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Structural Efficiency and Embodied Carbon Assessment of Pre-Engineered Versus Conventional Steel Beams

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Abstract

The increased focus on the reduction of greenhouse gas emissions in the building and construction sector has heightened the demand for structural systems that reduce both material and embodied carbon. Pre-engineered building (PEB) systems using tapered built-up steel beams could potentially offer a viable alternative to traditional hot-rolled prismatic sections by better matching and aligning the sectional capacity and the bending demand. However, there are still a limited number of studies that perform comparative analyses integrating structural and environmental impact. This study assessed the structural efficiency and embodied carbon of pre-engineered and conventional steel beams over spans of 6 to 20 m for fixed-end and pinned-end boundary conditions. Structural design was performed in accordance with AISC 360-16, and embodied carbon was assessed for life cycle modules A1–A5 following BS EN 15978. The results indicate that tapered built-up beams achieve higher utilisation ratios and smaller effective section sizes, particularly for short and intermediate spans. Life-cycle assessment shows that pre-engineered beams reduce embodied carbon by approximately 10–25% compared with conventional beams, primarily owing to their lower steel mass. These findings demonstrate that tapered built-up beams offer both structural and environmental advantages in the investigated design context.

Keywords: Conventional hot-rolled beam, Embodied carbon, Pre-engineered steel, Sustainability, Tapered built-up section

1. Introduction

Owing to the impact of global warming, the need to minimise the release of greenhouse gases, especially the CO_2 produced from burning fossil fuels such as coal, oil, and natural gas, has never been more pressing [1]-[4]. Consequently, the shift to renewable and low-carbon energy sources has become a global priority owing to the added economic and socio-economic gains, along with the environmental benefits [5]-[8].

The construction sector is one of the top contributors to current environmental and climate challenges. The construction, use, and maintenance of buildings and infrastructure accounted for 37% of global greenhouse gas emissions from human activity in 2022 [9]-[12]. Furthermore, this sector contributed approximately 20% of the global energy-related CO_2 emissions in 2020, and this figure is projected to increase in the absence of adequate mitigation efforts [13]-[16].

In this context, the industrial sector, particularly the steel subsector, is important. Steel, as one of the foremost materials in construction, accounts for over 50 percent of the world's steel consumption [17]-[20]. As structural systems grow in size, complexity, and resource consumption, the need for effective design strategies for low-carbon steel has increased. The focus has been placed on the operational and embodied carbon, which is determined by the amount of structural steel used and the efficiency of its use.

To mitigate these concerns, structural optimisation is used to consolidate the sustainability of steel constructions [21]-[25]. This allows for the effective redistribution of materials, and when paired with the reduction of the overall steel consumption, the embodied carbon in the steel structures is also reduced [26]. Several optimisation strategies have emerged in studies, including focusing on members alone, geometric optimisation, topological and material optimisation, striving towards environmentally friendly and structurally efficient designs [27]-

[29]. At a broader scale, Kanyilmaz et al. [30] developed a multi-objective optimisation framework based on the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to support low-carbon conceptual building design. The framework generates Pareto-optimal solutions by balancing the construction cost, embodied CO_2 emissions, and functional space across multiple structural and material design variables. While such system-level optimisation studies demonstrate the effectiveness of data-driven approaches in reducing embodied carbon during the early design stages, they do not explicitly investigate how structural member configuration, particularly beam geometry, influences material efficiency and carbon performance.

Recent developments in steel fabrication have allowed for the increased use of pre-engineered building (PEB) systems, which rely on non-standard or tapered built-up components [31]-[35]. The construction of PEB involves the use of beams and columns made of welded plate assemblies. The thickness and depth of these assemblies vary along the length of each member to correspond to the distribution of the bending moments. This method allows for a greater reduction in the amount of steel used, thereby decreasing the cost of the overall project, especially relevant for large span, single-story, and industrial buildings [36]. Owing to the custom disposition of tapered built-up members, their geometry can be efficiently adjusted to fulfil the requirements for strength and stiffness, ensuring that the structural capacity is not wasted [37], [38].

The difficulties faced in tackling the design and analysis of tapered built-up longitudinal members and their use in pre-engineered building (PEB) frames are overshadowed by the benefits of the buildings. Because the members are non-prismatic, they have more complicated stability issues, such as being more susceptible to local, lateral-torsional, and global buckling, as well as more complicated second-order behaviour, in contrast to standard prismatic sections [39]-[41]. Recent studies have developed various non-prismatic finite elements to address these issues. These studies have advanced the field of modal and dynamic analysis and established frameworks for second-order direct analysis that are free of codes and do not depend on effective length fabrication. These efforts have improved the understanding of tapered steel frames and the design of PEB, including the inelastic design and application in areas that are susceptible to earthquakes [42]-[44].

This study was conducted within the scope of steel building design and construction practice in Indonesia, which includes the use of conventional hot-rolled steel profiles and Pre-Engineered Building (PEB) systems in residential, commercial, and industrial applications. The selection of beam profiles was based on the availability of cross-sections in the domestic steel market, such that the analysed configurations reflected actual conditions commonly found in local construction practices. All structural analyses and strength verifications refer to the AISC 360-16 (American Institute of Steel Construction) specifications, a standard that has been widely adopted in professional steel design practice in Indonesia. This study provides geographic and regulatory clarifications that not only explain the assumptions being made but also allow researchers and practitioners worldwide to interpret the findings more broadly.

Limited research has been done on empirically evaluating the practical performance of tapered prefabricated beams compared to conventional hot-rolled beams, even after having a large number of research papers going on technical analysis, structural modelling, or even individual component behaviour. Very few papers look at the realistic performance of the component or the realistic constraints of the design. Therefore, the literature has a wide gap when it comes to the comparison of structural behaviour, stiffness, material efficiency of tapered prefabricated beams and conventional prismatic beams, and how this translates to the raw material and embodied carbon savings.

In response to this gap, this research performs a systematised comparative study of pre-engineered tapered beams versus traditional hot-rolled beams, analysing them using a uniform approach. This study aims to assess flexibility performance as well as lateral stiffness, and their roles in relation to the material efficiency, with respect to the steel weight and the embodied carbon, across various representative spans and support configurations. Overall, the multiplicative outcomes of this study provide a quantitative metric to assess the structural efficiency of pre-engineered tapered beams as well as prismatic beams. Hence, this study focuses on the positive and negative impact of pre-engineered beam systems, which is critical to the advancement of low-carbon steel construction.

2. Methodology

2.1. Beam Geometry and Structural Configuration

This study evaluated the structural performance of non-composite steel floor beams positioned on grid B1–2, as illustrated in Fig. 1. The analysis focuses on comparing pre-engineered steel beams (assembled tapered sections) and conventional hot-rolled steel beams by applying identical modelling and boundary conditions. The beam spans considered ranged from 6 to 20 m, chosen to represent a variety of short-, medium-, and long-span configurations commonly found in residential and low-rise buildings. The applied gravity loads were based on the standard requirements for residential buildings, namely a uniform dead load of 1 kN/m^2 and a uniform live load of 2 kN/m^2 [45]. Both types of loads were converted to equivalent line loads based on the beam influence width and applied uniformly to both beam systems to ensure an objective and consistent comparison of the structural performance.

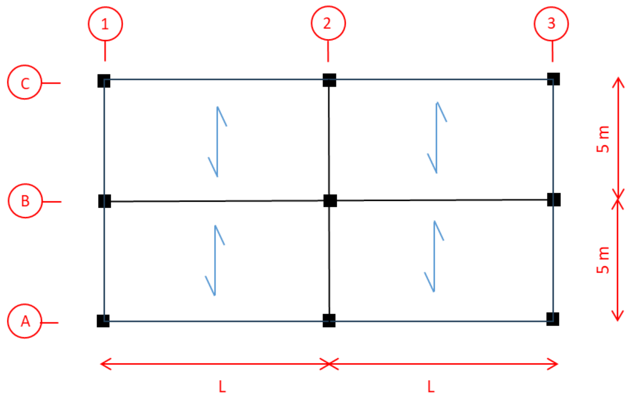


Figure 1. Plan view of the structural layout.

2.2. Structural Analysis and Design Procedure

All structural models in this study were developed and analysed using SAP2000 finite element software [46]. This software was chosen because of its ability to provide an integrated environment for the linear elastic analysis of steel structures, as well as its widespread use in calculating internal forces and deformations owing to gravity loads. The design code requirements were subsequently verified using the bending moments and deflections obtained from SAP2000 for each considered beam configuration. To ensure consistency in the material characteristics between the two beam systems, the material properties were defined with reference to JIS G 3101 SS400 structural steel with a minimum yield stress of 245 MPa.

To study the effect of connection stiffness on the structural response, each beam configuration was modelled with two ideal boundary conditions representing different end behaviours. The first represents a simply supported system with pinned–pinned ends, corresponding to beams connected through simple fin plate connections that provide negligible rotational restraint. The second represents a fully restrained system with fixed–fixed ends, corresponding to idealised moment-resisting connections. Considering both boundary conditions brackets the realistic range of end restraints encountered in practice and enables the assessment of their effects on the comparative behaviour of pre-engineered and conventional steel beams.

The steel beam design was conducted according to the provisions of AISC 360-16 [47]. The beams were assumed to be continuously laterally braced, reflecting the typical floor construction in which the steel beam is restrained by a cast-in-place concrete slab and structural screed; under this assumption, lateral–torsional buckling does not govern, and the flexural strength is controlled by section yielding. The optimisation adopted in this study was deterministic and iterative in nature. For each span and boundary condition, a predefined set of candidate sections was analysed, and the smallest section satisfying the flexural strength requirements was selected. All cases were evaluated manually to ensure transparency and consistency in the comparison between the pre-engineered and conventional steel beams.

The available flexural strength was evaluated using a resistance factor of φ = 0.90. For compact sections fully braced against lateral instability, the flexural strength capacity (M_c) is given by:

$$M_c = \phi M_n = 0.9 F_y Z \quad (1)$$

where F_y represents the yield stress of the steel section, and Z is the plastic section modulus. To ensure the consistency of the comparison basis, this formulation was applied uniformly to both beam systems, namely, pre-engineered tapered beams (evaluated at their critical sections) and conventional hot-rolled beams.

To quantify the efficiency of material utilisation at each beam cross-section, the utilisation ratio (UR) is defined as the ratio of the required bending moment (M_r) obtained from the structural analysis to the available flexural capacity (M_c) of the cross-section under consideration, as expressed in (2):

$$Utilisation\ ratio = \frac{M_r}{M_c} \quad (2)$$

This ratio provides a quantitative indicator of the extent to which the flexural capacity of a cross-section is mobilised in response to an applied load. A UR value ≤ 1.0 indicates that the section satisfies the strength requirement, whereas values approaching unity represent a more efficient use of material. Lower utilisation ratios indicate increasing levels of unused capacity and, consequently, reduced material efficiency. In this study, the utilisation ratios typically ranged between 0.75 and 0.90, reflecting sections that are both code-compliant and efficiently proportioned.

In this study, a pre-engineered steel beam was modelled as a tapered built-up member whose depth varied along the span in accordance with typical pre-engineered building (PEB) fabrication practices. As shown in Fig. 2, the beam geometry is represented using a three-segment linear taper comprising end segments of 0.3 L on each side and a central segment of 0.4 L, where L denotes the total beam span. This segmentation allows the depth variation to closely follow the bending-moment distribution while maintaining the plate fabrication efficiency.

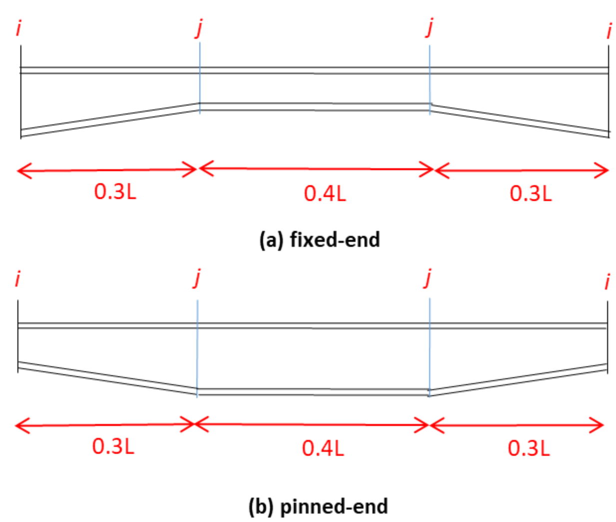


Figure 2. Tapered built-up beam configuration for the pre-engineered steel beam.

The tapered built-up beams were assumed to be fabricated from web and flange plates connected by continuous fillet welds along the member length, consistent with the common PEB fabrication practice. For the structural analysis and section property calculation, the welds were assumed to provide full composite action between the plates, and local weld strength checks were not explicitly modelled. A simplified fabrication assumption was adopted, whereby the weld configuration was sufficient to develop the full strength of the connected plates; therefore, the influence of welding on the global flexural behaviour was neglected. This assumption was applied consistently across all tapered beam configurations, as the study focused on comparative structural performance rather than detailed fabrication design.

An optimisation-based approach was adopted to select the steel beam profiles for both conventional hot-rolled beams and pre-engineered tapered built-up beams. For each span and boundary condition, a predefined set of candidate sections was evaluated based on their ability to satisfy the required flexural strength under the governing design load, according to AISC 360-16. The optimisation process was carried out iteratively by progressively eliminating inadequate sections, such that the smallest section meeting the flexural strength requirement was selected as the optimal solution for each case study. The hot-rolled section series considered in this study, as summarised in Table 1, comprises profiles commonly available in the Indonesian steel market, thereby ensuring that the analysis reflects local construction practices and that the results are directly applicable to practical design conditions.

Table 1. Dimensions of steel beam sections considered in this study.

Section	Height (mm)	Width (mm)	Thickness (mm)		Mass (kg/m)
			Web	Flange	
I200x100	200	100	5.5	8	21.3
I250x125	250	125	6	9	29.6
I300x150	300	150	6.5	9	36.7
I350x175	350	175	7	11	49.6
I400x200	400	200	8	13	66.0
I450x200	450	200	9	4	76.0
I500x200	500	200	10	16	89.6
I600x200	600	200	11	17	106.0
I600x300	588	300	12	20	151.0
I700x300	700	300	13	24	185.0
I800x300	800	300	14	26	210.0
I900x300	900	300	16	28	243.0

For the pre-engineered tapered built-up beams, the web and flange plate thicknesses were selected to be comparable to those implied by the corresponding conventional hot-rolled beam sections, ensuring a consistent and unbiased basis for comparison. This approach was adopted to ensure that the differences in structural performance, steel mass, and embodied carbon primarily arise from geometric variations along the span (i.e., tapering of beam depth) rather than from differences in material thickness. In accordance with the common pre-engineered building fabrication practice, the plate thicknesses were kept constant along the member length, whereas the beam depth varied linearly to reflect the bending moment distribution. The adopted plate thicknesses and corresponding section identifiers are explicitly reported to ensure the transparency and reproducibility of the analysis.

2.3. Embodied Carbon Assessment

The evaluation of the environmental consequences linked to the construction of steel beams consists of calculating the embedded carbon of the specified beam configurations, considering the sustainability assessment in this study. The assessment aligns with and follows the principles and system boundaries of BS EN 15978:2011[48], which describes the life-cycle environmental performance across several modules. Consistent with the objectives of early-stage structural design studies, the assessment focused on the product stage (A1–A3), including raw material extraction (A1), transportation to manufacturing facilities (A2), and manufacturing processes (A3), as well as the construction stage (A4–A5), which comprises material transport to the site (A4) and construction-related activities (A5). These stages were selected because they represent the dominant contributors to the embodied carbon in steel structural systems.

Emissions associated with fabrication processes specific to built-up members, such as welding or riveting, were not explicitly quantified in the present assessment because of the absence of project-specific fabrication data. This assumption is reasonable for a comparative study because the embodied carbon of steel structures is primarily governed by the material quantity at the product stage, whereas fabrication-related emissions typically constitute a relatively small proportion of the total emissions [23], [49].

The product stage encompasses raw material extraction, processing, manufacturing, and material transportation to fabrication facilities. The embodied carbon associated with stage $EC_{A1\text{-}A3}$ was determined using the following:

$$EC_{A1-A3} = \sum Q_i CF_{A1-A3} \quad (3)$$

where Q_i is the amount of material, and $CF_{A1\text{-}A3}$ is the carbon factor for steel production. A carbon factor of 2.0 $kgCO_2e/kg$ was adopted based on a comprehensive carbon and energy inventory derived from the Circular Ecology Database [50]. The same emission factor was applied to both pre-engineered tapered and conventional hot-rolled beams to ensure that the differences in embodied carbon reflect variations in structural mass and material utilisation, rather than differences in the assumed material carbon intensity.

For pre-engineered tapered built-up beams, a screening-level estimation was adopted to account for the welding-related embodied carbon. Welding energy consumption was assumed to be 1 kWh per meter of weld, which is consistent with the values commonly reported for structural steel fabrication [51]. The total weld length was conservatively approximated as twice the beam span, reflecting continuous longitudinal welds along the web–flange interfaces. An electricity emission factor of 0.78 $kgCO_2e/kWh$ was adopted, which is representative of the Indonesian grid mix [52]. Based on these assumptions, the embodied carbon associated with welding was calculated as an additional contribution to the total embodied carbon of the pre-engineered beam.

Module A4 accounts for emissions associated with transporting the fabricated materials to the construction site. The embodied carbon for this stage is expressed as:

$$EC_{A4} = \sum Q_i CF_{A4} \tag{4}$$

where the transportation carbon factor CF_{A4} is calculated as:

$$CF_{A4} = \sum TD \times TEF \tag{5}$$

where *TD* represents the transport distance, and *TEF* is the transport emission factor, which is taken as 0.10749 $gCO_2e/kg/km$[49]. This formulation enables the quantification of emissions arising from material logistics between fabrication facilities and construction sites.

Module A5 captures the emissions associated with installation activities and on-site material wastage. In accordance with BS EN 15978, the total embodied carbon of the construction stage was separated into emissions from material waste (A5w) and emissions from general construction activities (A5a).

The material wastage emissions EC_{A5w} are calculated as follows:

$$EC_{A5w} = WF_i \times (CF_{A1-A3} + CF_{A4}) \tag{6}$$

where the waste factor WF_i is derived from the waste rate WR_i as:

$$WF_i = \frac{1}{1-WR_i} - 1 \tag{7}$$

A waste rate of 1% was adopted for the steel structures[49].

Additionally, Emissions associated with energy use and site operations EC_{A5a} were estimated using a cost-based approach defined by:

$$EC_{A5a} = CAEF \times \frac{PC}{100{,}000} \tag{8}$$

where *CAEF* represents the construction activities emission factor of 700 $kgCO_2e$/£100,000, and *PC* is the project cost [49]. This method provides a standardised estimate of on-site operational emissions during beam installation.

The project cost (PC) used in this study represents the estimated construction cost associated with the fabrication and installation of steel beam systems. The cost assessment was based on unit cost data representative of Indonesian construction practices and included labour, equipment, and material costs [53]. While the labour and equipment costs were assumed to be identical for conventional hot-rolled and pre-engineered tapered beams, differences in material costs were considered to reflect the additional fabrication requirements for tapered built-up sections. The total project costs for each beam configuration are summarised in Table 2.

Table 2. Unit construction cost of steel beams based on Indonesian construction practice.

Item	Unit rate per kg (IDR)			
	Labour	Equipment	Material	Total
Conventional	811	1,507	22,798	25,116
Pre-engineered	811	1,507	25,200	27,518

*£ 1 = IDR 22,000.

3. Results and discussion

Tables 3 and 4 illustrate the design outcomes for pre-engineered (tapered assembly) and conventional hot-rolled beams. The analysis spans from 6 to 20 m for two boundary conditions: pin-pin and pin- pinned supports. Within each span arrangement, the chosen cross-section dimensions with their associated utilisation ratios are indicated. This concise summary methodically depicts the effect of tapered geometry on the flexural strength efficiency, especially in relation to the performance of conventional prismatic sections.

Studies show that pre-engineered beams are more material efficient than traditional prismatic beams, particularly for short to medium spans with fixed supports. This is evident by their greater utilisation ratios along with consistent decreases in steel mass. Table 5 summarises that pre-engineered beams use less steel than traditional beams for all spans. This is especially true for fixed-support spans, where the support area is less critical in bending, facilitating more efficient use of materials.

Geometrically, the depth of pre-engineered beams is typically smaller than or at least comparable to that of standard hot-rolled beams. This shows the benefit of the tapered shape for material allocation by preferentially concentrating material in regions of high moment demands (e.g., mid-span) and reducing it in regions of low moment demands (e.g., near the supports). Such a method increases the recovery efficiency and decreases total material usage.

For spans between 6 and 20 m, pre-engineered beams get utilisation ratios between 0.75 and 0.90. In comparison, standard prismatic beams with the same spans show persistently lower utilisation ratios. This difference shows the problems with prismatic sections, which include having too much structural capacity in regions with low bending demands, particularly near the supports.

On the other hand, tapered pre-engineered beams are better aligned regarding section capacity and the distribution of bending moments along the span. This feature provides an opportunity for optimized material distribution and, therefore, greater structural efficiency for the applied loads. For these reasons, tapered shapes are better suited for varying bending demands, especially in small to medium span applications.

From the information given, it is clear that tapered built-up beams have definite advantages when employed in frameworks with uneven bending moment distributions and where the bending demand fluctuates greatly across the span, in comparison with standard prismatic beams, which have their cross-sections fixed. Standard prismatic beams create large areas that have little to no bending demand and therefore little to no flexural demand, meaning that the beams are over-designed and materials are being wasted. When the span is lengthened, the dominant design factor is the maximum bending moment that will occur. As this factor is considered, there is an increased demand for consistency in section stiffness and flexural capacity across the length of the beam. As this occurs, the advantages of tapering are reduced, and prismatic and tapered beams behave similarly.

Fig. 3a and 3b show the embodied carbon of the pre-engineered (tapered built-up) and conventional hot-rolled steel beams for spans between 6-20 m under fixed-end and pinned-end support conditions. An even steel emission factor was used for both beam systems; therefore, the differences in the embodied carbon predominantly stemmed from differences in structural mass. Remaining consistent with this, the pre-engineered tapered beams showed consistently lower embodied carbon than the prismatic beams for all spans and support conditions. These reductions arise from the improved material utilisation achieved through depth variation along the beam length, which allows steel to be concentrated in regions of higher bending demand while minimising excess material in regions of lower demand. Therefore, the results quantify the magnitude and robustness of mass-driven embodied carbon reductions achievable through tapered beam design under realistic structural constraints.

Table 3. Design results pre-engineered vs conventional beam in fixed-end conditions.

Span (m)	Pre-engineered			Conventional	
	Section i	Section j	Ratio	Section	Ratio
6	I350x175	I250x125	0.90	I350x175	0.63
8	I400x200	I350x175	0.79	I400x200	0.74
10	I500x200	I400x200	0.76	I500x200	0.71
12	I600x200	I450x200	0.82	I600x200	0.75
14	I600x300	I500x200	0.84	I600x300	0.69
16	I600x300	I600x200	0.93	I600x300	0.90
18	I700x300	I600x300	0.84	I700x300	0.80
20	I800x300	I600x300	0.84	I800x300	0.78

Table 4. Design results pre-engineered vs conventional beam in pinned-end conditions.

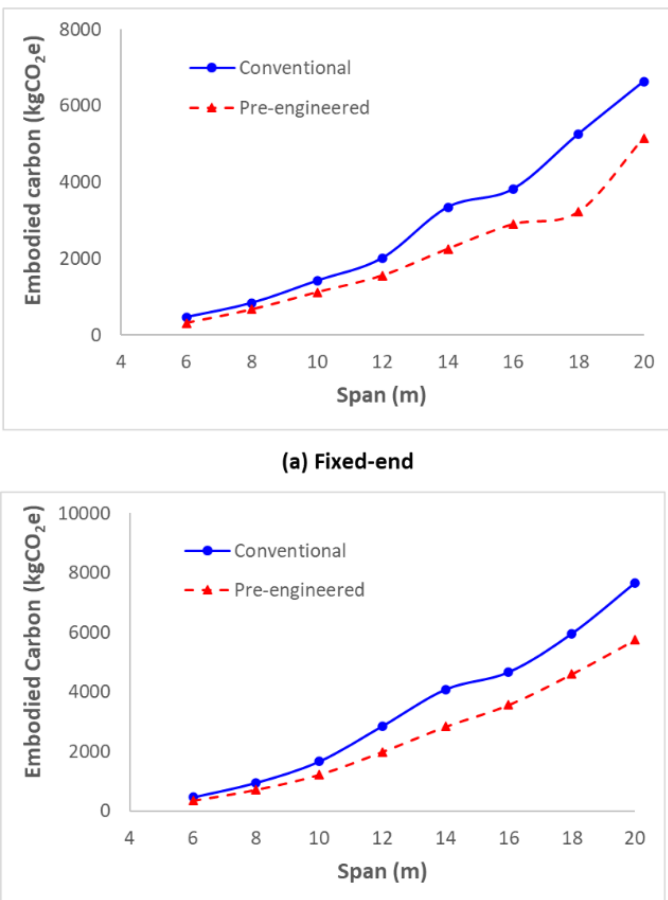
Span (m)	Pre-engineered			Conventional	
	Section i	Section j	Ratio	Section	Ratio
6	I200x100	I350x175	0.99	I350x175	0.95
8	I250x125	I450x200	0.93	I450x200	0.88
10	I300x150	I600x200	0.84	I600x200	0.78
12	I300x150	I600x300	0.86	I600x300	0.76
14	I350x175	I700x300	0.75	I700x300	0.72
16	I450x200	I700x300	0.97	I700x300	0.95
18	I500x200	I800x300	0.97	I800x300	0.95
20	I500x200	I900x300	0.98	I900x300	0.93

Table 5. Total steel mass (kg) of pre-engineered and conventional beams for different spans and boundary conditions.

Span (m)	Pre-engineered		Conventional	
	Fixed ends	Pinned ends	Fixed ends	Pinned ends
6	202	231	297.6	297.6
8	425	461	528	608
10	710	782	896	1060
12	987	1267	1272	1812
14	1428	1834	2114	2590
16	1836	2264	2416	2960
18	2040	2917	3330	3780
20	3263	3641	4200	4860

For both support conditions, the carbon beams embodied an increase in a nonlinear manner with the span length, consistent with a proportional relationship with an increased required section size and steel mass. But for each span, pre-engineered and tapered beams experienced, as a result of pre-engineered and tapered beams, lower embodied carbon than conventional designs. The span-to-carbon reduction from the standard design was approximately 10% for shorter spans and increased to 20-25% for mid-spans, demonstrating the material efficiency gained by the tapered designs.

For shorter spans (6-10 m), the variations between the two systems are small, and both configurations use small section sizes. For larger spans, the differences between the two systems increase, with the pre-engineered beams having a lower carbon footprint. This is because beam systems use a more efficient allocation of materials, resulting in less steel stored in a section due to a better-fitting section, as constant-depth prismatic sections have greater amounts of unnecessary steel.



(a) Fixed-end

(b) Pinned-end

Figure 3. Embodied carbon of pre-engineered and conventional steel beams.

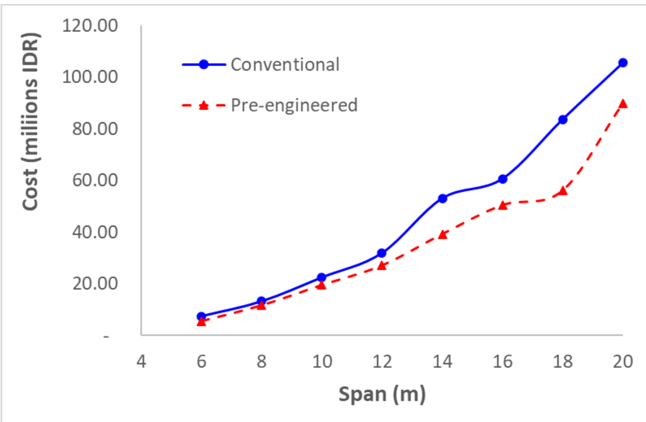
Although both beam systems exhibited a substantial increase in embodied carbon for spans exceeding 16 m, the pre-engineered beams continued to demonstrate a relative advantage within the scope of this study. For spans of 18–20 m, the tapered built-up beams achieved embodied carbon reductions of approximately 12–18% compared with conventional prismatic beams, primarily owing to a more efficient material distribution. However, it should be noted that these long-span cases represent an idealised member-level comparison. In the context of practical engineering applications, it should be noted that long spans—particularly those near the upper limit of the range in this study —can generally be handled more effectively through alternative structural systems, such as trusses or Vierendeel configurations, which are not within the scope of this analysis. Therefore, the results obtained for the longest spans should be viewed as comparative indicators for understanding the relative behaviour between beam systems rather than as final design recommendations. This interpretation is important to avoid overgeneralisation and to place the study's findings in the proper practical perspective.

Comparing Fig. 3a and 3b shows that the pattern of embodied carbon is fairly similar for both boundary conditions investigated – fixed and hinge supports. The pre-engineered beam system achieved the same percentage reductions across most support conditions, illustrating that the tapered beam's environmental efficiency was not highly responsive to variations in end restraint assumptions.

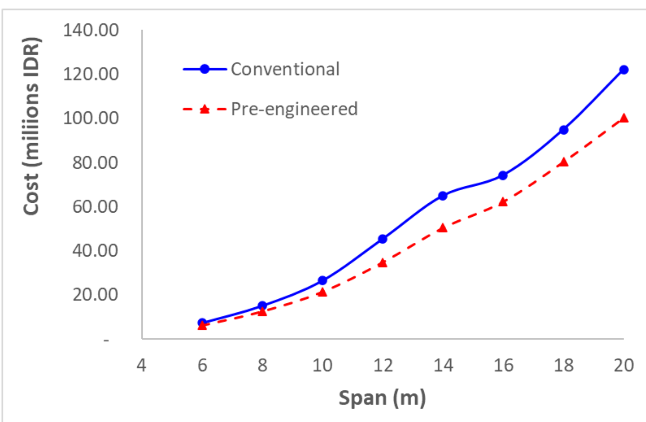
This supports the case that the pre-engineered approach offers flexibility in terms of the varying support conditions typical in real-world building situations. More specifically, the environmental advantages of tapered geometry, specifically the reduction of embodied carbon emissions, appear to be universally applicable independent of end restraint configuration, assuming the bending moment distribution is such that material is optimally utilised. This further illustrates the pre-engineered beam systems' sustainability as adaptable to various structural parameters.

The carbon footprint reduction observed in prefabricated tapered beams primarily stems from their increased material efficiency. Unlike prismatic hot-rolled steel sections that maintain a constant depth throughout the span, thus tending to store excess material in areas with low bending demands, such as around supports, prefabricated beams adopt variable geometries that adapt to the distribution of bending moments. This alignment between the section capacity and internal force requirements allows for a more proportional distribution of material, which, in turn, reduces the total steel mass and directly contributes to reduced embodied carbon emissions. In other words, the efficiency of tapered geometries not only improves the structural performance but also provides significant environmental benefits through optimised material use.

Fig. 4a and 4b present a comparison of the construction costs between pre-engineered (tapered built-up) and conventional hot-rolled steel beams for spans ranging from 6 to 20 m under fixed-end and pinned-end conditions. For both systems, the total cost increases nonlinearly with the span length owing to the increasing steel mass and section size; however, pre-engineered beams consistently exhibit lower overall costs across all spans and support conditions. The cost difference is relatively small for short spans (6–8 m), where the section sizes are comparable, and the benefits of tapering are limited, but it becomes more pronounced for intermediate spans (10–16 m), where the material savings from geometric optimisation outweigh the additional fabrication effort associated with welded built-up members. At longer spans (18–20 m), although the absolute costs increase substantially for both systems owing to the governing strength and stiffness requirements, pre-engineered beams maintain a clear cost advantage. This screening-level cost assessment, using unit rates representative of Indonesian construction practices, shows that, where manufacturing and construction conditions are favourable, pre-engineered tapered beams, in addition to lowered embodied carbon, can offer an economically viable alternative to traditional hot-rolled beams.



(a) Fixed-end



(b) Pinned-end

Figure 4. Cost of pre-engineered and conventional steel beams.

However, the adoption of pre-engineered beam systems must be considered within a broader practical and regional context. Although tapered built-up beams offer greater optimisation potential in terms of material efficiency, their use typically entails increased fabrication effort, including additional welding, skilled labour, quality control requirements, and access to specialised manufacturing facilities. Notably, pre-engineered tapered elements potentially require more complex beam-column connection details than conventional hot-rolled profiles, such as thicker end plates, additional stiffeners, and increased welding volume, to accommodate variations in element depth and force transfer. Although these aspects were not explicitly analysed in this study, they were qualitatively recognised as practical considerations that can impact construction time, project cost, and total embodied carbon emissions. A detailed evaluation of the connection behaviour and fabrication impacts is beyond the scope of this study and is recommended as a direction for further research.

Overall, pre-engineered tapered assembly beams consistently demonstrate performance advantages over conventional hot-rolled beams across the span range and boundary conditions considered, as reflected in higher structural efficiencies and significant reductions in embodied carbon and material costs. Despite the convergence of cross-sectional requirements over long spans owing to the dominance of stiffness requirements, the comparative performance trends remain similar across both support conditions (clamped and hinged). This indicates that the efficiencies afforded by the tapered geometry are relatively insensitive to variations in the end restraint assumptions. The environmental analysis also confirmed that the reduction in steel mass directly correlated with a reduction in embodied carbon emissions and costs within the life cycle stages adopted in this study.

In contrast, hot-rolled steel profiles offer competitive advantages through product standardisation, simplicity of fabrication processes, and ease of construction. These attributes allow them to be more economical and practical, especially for applications with short spans or when fabrication capabilities are limited. Regional construction practices also impact the preference for this type of profile. For example, in Europe, there are more hot-rolled profiles, while in Europe, there are more assembled or welded profiles in the more developed fabrication industry zones. In Indonesia, the pre-engineered building system is dominant in the industry and warehousing sectors. Here, the need for repetitive geometries and for fab-controlled environments and for spans in the mid to long range is focused on taper beam solutions.

Therefore, this study shows that prefabricated tapered beams, when placed within specific designed and built parameters, can be useful as low-carbon structural components, especially within the scope of industrial and medium span applications, where there is sufficient fabrication capacity. Furthermore, it is critical that tapered beam systems must not be considered as a blanket substitute for standard hot-rolled sections. They are a design alternative that, when tailored to a specific situation, can offer considerable structural and ecological advantages.

This study only examines ultimate limit state (ULS) design of steel beams, without regard to serviceability limit state (SLS) conditions such as deflection control. In real-world floor systems, the requirements for deflection control may dictate the choice of beam size, especially if the spans are longer or the floor is lightly loaded, potentially offsetting some of the efficiency improvements resulting from strength-based optimization. However, by adopting a consistent ULS-based design framework for both pre-engineered and conventional beams, the present comparison provides a clear assessment of their relative structural efficiency and embodied carbon trends in the early design stage. The incorporation of serviceability criteria, including short- and long-term deflection and vibration performance, has been identified as an important area for future research.

4. Conclusions

This study investigated the structural performance and embodied carbon of pre-engineered tapered built-up steel beams compared with conventional hot-rolled prismatic beams across a range of spans and boundary conditions. The analysis was based on structural design in accordance with AISC 360-16, a deterministic and iterative evaluation of predefined candidate sections to identify the minimum section satisfying flexural strength requirements, and a life-cycle assessment of embodied carbon covering the product (A1–A3) and construction (A4–A5) stages in accordance with BS EN 15978. Based on the results obtained, the following conclusions were drawn:

1. Pre-engineered tapered beams demonstrate superior material efficiency at short and intermediate span lengths.

   In short-to medium-span (6–16 m) bridges, tapered precast beams generally require smaller cross-sectional sizes, or at least comparable sizes to conventional hot-rolled beams, while still achieving higher utilisation ratios. This phenomenon reflects the advantage of the tapered geometry in aligning the cross-sectional capacity with the bending moment distribution more proportionally. Consequently, excess material in areas with low bending requirements, particularly around supports, can be minimised, thereby increasing the overall structural efficiency without sacrificing the required mechanical performance.

2. The relative efficiency of the pre-engineered beams was robust across the boundary conditions.

   Comparative trends between tapered and prismatic consistent beams under pinned and hinged support conditions. Although the pinned condition slightly increases the utilisation ratio of the tapered beams owing to the reduction in moments at midspan, the overall advantages of the pre-engineered system are maintained. This indicates that the material efficiency of the tapered geometry is robust and does not depend significantly on variations in the end restraint.

3. Pre-engineered beams achieve meaningful reductions in the embodied carbon.

   The life cycle analysis results show that tapered assembly beams produce a 10–25% lower carbon footprint than conventional prismatic beams across the entire span. This reduction is primarily due to higher material efficiency, where the optimisation of the cross-sectional geometry with respect to the moment distribution significantly reduces the steel mass.

4. Pre-engineered tapered beams also exhibit favourable cost performance.

   Tapered beams may provide a combination of environmental and economic benefits to the construction sector. Pre-engineered beams, for instance, tend to be more cost-effective when compared to typical hot-rolled beams, particularly on medium spans. Cost savings on steel fabrication tend to be greater than the cost of steel used in the beams.

5. Tapered built-up beams represent a viable strategy for low-carbon steel design within the scope of this study.

   Pre-engineered beams assist in lowering the carbon footprint of steel constructions by combining improved structural efficiency with decreased use of materials. The tapered beam systems help short to mid-range steel construction systems, as the consistency of their benefits in spans and boundary conditions is broad.

In summary, this parametric study demonstrated that pre-engineered tapered assembly beams offer higher structural efficiency and significant embodied carbon reduction compared with conventional hot-rolled beams. The primary advantage stems from the adjustment of the beam depth geometry to the bending moment distribution, which improves the material utilisation and reduces the steel mass. However, fabrication contributions, such as welding, plate cutting, and waste, were not quantified in this analysis owing to specific data limitations, potentially affecting the results. Although alternative systems may be more appropriate for very long spans, this study supports the use of pre-engineered beams as an effective contextual solution for reducing material use and carbon emissions in short- to medium-span steel buildings, in line with efforts to achieve more sustainable structural engineering practices.

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Conflict of interest

The authors have no conflict of interest to declare

Author Contribution Statement

Riza Suwondo prepared the manuscript, Made Suangga reviewed the manuscript, Militia Keintjem performed the analysis, and Traad Alzhrani reviewed the manuscript.

Data Availability (Optional)

Data analysis https://zenodo.org/records/17626185

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