be attributed to the design constraints of the tapered members, which necessitate additional material to meet the structural safety requirements at this span length.

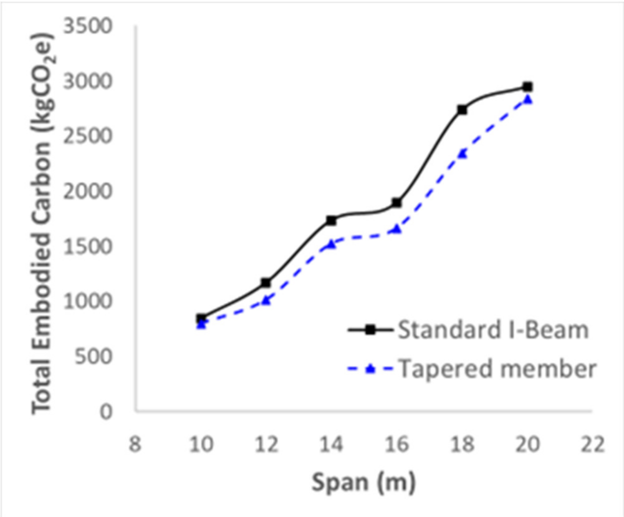

Fig. 3. Total EC of gable steel frame for different spans.

Building on the findings of the EC analysis, the cost analysis further underscores the benefits of employing tapered members in the design of gable steel frames. Figure 4 presents the comparative cost results for both the standard I-beams and tapered members across the range of span widths. The observed trends align with the material efficiency demonstrated in EC analysis, reinforcing the dual benefits of the tapered members in terms of environmental sustainability and economic viability.

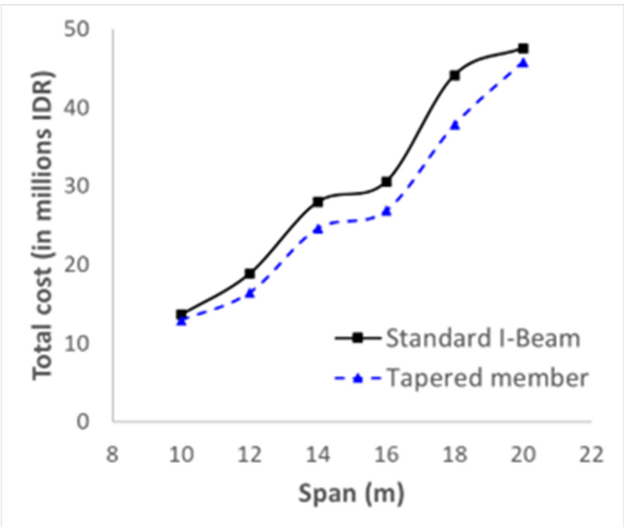

Fig. 4. Total cost of gable steel frame for different spans.

For shorter spans (10 m and 12 m), the tapered members exhibited cost savings of 5.3% (12,913,225 IDR versus 13,633,389 IDR) and 13.0% (16,387,598 IDR versus 18,844,056 IDR) compared with the standard I-beams. These savings reflect the reduced material requirements of the tapered members owing to their optimized design, which efficiently aligns with the structural demands. As the span increases, the cost advantages of the tapered members become increasingly pronounced. These cost savings demonstrate the reductions in EC for the same span lengths, emphasizing the strong correlation between material efficiency and cost-effectiveness in structural steel designs.

For the largest span (20 m), the cost difference between the two design approaches decreases significantly. The tapered members incur a slightly lower cost (45,820,219 IDR) than the standard I-beams (47,569,005 IDR), achieving modest cost savings of 3.7 %. This result is consistent with the EC analysis, which shows a diminished efficiency advantage for the tapered members at this span length. This smaller margin highlights the challenges of optimizing the material usage for very large spans while maintaining the structural safety and performance.

The cost analysis demonstrates that the tapered members not only reduce environmental impacts, but also offer significant economic advantages for most span lengths. These findings reinforce the value of tapered members as an effective design strategy, particularly for medium-to-large spans, where the benefits of material savings are maximized. Integrating tapered members into design practices presents a compelling case for achieving both the cost efficiency and sustainability of the steel structures.

The adoption of tapered members in the steel construction industry aligns with the growing global demand for sustainable and resource-efficient building practices. As sustainability has become a focus for both governments and industry stakeholders, materials and design strategies that reduce the environmental impact are valued. The results of this study demonstrate that the tapered members can contribute to meeting the sustainability goals set by both international and national standards by offering significant reductions in material usage and EC.

This study contributes new insights by quantifying the EC reduction potential of tapered members within a gable steel frame system using a cradle-to-gate Life Cycle Assessment (LCA) approach. While existing research has focused on the structural behavior, buckling resistance, or fabrication optimization of the tapered members [16, 18, 34], few studies have integrated environmental and cost evaluations into the design decision-making process. Compared to previous research that explored tapered beams primarily for load efficiency and structural optimization, this study highlights the broader sustainability implications of positioning tapered members as a strategy for EC reduction in steel structures. This integrated assessment of structural performance, embodied carbon, and cost offers a more holistic understanding of the potential benefits of the tapered members, providing practical insights for advancing sustainable structural design.

IV. CONCLUSIONS

This study investigates the effectiveness of tapered steel members compared with standard I-beams in gable steel frame structures, with a focus on the Embodied Carbon (EC), cost analysis, and overall structural efficiency. The results indicated that the tapered members generally offer a higher level of design efficiency and reduced EC across various span lengths, with the most significant benefits being observed in the spans of 14, 16, and 18 m. The EC for the tapered members was consistently lower than that for the standard I-beams, resulting in environmental benefits that align with the global sustainability goals.

From a cost perspective, the tapered members demonstrate cost savings in shorter spans, although the initial investment in their production and fabrication may offset these benefits in longer-span applications. The cost advantage of the tapered members, particularly for shorter spans, can be important in regions or projects where budget constraints are a significant consideration. However, for larger spans, the complexity and cost of fabricating tapered members must be carefully weighed against potential savings in EC and material usage.

This study provides new insights by quantifying the EC reduction potential of the tapered members within a gable steel frame system using a cradle-to-gate Cycle Assessment (LCA) approach, which has been underrepresented in previous studies. While existing research has focused primarily on structural behavior, buckling, or fabrication methods, this study uniquely integrates environmental and cost evaluations into the design decision-making process. Compared to previous studies [16,18,34], which explored tapered beams primarily for load efficiency, this study highlights the broader sustainability implications, positioning tapered members as a viable strategy for carbon reduction in steel structures.

The findings also underscore the importance of sustainability in steel construction, particularly regarding the focus on reducing the carbon emissions and meeting the energy-efficiency targets. The use of tapered members enables meeting these demands by optimizing the material use and lowering the environmental impact. The adoption of these members can be facilitated by advancements in fabrication technologies and their integration into design standards and building codes.

While this study demonstrates the potential of tapered members in structural design, broader industry adoption will depend on overcoming the challenges related to fabrication complexity, cost, and regulatory integration. Future research and development efforts should focus on refining the manufacturing techniques, expanding the range of applicable design codes, and exploring the long-term economic and environmental benefits of the tapered members. With continued innovation and standardization, the tapered steel members may become widely adopted solutions for sustainable, efficient, and cost-effective steel construction.

Tapered steel members represent a significant advancement in steel-frame design, offering both environmental and economic advantages in the context of sustainable building practices. While challenges remain, their adoption could play a key role in reducing the carbon footprint of the built environment and contribute to global sustainability efforts. Further exploration of their applications in diverse structural contexts is essential for determining their full potential and optimizing their use in future construction projects.

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DATA AVAILABILITY

https://zenodo.org/records/14954743

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