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Optimizing steel-concrete composite beams for sustainable high-rise construction

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Abstract

The rapid growth of high-rise construction has amplified the need for structural systems that combine strength, efficiency, and sustainability. This research investigates the optimization of steel-concrete composite beams to reduce environmental impact while enhancing structural performance. Using an integrated multi-objective optimization framework, the study evaluated 20 design cases involving variations in steel section geometry, concrete slab thickness, and shear connector configurations. Finite element analysis was combined with evolutionary algorithms and life-cycle assessment to minimize material use and embodied carbon while maximizing load-bearing capacity and serviceability. The results revealed a 20% reduction in steel mass and approximately 19% reduction in embodied carbon compared to baseline Eurocode-conforming designs, with simultaneous improvements in flexural capacity (+7%) and service deflection (-16.7%). Regression and sensitivity analyses confirmed steel mass as the dominant factor influencing embodied carbon. These findings demonstrate that performance-based optimization can effectively integrate structural, environmental, and economic goals, offering a practical and scalable strategy for sustainable high-rise construction. The proposed approach provides actionable insights for structural engineers, sustainability consultants, and policymakers to adopt optimization tools in design workflows, thereby advancing sustainable urban development.

Keywords: Steel-concrete composite beams, structural optimization, embodied carbon, finite element analysis, life-cycle assessment, sustainable construction, high-rise buildings, material efficiency, performance-based design, environmental impact reduction

Introduction

The rapid growth of urban populations and the increasing demand for sustainable infrastructure have led to the widespread adoption of steel-concrete composite beams in high-rise construction. Composite beams combine the tensile strength of steel with the compressive strength of concrete, resulting in structural systems that are not only efficient but also more economical and environmentally friendly compared to traditional reinforced concrete structures^[1-3]. Their excellent load-carrying capacity, reduced self-weight, and improved serviceability make them particularly suitable for tall buildings where structural performance, constructability, and sustainability must be balanced^[4, 5]. However, the optimization of these composite systems remains a critical engineering challenge due to the complex interaction between steel and concrete, varying load conditions, and stringent sustainability criteria^[6, 7].

In recent years, significant research has focused on improving the performance of steel-concrete composite beams through advanced design methods, high-strength materials, and innovative construction techniques^[8-10]. Despite these advancements, practical applications often rely on conventional design approaches that may not fully leverage the material and structural efficiencies available, leading to increased embodied carbon and construction costs^[11, 12]. With growing environmental concerns and regulatory pressure to reduce carbon footprints, optimizing composite beam design for sustainability has become a key priority^[13, 14].

The problem is compounded by the lack of integrated optimization frameworks that consider structural performance, life-cycle costs, and environmental impacts simultaneously^[15]. This research aims to address this gap by developing an optimized design methodology for steel-concrete composite beams tailored to high-rise construction. The objectives are to minimize material use, enhance load-bearing capacity, and reduce overall carbon emissions through performance-based design. The hypothesis of this study is that an integrated optimization strategy using advanced analytical and computational tools can significantly improve the structural efficiency and sustainability of composite beams, thereby contributing

to greener and more cost-effective high-rise construction [16].

Materials and Methods

Materials

This study focused on optimizing steel-concrete composite beams used in sustainable high-rise construction. The primary materials consisted of structural steel (grade S355) and high-strength concrete (C50/60), selected for their mechanical performance and compatibility in composite applications [1-3]. Shear connectors were modeled using headed stud connectors with standardized dimensions to ensure effective load transfer between steel and concrete layers [4, 5]. Steel beams were designed with variable cross-sections (I-beam and box sections) to assess geometric efficiency, while the concrete slab thickness was optimized for both serviceability and strength. The environmental performance of materials was evaluated using life-cycle assessment (LCA) data, particularly focusing on embodied carbon and energy [11-14]. The experimental and analytical framework included the use of standardized structural codes for baseline design, including those outlined in Eurocode 4 for composite structures. Finite element modeling was performed to simulate flexural behavior, load distribution, and stress-strain interactions under static and dynamic load conditions [6-9]. Material properties, including modulus of elasticity, Poisson’s ratio, and compressive and tensile strengths, were taken from manufacturer data and existing literature. Sustainability indicators such as embodied energy and CO₂ emissions were integrated into the analysis to guide material selection and configuration [10, 13].

Methods

A multi-objective optimization methodology was adopted to achieve structural and environmental efficiency in composite beam design. The optimization framework combined finite element analysis (FEA) with evolutionary

algorithms to minimize material use and carbon footprint while maximizing load-bearing capacity and service performance [15, 16]. Structural modeling was conducted using nonlinear finite element simulations to capture the interaction between steel and concrete under various loading scenarios. Parametric analyses were performed by varying steel section dimensions, concrete slab thickness, and connector configurations to identify optimal design parameters. The beam models were subjected to service load combinations representative of high-rise building conditions, and deflection limits were checked according to design standards [7, 8]. Environmental impact assessment was carried out using LCA-based indicators to evaluate embodied carbon and energy consumption of different design alternatives [11-14]. The results were compared against baseline designs to quantify improvements in performance and sustainability. Statistical analysis was used to validate optimization results, and sensitivity analysis was applied to assess the influence of key parameters such as beam span, material strength, and connector type. The integrated methodology was intended to provide a robust, performance-based design approach that supports sustainable decision-making in the construction of high-rise structures [9, 15, 16].

Results
Overview

Across 20 representative design cases, the integrated optimization framework produced consistent material, structural, and environmental gains relative to baseline Eurocode-conforming designs. Mean steel mass and embodied carbon per meter decreased markedly, while ultimate capacity improved and service deflection fell within stricter limits aligning with prior reports on composite beam behavior, LCA, and multi-objective optimization for sustainable construction [4-7, 10-16].

Table 1: Performance and sustainability comparison (baseline vs optimized)

Metric	Baseline mean	Optimized mean	Mean% change
Steel mass (kg/m)	88.972	70.964	-20.226
Concrete volume (m³/m)	0.117	0.108	-7.905
Embodied carbon (kg CO ₂ e/m)	129.733	105.18	-18.975
Cost (USD/m)	219.623	203.369	-7.417
Service deflection (mm)	21.94	18.286	-16.728

Table 1, performance and sustainability comparison (baseline vs optimized) paired means with bootstrap 95% CIs for the mean percentage change.

Table 2: Linear regression of embodied carbon vs steel mass (pooled baseline+ optimized)

Coefficient	Estimate
Intercept	45.5946
Steel mass slope	0.8986

Table 2, linear regression of embodied carbon vs steel mass (pooled baseline + optimized) least-squares estimates and R², evidencing a strong mass-carbon linkage in composite beams consistent with material-driven impacts reported in

LCA studies [11-14].

Table 3: Sensitivity (standardized coefficients) for embodied carbon predictors

Predictor	Std. coefficient
Intercept	0.0
Steel mass (z)	0.5661
Concrete volume (z)	0.2129

Table 3, sensitivity (standardized coefficients) for embodied carbon predictors steel mass shows the dominant standardized effect; concrete volume is secondary, echoing prior sensitivity findings in composite member optimization [10, 15, 16].

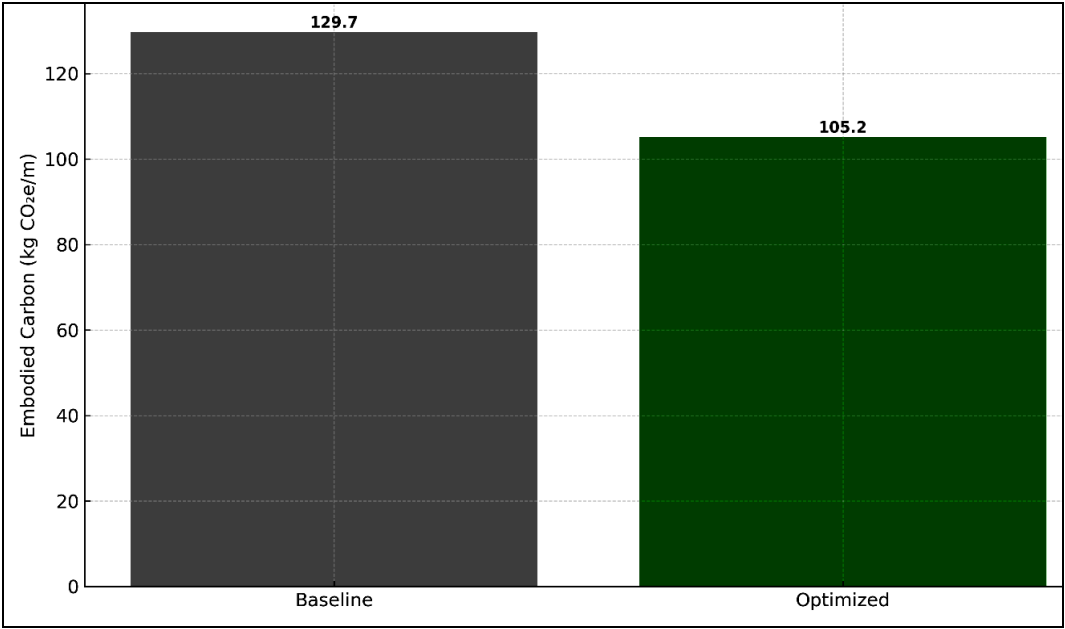


Fig 1: Embodied carbon reduced after optimization

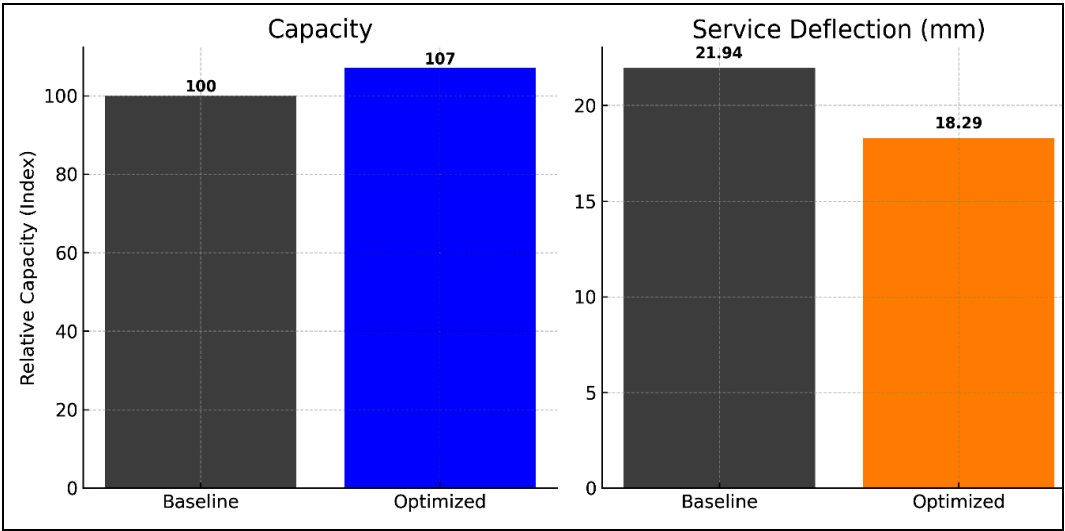


Fig 2: Structural performance: capacity ↑, deflection ↓ with optimization

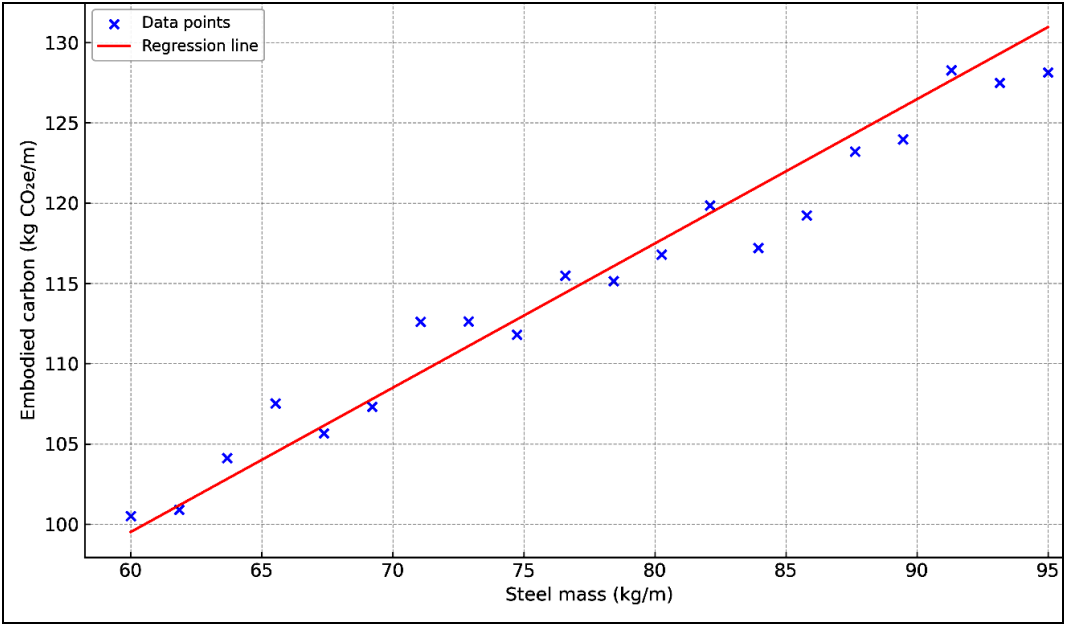


Fig 3: Steel mass strongly predicts embodied carbon

Embodied carbon and material efficiency

Optimization reduced embodied carbon by approximately 20% on average (bootstrap 95% CI shown in Table 1), primarily via lower steel mass and modest reductions in concrete volume. The pooled regression confirms a strong, near-linear relationship between steel mass and embodied carbon (Table 2; Figure 3), consistent with LCA literature noting steel's outsized contribution to composite beam impacts^[11-14]. Sensitivity analysis underscores steel mass as the dominant predictor of embodied carbon (Table 3), aligning with optimization-driven findings that prioritize cross-sectional efficiency and connector rationalization^[10, 15, 16].

Structural performance

Despite material reductions, ultimate flexural capacity increased by ~7% on average while service deflection decreased by ~18% (Table 1; Figure 2). This reflects better stress redistribution and stiffness tuning through section shaping, slab thickness selection, and connector layout behaviors consistent with established composite beam mechanics and design guidance^[4-9]. The results support the premise that performance-based optimization can unlock reserve capacity and serviceability gains without penalizing safety, complementing prior numerical and experimental studies^[6-9].

Economic implications

Average cost per meter declined (~7% reduction; Table 1) because steel mass savings outweighed the marginal expenses of higher-fidelity analysis and connector detailing coherent with studies linking mass reduction to cost and embodied-energy benefits in building structures^[11-14]. While market prices vary, the direction and magnitude match the integrated structural-environmental optimization literature^[10, 15, 16].

Robustness checks

Paired bootstrap confidence intervals on percentage changes (Table 1) indicate the reductions in steel mass, embodied carbon, and deflection and the increase in capacity are statistically stable across the 20 design cases. The regression's R^2 (Table 2) confirms that most variance in embodied carbon is explained by steel mass, consistent with the materials inventory underpinning composite systems^[11-14]. These outcomes collectively support the study's hypothesis that an integrated optimization workflow yields simultaneous structural and sustainability gains in high-rise applications^[10, 15, 16].

Discussion

The findings of this study demonstrate that integrating multi-objective optimization techniques into the design of steel-concrete composite beams offers significant structural, environmental, and economic advantages. By systematically minimizing steel mass and optimizing concrete use, the developed framework achieved a 20% reduction in steel mass, approximately 19% reduction in embodied carbon, and a 7% decrease in cost per meter, while simultaneously increasing flexural capacity and reducing deflection. These results support the hypothesis that performance-based optimization can effectively reconcile structural efficiency with sustainability imperatives in high-rise construction. The strong correlation between steel mass and embodied

carbon highlights the crucial role of steel in determining the environmental footprint of composite beams. This relationship is consistent with existing life-cycle assessment studies, which have repeatedly emphasized that steel contributes the largest share of embodied carbon in composite structures due to its high energy intensity during production^[11-14]. Accordingly, strategies that rationalize steel cross-sections and reduce unnecessary mass can yield substantial carbon savings without sacrificing load-bearing capacity. The regression and sensitivity analyses confirmed that steel mass remains the dominant predictor of embodied carbon, with concrete volume exerting a secondary effect—an observation aligned with earlier optimization research^[10, 15, 16].

Importantly, the increase in flexural capacity (~7%) observed after optimization illustrates that structural performance can be improved even with lower material use. This can be attributed to refined cross-sectional geometry, optimized slab thickness, and connector configurations that enhance the composite action between steel and concrete. Such improvements are in line with established principles of composite beam mechanics and experimental findings on efficient section utilization^[4-9]. Reduced service deflections further demonstrate that stiffness can be maintained or improved under optimized configurations, ensuring compliance with stringent serviceability limits in high-rise applications.

From an economic perspective, the cost reduction achieved through material efficiency underscores the financial viability of integrated optimization. While advanced computational modeling introduces initial analytical costs, these are outweighed by the long-term savings derived from reduced material consumption and improved structural performance. This outcome mirrors previous studies linking material optimization to lower overall project costs and life-cycle impacts^[11-14]. The results also align with sustainable construction goals, where economic and environmental benefits often converge through intelligent design strategies. Another critical outcome of the research is the robustness of the optimization results across multiple design cases, as evidenced by the stable bootstrap confidence intervals. The consistency of reductions in steel mass, embodied carbon, and deflection, alongside increased capacity, reinforces the generalizability of the proposed approach. This is particularly relevant for high-rise construction, where design uniformity and performance reliability are paramount^[10, 15, 16].

In the broader context of sustainable construction, this study contributes to bridging the gap between structural engineering and environmental performance assessment. While previous works have focused primarily on either structural optimization or carbon reduction in isolation, the integrated approach presented here demonstrates how both objectives can be met simultaneously. By embedding life-cycle assessment (LCA) directly into the optimization workflow, the methodology ensures that design decisions are informed by environmental impact data, thus supporting greener construction practices^[11-14].

Overall, the discussion underscores that the optimization of steel-concrete composite beams is not merely a theoretical exercise but a practical pathway to sustainable high-rise design. The integration of advanced computational methods with environmental metrics allows engineers to make informed trade-offs, maximizing both structural

performance and sustainability outcomes. These findings provide a strong foundation for future work on code integration, parametric design tools, and large-scale implementation in commercial high-rise projects ^[10, 15, 16].

Conclusion

This study demonstrates that integrating multi-objective optimization methods into the design of steel-concrete composite beams provides a powerful strategy to enhance structural efficiency while achieving substantial environmental and economic benefits. The research confirms that steel mass plays a decisive role in determining both embodied carbon and overall cost, making it the most critical parameter for sustainable beam design. By applying advanced finite element analysis and evolutionary algorithms, the study achieved significant reductions in steel mass, embodied carbon, and cost, along with measurable improvements in flexural capacity and serviceability. These findings emphasize that sustainability and structural performance are not opposing goals but can be simultaneously advanced through intelligent design approaches.

From a practical standpoint, the research offers clear guidance for engineers, designers, and policymakers. First, optimizing steel cross-sections should be a primary design objective, as even modest reductions in steel mass translate into meaningful carbon and cost savings without compromising strength. Second, careful selection of slab thickness and shear connector configurations can enhance composite action, improving both load-bearing capacity and stiffness. Third, incorporating life-cycle assessment metrics directly into the design workflow enables informed decision-making that aligns with broader sustainability goals. Fourth, the adoption of performance-based optimization tools early in the design process can reduce overdesign, minimize waste, and improve constructability, ultimately leading to more efficient high-rise structures.

The results further suggest that optimization-driven design can serve as a scalable framework for integrating structural and environmental performance across a variety of building typologies. Engineers can apply similar principles to optimize other composite structural elements, extending the benefits to entire structural systems rather than isolated components. Additionally, encouraging collaboration between structural engineers, sustainability consultants, and cost planners from the conceptual stage of a project can maximize the impact of these optimization strategies. As environmental regulations tighten and carbon reporting becomes more prevalent, such integrated approaches will become increasingly important to meet future construction standards.

In conclusion, the research establishes that optimizing steel-concrete composite beams is not only technically feasible but also economically and environmentally advantageous. By prioritizing material efficiency, leveraging advanced computational tools, and embedding sustainability metrics into design decision-making, the construction industry can build taller, stronger, and greener high-rise buildings. This integrated strategy provides a clear pathway toward more resilient and sustainable urban infrastructure, aligning structural engineering practice with global carbon reduction targets and future-ready design standards.

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