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RESEARCH ARTICLE

Integrated assessment of embodied carbon and financial costs in simply supported beams

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Abstract
With escalating concerns over environmental sustainability, the construction industry is facing increasing pressure to minimize its carbon footprint. This study investigated the embodied carbon assessment and cost implications of simply supported beams constructed from concrete and steel materials. The objective was to provide guidance for structural engineers in material selection, particularly for beam structures. The methodology involved a comprehensive analysis of embodied carbon at different stages of the construction process, including product procurement, transportation, and on-site construction activities. Additionally, a cost analysis was conducted to evaluate the financial implications of the material choices. The findings reveal significant differences in the embodied carbon between concrete and steel beams, with steel beams exhibiting lower carbon emissions for shorter spans, whereas concrete beams are more environmentally friendly for longer spans. Moreover, cost analysis underscores the influence of material selection on the overall project cost, with steel beams generally being more expensive than concrete beams. These results highlight the importance of balancing the structural, environmental, and financial considerations in material selection, ultimately contributing to the advancement of sustainable construction practices.

Keywords Sustainable structures · UN SDG 13: Climate action · Embodied carbon · Optimal design · Structural design

1 Introduction

In recent years, the escalation of global warming has underscored the urgent need to address greenhouse gas emissions, particularly carbon dioxide (CO_2), originating primarily from the combustion of fossil fuels, such as coal, oil, and natural gas [21, 26]. The adoption of renewable energy sources has emerged as a critical strategy for mitigating CO_2 emissions, offering both environmental benefits and substantial economic and socioeconomic advantages [4, 5].

The building construction sector has emerged as a significant contributor to the global energy consumption and CO_2 emissions. According to the United Nations Environment Program (2022), there has been a notable increase in building energy demand, with a documented rise of approximately 4% since 2020, reaching 135 exajoules (EJ). This surge represents the most substantial increase observed over the past decade. Moreover, CO_2 emissions attributable to building operations have witnessed an unprecedented peak, experiencing a 5% increase from 2020, surpassing the previous highest recorded level in 2019 by 2% [24].

With the expansion of the economy and ongoing urbanization, there has been a sustained increase in the construction of residential buildings, exerting a significant impact on carbon emissions. A comprehensive understanding of the entire building lifecycle, encompassing activities such as material extraction, manufacturing, transportation, construction, maintenance, and disposal, is imperative for effectively mitigating CO_2 emissions. Buildings utilize a variety of materials, each contributing to energy consumption and CO_2 emissions throughout their lifecycle, collectively termed embodied energy and embodied carbon (Ali, Ahmad and Yusup, 2020).

As an integral facet of mitigation endeavors, the assessment of embodied carbon in building materials has emerged as a pivotal approach, with the capacity to significantly attenuate the carbon footprint. The adoption of sustainable

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building materials holds promise for yielding an approximately 30% reduction in embodied CO_2 emissions over the lifespan of a building [14]. Strategies encompassing the substitution of low-carbon materials, the optimization of material utilization, and the prioritization of locally sourced materials present avenues for fostering carbon reduction. The adoption of a cascaded strategy has been identified as potentially yielding a substantial 28.8% decrease in the average embodied carbon intensity [27].

The imperative of low-carbon buildings, recognized as pivotal in averting severe global climate change [15], has garnered widespread attention globally [25]. Extensive literature underscores building materials as the primary contributors to CO_2 emissions, advocating reduction strategies during the construction phase as an effective means of curbing emissions [14], Lee, Park and Lee, 2013; [16], Ahmadian F.F. et al., 2017; [17]. For instance, González and Navarro (2006) elucidated that the integration of low-environmental-impact building materials could potentially yield up to a 28% reduction in CO_2 emissions at construction sites. Numerous studies advocate for the substitution of conventional building materials with high-strength alternatives as a means of mitigating CO_2 emissions [6, 12, 20]. Given the prevalence of reinforced concrete structures and buildings in the construction industry, significant attention has been directed towards reducing CO_2 emissions through the adoption of high-strength materials. Concrete and rebar, the primary constituents of reinforced concrete, have been focal points for material enhancement efforts [19, 22, 23]. Pacheco-Torres et al. [19] underscored the importance of architects and designers prioritizing environmentally friendly building materials during the design phase to minimize CO_2 emissions associated with entire construction projects. Additionally, advocates of sustainability have championed the utilization of recycled materials. Cho and Chae [12] recommended the incorporation of recycled materials and by-products such as blast furnace slag and silica fume as construction materials. Furthermore, design optimization strategies, including structural system replacements, have been highlighted as beneficial approaches during the early stages of construction projects [1, 7, 11].

One effective strategy for reducing CO_2 emissions during the construction phase is to minimize the quantities of building materials and optimize the design of buildings or facilities. Although concrete and steel are commonly employed materials in building structures, there is a relative scarcity of research concerning the environmental and economic impacts of simply supported beams constructed from these materials. Despite numerous studies focusing on the reliability of structural performance, comprehensive assessments of the environmental implications and economic efficiency of simply supported concrete and steel beams remain limited. This study aims to address this gap by evaluating the environmental impacts and economic efficiency of voided slab systems compared with conventional reinforced concrete slabs. The performance of both steel and concrete beams will be thoroughly analyzed through an assessment of the embodied carbon and total construction costs.

2 Methodology

In this study, a fully restrained noncomposite floor beam, denoted by grid line B1-2, as shown in Figure 1, was investigated. This study compares beam designs utilizing reinforced concrete and steel structures, considering a range of lengths varying between 4 and 12 m, which are typical spans for residential buildings. The beam was designed to support a concrete slab with a thickness of 150 mm and was

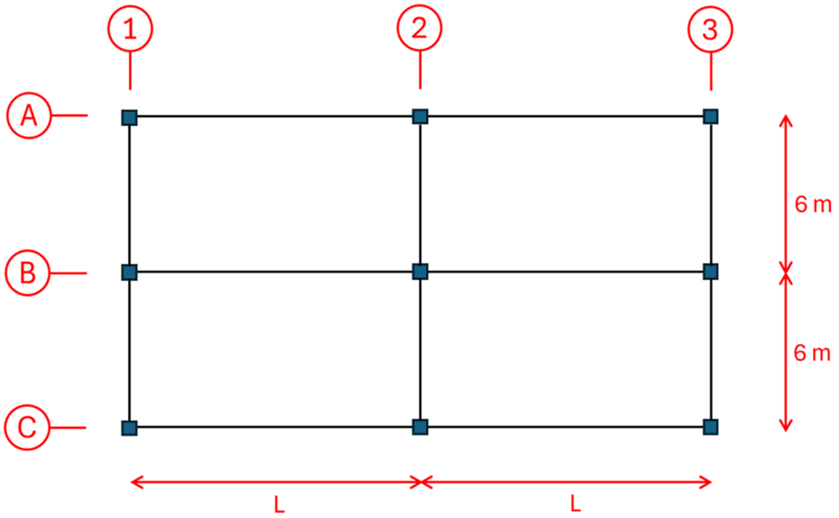

Fig. 1 Generic floor

subjected to a superimposed dead load of 1 kN/m^2 along with a live load of 3 kN/m^2.

2.1 Concrete beam design

The methodology employed for the concrete beam design adheres to the Indonesian Standard SNI 2847-2019 [9]. According to this standard, the minimum depth of the beam (h) was determined as a fraction of the beam span length (l), specifically set at l/16.

Concrete beam design commences with the determination of the reinforcement design following the establishment of the beam section. This involves considering both the flexural and shear aspects. For flexural strength assessment, Equation 1 was employed to compute the nominal moment capacity (ϕM_n) of the beam:

$$\phi M_n = 0.9 A_s f_y (d - a/2) \tag{1}$$

where A_s represents the area of the longitudinal reinforcement, f_y denotes the yield strength of the longitudinal reinforcement, d denotes the distance from the compression fiber to the centroid of the longitudinal reinforcement, and a is the depth of the equivalent rectangular stress block.

Similarly, Equation 2 was used to determine the shear strength of the beam (ϕVn).

$$\phi V_n = 0.17 \lambda b_w d \sqrt{fc'} + A_v f_{yt} d/s \tag{2}$$

where λ is typically considered to be 1.0, b_w represents the width of the beam section, f_c' denotes the compressive strength of concrete, A_v denotes the area of shear reinforcement, f_{yt} denotes the yield strength of shear reinforcement, and s denotes the spacing of shear reinforcement.

In this study, concrete grade K300, distinguished by a compressive strength of 25 MPa, was employed. The steel reinforcement conformed to the specifications outlined in BjTS 420A, which possesses a yield strength of 420 MPa. Furthermore, the nominal moment and shear capacity of the beam are rigorously assessed and subsequently compared with the factored moment (M_u) and shear force (V_u) obtained from structural analysis. This comparative analysis serves as a crucial step in ensuring the structural integrity and safety of the beam design, providing validation and verification of the proposed reinforcement strategy.

2.2 Steel beam design

The steel design procedure adheres to the specifications outlined in the Indonesia Standard SNI 1729-2020 [10]. The beam is assumed to be continuously braced, considering the concrete slabs are fully grouted and covered with a structural screed.

For the determination of flexural strength in steel beams (ϕM_n), Equation 3 is utilized.

$$\phi M_n = 0.9 F_y Z \tag{3}$$

where F_y represents the yield stress of the steel section and Z is the plastic section modulus. The shear strength of the steel beam is determined using Equation 4.

$$\phi V_n = 0.6 F_y A_w \tag{4}$$

where A_w signifies the total area of the web. These equations serve as fundamental tools in assessing the flexural and shear strengths of the steel beam, critical parameters essential for ensuring structural adequacy and reliability.

The selection of the steel profile is conducted through optimization, considering its capacity to withstand the ultimate load applied to the building. For the steel structures examined in this study, the JIS G 3101 SS400 profile with a yield strength of 245 MPa has been chosen. The details of the steel profile selection are presented in Table 1. This particular profile was selected due to its widespread availability in the Indonesian market, ensuring practicality and conformity with local industry standards, thus facilitating ease of procurement.

2.3 Embodied carbon calculation

The assessment of construction sustainability demands a thorough investigation into its environmental footprint across the different phases of its life cycle, as outlined in BS EN 15978 (2011). These phases encompass product, construction process, use, and end-of-life stages as shown in Figure 2. This study focuses specifically on analyzing the embodied carbon during the product (A1-A3) and construction process stages (A4-A5).

The product stage involves activities such as sourcing raw materials, material transportation, and manufacturing processes. Conversely, the construction process stage encompasses activities related to transportation and construction installations. By delving into these stages, this study aims to gain insight into the environmental impact associated with the production and construction phases of the evaluated structures.

Table 1 Steel profile used in this study

I Beam	
IWF 150 × 100	IWF 350 × 175
IWF 200 × 100	IWF 400 × 200
IWF 200 × 150	IWF 450 × 200
IWF 250 × 125	IWF 500 × 200
IWF 300 × 150	IWF 600 × 200

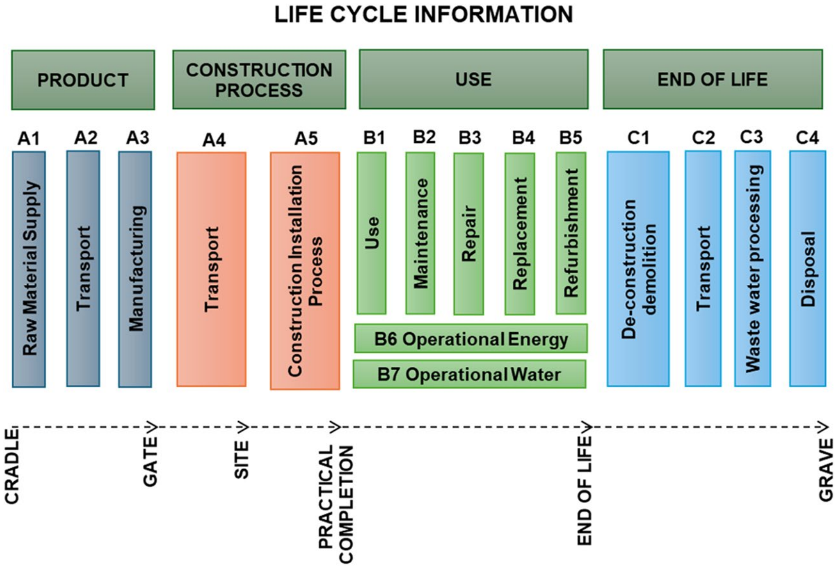

Fig. 2 Life cycle stages, based on BS 15978

The assessment of embodied carbon during the product stage ($EC_{A1\text{-}A3}$) involves the application of Equation 5, enabling the determination of the quantity of embodied carbon in $kgCO_2e$.

$$EC_{A1-A3} = \sum Q_i \times CF_{A1-A3} \tag{5}$$

where Q_i is the material quantity and $CF_{A1\text{-}A3}$ represents the carbon factors ($CF_{A1\text{-}A3}$) obtained from an inventory of carbon and energy, following circular ecology principles outlined by Hammond and Jones (2008). The following representative values of $CF_{A1\text{-}A3}$ have been adopted for environmental impact.

- Reinforcing steel: 1.99 $kgCO_2e/kg$
- Concrete grade K350: 285.6 $kgCO_2e/m.^3$
- Steel section: 1.55 kg CO_2e/kg

These factors serve as the foundation for quantitatively assessing the embodied carbon in concrete slabs, thereby offering valuable insights into the environmental implications of the selected materials and design parameters.

The evaluation of embodied carbon during the transportation stage (EC_{A4}) is conducted using Equation 6:

$$EC_{A4} = \sum Q_i \times CF_{A4} \tag{6}$$

where the carbon factor for transportation of each material to site (CF_{A4}) is determined using Equation 7.

$$CF_{A4} = \sum TD \times TEF \tag{7}$$

where TD represents the transport distance and TEF is the transport emission factor, which is taken as 0.10749 $gCO_2e/kg/km$ (Gibbon et al., 2022). These equations facilitate the quantification of embodied carbon emissions associated with transportation activities, thereby providing insights into the environmental impact of material transportation to the construction site.

The evaluation of embodied carbon during the construction process stage (ECA5) is broken down into two subsets. Emissions associated with the volume of each material that is wasted on site are identified as EC_{A5w}. Emissions due to general construction activities e.g. energy use from machinery and temporary site offices, are identified separately as EC_{A5a}.

The assessment of embodied carbon during the construction process stage (EC_{A5}) is delineated into two distinct components. Firstly, emissions stemming from material wastage on-site are quantified as EC_{A5w}. Secondly, emissions attributable to general construction activities, including energy consumption from machinery and temporary site facilities, are identified as EC_{A5a}.

EC_{A5w} is determined using Equation 8.

$$EC_{A5w} = WF_i \times \left(CF_{A1-A3} + CF_{A4}\right) \tag{8}$$

where WF_i represents the waste factor determined by converting the waste rate (WR_i) to quantify the materials wasted on-site as a percentage of the material quantities utilized in the final asset (Equation 9).

$$WF_i = \frac{1}{1 - WR_i} - 1 \tag{9}$$

where WR_i represents the waste rate based on Table 2

Table 2 The waste rate, WR_i (Gibbon et al., 2022)

Material	WR_i
Concrete	5%
Steel reinforcement	5%
Steel frame	1%

Additionally, EC_{A5a} is determined by multiplying the construction cost by a construction activities emissions factor, as denoted in Equation 10.

$$EC_{A5a} = CAEF \times \frac{PC}{100,000} \tag{10}$$

where $CAEF$ represents construction activities emission factor of 700kgCO$_2$e/£100,000 and PC is the project cost. These calculations facilitate the comprehensive assessment of embodied carbon emissions associated with both material wastage and general construction activities, providing a holistic understanding of the environmental impact of the construction process.

2.4 Cost analysis

This study incorporates typical construction costs pertinent to the Indonesian context, as presented in Table 3. These cost parameters play a crucial role in evaluating the economic ramifications of the designed slabs, particularly in relation to variations in concrete grade and slab thickness. By anchoring the analysis in local construction cost data, the study ensures that its findings are not only environmentally pertinent but also economically viable within the specific context of the study area.

Table 3 Unit cost of materials

Work description	Unit rate (Rupiah)			
	Labour	Equipment	Material	Total
Concrete K-300 (m^3)	5,917.00	168,218.00	1,301,136.00	1,475,271.00
Rebar (kg)	4,053.00		17,721.00	21,774.00
Steel section (kg)	811.00	1,507.00	22,798.00	25,116.00

3 Results and discussion

Table 4 presents the design outcomes of simply supported beams for both concrete and steel structures. Structural design outcomes are commonly perceived as not entirely uniform, as they may vary depending on the individual designer's approach. However, it is noteworthy that the structural designs adopted in this study adhere to established industry norms and practices.

As previously discussed, the beam design process encompasses considerations of both flexural and shear aspects. The findings indicate that the design of both concrete and steel structures is predominantly governed by the flexural aspect. Furthermore, this study investigates the design efficiency by comparing the factored moment (M_u) obtained from structural analysis with the nominal design capacity of the beam (ϕM_n), as shown in Figure 3. The results reveal a notable disparity in efficiency between reinforced concrete and steel beams. Specifically, the reinforced concrete beam exhibits greater efficiency compared to its steel counterpart. This discrepancy can be attributed to the inherent characteristics of concrete, which afford greater flexibility in determining reinforcement and section dimensions. Conversely, steel structure design is constrained by the availability of standardized steel sections in the market. This distinction underscores the nuanced considerations inherent in material selection and structural design processes, particularly in balancing performance requirements and practical constraints.

The variation in embodied carbon across different beam spans is presented in Figure 4. As expected, a clear trend

Table 4 Concrete and steel design results

Span (m)	Concrete				Steel
	b (mm)	h (mm)	Longitudinal Reinforcement	Shear reinforcement	
4	250	500	4D13	D10-200	IWF 250 × 125
5	250	500	4D16	D10-200	IWF 300 × 150
6	250	600	5D16	D10-250	IWF 350 × 175
7	250	700	5D16	D10-300	IWF 400 × 200
8	250	800	6D16	D10-300	IWF 400 × 200
9	250	850	7D16	D10-350	IWF 450 × 200
10	250	850	9D16	D10-350	IWF 500 × 200
11	250	900	10D16	D10-400	IWF 600 × 200
12	250	1000	10D16	D10-400	IWF 600 × 200

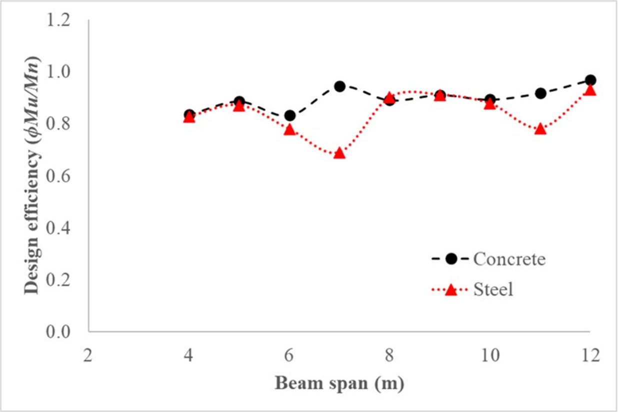

Fig. 3 Beam design efficiency for different spans

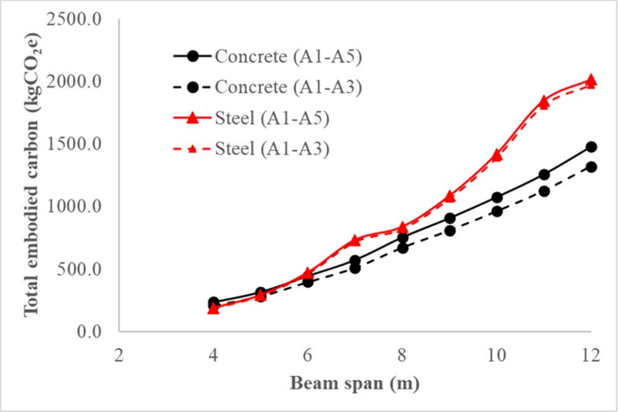

Fig. 4 Total embodied carbon of the beam for different spans

emerges, revealing that the total embodied carbon exhibits a consistent rise with increasing span lengths for both concrete and steel beams. This observation aligns with theoretical expectations, as larger spans typically require a greater volume of material, consequently leading to higher embodied carbon emissions.

A noteworthy observation arises concerning the embodied carbon during the product stage (A1-A3). It becomes apparent that, for both concrete and steel structures, the product stage represents a substantial contributor to the overall embodied carbon. Interestingly, the contribution of the construction process appears relatively minimal in comparison. Specifically, in concrete structures, the construction process accounts for approximately 10% of the total embodied carbon, whereas in steel structures, this contribution is merely 2%.

This finding underscores the significant impact of material sourcing, manufacturing, and transportation activities on the embodied carbon of structural elements. Moreover, it highlights the relatively smaller influence of on-site construction processes in comparison, underscoring the importance of prioritizing sustainable material choices and supply chain management strategies in reducing overall carbon emissions within the construction industry.

The comparison shown in Figure 4 reveals an intriguing trend: for span lengths up to 6 m, the embodied carbon of steel beams is lower than that of concrete beams. However, beyond this threshold, the embodied carbon of steel beams increases significantly, surpassing that of concrete beams. Moreover, as the span length extends, the disparity between the embodied carbon of steel and concrete beams widens further.

These findings suggest that, for shorter spans (up to 6 m), steel beams exhibit greater environmental friendliness compared to concrete beams. However, as span lengths exceed 6 m, concrete beams become the more environmentally favorable option. This nuanced understanding underscores the importance of considering span length as a crucial factor in determining the most sustainable structural solution. Moreover, it underscores the necessity of evaluating the environmental implications of material selection within the context of specific project requirements and constraints.

Additionally, it's crucial to consider the inherent characteristics of concrete and steel materials. Concrete, being more flexible in terms of design and application, offers versatility in construction projects. Furthermore, recent advancements in concrete technology have led to the development of innovative materials with lower embodied carbon. Utilizing these advanced concrete materials presents a promising avenue for substantial reductions in the embodied carbon of buildings.

This acknowledgment underscores the evolving nature of construction materials and the potential for leveraging technological innovations to enhance sustainability in the built environment. By embracing these advancements, stakeholders can actively contribute to mitigating the environmental impact of construction activities, thus fostering a more sustainable and resilient built environment for future generations.

In striving for a harmonious integration of structural efficiency, environmental sustainability, and financial viability, this study undertook an examination of the cost implications associated with the beam structures. As illustrated in Figure 5, the total cost of the beam was evaluated for both concrete and steel structures. The findings indicate a significant influence of the structural material choice on the overall cost of the beam. Specifically, it is observed that the cost of a steel beam exceeds that of a concrete beam. Moreover, this cost disparity becomes more pronounced as the span length increases.

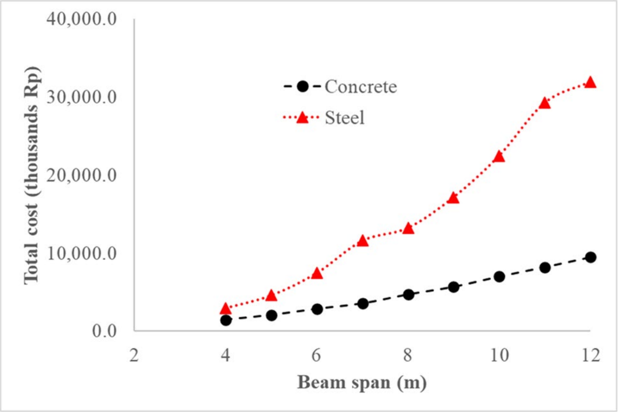

Fig. 5 Total cost of the beam for different spans

This observation highlights the importance of carefully considering material selection in structural design processes, particularly in balancing cost considerations with performance requirements and environmental objectives. By elucidating the financial implications of material choices, our study contributes to a more comprehensive understanding of the multifaceted considerations inherent in sustainable construction practices.

4 Conclusions

This study offers valuable insights into the holistic assessment of structural design, encompassing considerations of embodied carbon and cost implications for simply supported beams constructed from concrete and steel materials. Through a comprehensive analysis, this study demonstrated the intricate interplay between structural performance, environmental impact, and financial feasibility in the decision-making process.

The findings highlight the significant role of material selection in shaping the sustainability profile and economic viability of structural systems. Specifically, while steel beams exhibit advantages in terms of embodied carbon for shorter spans, concrete beams emerge as a more environmentally friendly option for longer spans. Additionally, This investigation underscores the importance of adopting advanced concrete materials with lower embodied carbon as a promising avenue for reducing environmental impact in construction projects.

Moreover, this study emphasizes the need for a balanced approach that considers not only structural requirements but also environmental and financial considerations. By integrating these dimensions into the decision-making process, stakeholders can strive towards achieving more sustainable and economically viable construction practices.

In essence, this study underscores the importance of a holistic approach to structural design, one that acknowledges the interconnectedness of structural, environmental, and financial factors. Fostering a deeper understanding of these dynamics can pave the way towards more sustainable and resilient built environments, ultimately contributing to the broader goal of mitigating climate change and promoting sustainable development.

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Declarations

Competing interests The authors have no conflict of interest to declare.

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