

Article

Towards Sustainable Structure of Tall Buildings by Significantly Reducing the Embodied Carbon

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Abstract: Addressing global warming has become an urgent priority. According to a recent United Nations study, the global population is expected to exceed 9.7 billion by 2050, with the majority residing in urban areas. Consequently, high-rise buildings are anticipated to dominate the built environment, emphasizing the need for their sustainability. Currently, reinforced concrete and structural steel are the primary materials used in the construction of tall buildings and remain the standard for most skyscrapers. This paper examines the significant issue of embodied carbon in these materials. In structural engineering practice, efficiency and constructability are key considerations. The sustainability of steel construction has been well-documented, with organizations such as the American Institute of Steel Construction (AISC) leading efforts in this area. The primary objective of this study is to demonstrate that structural steel systems in tall buildings are not only efficient, constructible, and durable but also sustainable. By conducting life cycle assessments, this paper illustrates how structural efficiency, construction sequencing, and design compatibility can significantly reduce the embodied carbon of steel systems used in high-rise buildings. Similarly, substantial global efforts are underway to reduce the embodied carbon of reinforced concrete, with cement being the primary contributor to carbon emissions. Recent advancements in non-cementitious materials are improving the sustainability of reinforced concrete. This study applies the same life cycle assessment methodologies to demonstrate that well-designed and well-constructed reinforced concrete structures can achieve a minimal embodied carbon footprint.



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1. Introduction

Mitigating global warming has become increasingly urgent, and efforts within the built environment are crucial due to its significant contribution to climate change. The construction industry, responsible for approximately 40% of global carbon emissions [1], significantly impacts the environment through raw material extraction, manufacturing, transportation, construction, and demolition [2,3]. With the global population projected to exceed 9.7 billion by 2050 [4] and urbanization intensifying, the demand for tall buildings is expected to rise. Consequently, the development of low-carbon tall buildings presents a strategic opportunity to reduce the environmental footprint of the construction sector.

Reinforced concrete and structural steel are the predominant structural materials for tall buildings, yet they are among the largest contributors to global warming [5]. This has led to misinformed criticism and policy proposals. For example, New York City Mayor Biil de Blasio once stated, “We are going to introduce legislation to ban the glass and steel skyscrapers that have contributed so much to global warming. They have no place in our

city or on our Earth anymore” [6]. Such assertions, however, fail to consider the potential sustainability of these materials when optimally designed for structural efficiency.

Despite the challenges of constructing tall buildings with concrete and steel, these materials remain essential due to their structural performance and potential to reduce environmental impact. This study aims to demonstrate that well-designed structural steel and reinforced concrete systems are not only efficient, constructible, and durable but also sustainable. The research examines the environmental impact of these materials, with a focus on embodied carbon emissions. Five structural design alternatives, incorporating steel, concrete, or hybrid systems, were developed and analyzed to evaluate their potential for reducing embodied carbon. Life cycle assessments (LCAs) were conducted to quantify their environmental performance.

1.1. Literature Review

Before examining the literature on the environmental impact of steel and concrete as primary structural materials for tall buildings, it is essential to provide a brief overview of the lateral structural systems of tall buildings. Designing an efficient structure requires the development of a compatible lateral system. One of the earliest systems introduced was the frame tube, pioneered by Dr. Fazlur Khan of Skidmore, Owings & Merrill, for a reinforced concrete apartment tower, DeWitt Chestnut, Chicago, in 1974 [7]. The first author has previously explored the tubular structural system for tall steel structures in greater detail [8] and examined the relationship between architectural form and structure within the context of structural efficiency [9]. During this period and beyond, significant work was conducted on optimizing structural systems [10,11]. Additionally, extensive research to advance collaboration between architects and structural engineers was conducted at the graduate program of the College of Architecture, Illinois Institute of Technology in Chicago [12]. Recently, research and development have been expanded to include the concept of sustainable tall buildings [13,14].

As previously demonstrated, steel and concrete, widely used in tall buildings worldwide, are among the most significant contributors to environmental impact [5]. The literature review examines recent studies on concrete and steel structures in the context of tall buildings, focusing on their environmental impact and strategies for reducing it. Through a comprehensive review, research gaps are identified, followed by the formulation of research motivations and objectives.

To assess the relationship between material use and environmental impact in construction, the LCA has emerged as a widely adopted method. An LCA provides a holistic evaluation of environmental performance throughout a material’s entire life cycle, including both the cradle-to-grave approach, which covers raw material extraction to end-of-life disposal, and the cradle-to-cradle approach, incorporating recycling and reuse [15,16].

Using LCAs, researchers have found that concrete production alone is responsible for 8–9% of global greenhouse gas emissions [17]. Notably, the material production phase accounts for over 90% of CO₂ emissions in buildings that use concrete as a primary structural material, while transportation and on-site construction contribute less than 10% [18]. Similarly, steel holds the second-largest share of embodied carbon among all construction materials, with steel products comprising approximately 35% of the embodied carbon in buildings [19,20].

Given the carbon-intensive nature of the construction industry, especially its reliance on concrete and steel, researchers have focused on developing alternative materials and technologies to mitigate environmental impacts [21]. Since tall buildings, in particular, tend to have higher energy consumption and carbon emissions than other building types, primarily due to their significant material demands and construction complexities [22],

reducing carbon emissions through optimized structural designs and efficient material use is a critical priority. Mass timber construction has emerged as a promising alternative, offering the potential to significantly reduce environmental impacts compared to traditional concrete and steel [23–25]. However, most studies have primarily focused on mid-rise and lower high-rise buildings due to the structural limitations of mass timber, and high upfront costs remain a considerable challenge for broader adoption.

For these reasons, extensive research has been conducted to explore low-carbon concrete and steel materials for their potential benefits in tall buildings [20,26]. For instance, Falliano et al. [27] examined the CO₂ emissions of four different concrete types, including recycled and lightweight aggregate variants. The study demonstrated that while recycled and lightweight aggregate concretes can offer significantly lower CO₂ emissions compared to conventional concrete, achieving equivalent density and compressive strength remains a challenge. Other major efforts for low-carbon concrete focus on the development of supplementary cementitious materials using fly ash, slag, limestone, and other alternatives to replace ordinary cement and reduce CO₂ emissions without compromising strength and durability [26,28]. Recent studies show that using low-carbon cementitious binders could reduce embodied carbon emissions by up to 52.6% [29]. Another advanced type of composite reinforced concrete column utilizes an engineered cementitious composite jacket made with supplementary cementitious materials, such as fly ash [30]. In the case of steel, conventional material production stages relying on basic oxygen furnaces represent a significant barrier to reducing carbon emissions. Various approaches, including hydrogen injection and solid biomass substitution, have been studied as potential solutions for decarbonization [31]. Additionally, recent studies highlight that reusing steel in construction can significantly reduce carbon emissions [32]. For example, a recent case study reported savings of 35 tons of CO₂ emissions by reusing 25 tons of recycled steel in building construction [33].

Another strategy for reducing carbon emissions is the optimization of concrete and steel-framed structures to minimize material usage. Hosseini and Faghani [34] examined various structural design parameters and building construction site conditions with concrete and steel structures to assess their impact on carbon emissions. The study showed that replacing steel structures with concrete could achieve a 24.46% reduction in carbon emissions and that site soil stiffness significantly contributes to emissions, with differences of approximately 15%. Yeo and Potra [35] investigated the impact of optimally designed reinforced concrete structures on carbon emissions and economic factors, demonstrating reductions of 5% to 10% in carbon emissions relative to cost. Similarly, Park et al. [36] studied the optimal design of steel-reinforced concrete columns in high-rise buildings, optimizing the weight of steel and concrete used to minimize construction costs and CO₂ emissions. Lai et al. [37] demonstrated that steel-reinforced concrete columns made with high-strength materials can reduce member size, thereby lowering carbon emissions, and provided design recommendations. Additionally, hybrid systems incorporating wood elements into concrete structures offer additional potential for reducing emissions [38,39].

Although extensive research has explored strategies for reducing carbon emissions in concrete- and steel-based buildings, most studies primarily focus on material improvements. While promising advancements have been made, challenges remain in market adoption and the practical availability of low-carbon materials.

In structural optimization studies, most efforts have concentrated on enhancing the design of concrete or steel-framed structures independently. Research on composite structures is often limited to the integration of wood or specific structural elements. Moreover, few comprehensive studies focus specifically on tall buildings, as most research has been directed toward low- or mid-rise structures.

1.2. Motivations and Objectives

Extensive research has explored alternative structural materials and systems for tall buildings. However, when designed for optimal structural durability and construction efficiency, concrete and steel can remain viable and sustainable options, as supported by well-established studies and practices.

Therefore, this study aims to address the following questions:

1. If tall building structures using concrete and steel are optimally designed, to what extent can embodied carbon emissions be reduced?
2. How can material reuse, recycling after demolition, and the incorporation of recycled materials further contribute to lowering the environmental footprint of steel and concrete?

To answer these questions, this study develops structural alternatives for a tall building using steel and concrete. The structural systems adopted in this study are well-established steel and concrete systems, including frame tube, tube-in-tube, and moment frame systems. The primary aim is to optimize material weight while maintaining equivalent structural performance.

Based on the proposed structural systems, this study conducts a comprehensive embodied carbon assessment to evaluate the impact of optimally designed structural systems on reducing environmental impacts.

2. Methodology

As previously mentioned, this study employs a case study approach, introducing five structural alternatives and examining their potential embodied carbon emissions throughout their entire life cycle using LCAs. The methodology consists of two main sections.

The first section presents five structural systems for a typical sixty-story office building. These theoretical models include three steel-framed lateral systems: frame tube, tube-in-tube, and moment frames. Additionally, a reinforced concrete (RC) frame tube lateral system and a composite structural system are considered.

The second section evaluates the life cycle environmental impacts of the proposed structural systems using a Building Information Modeling (BIM)-LCA integration method with a particular focus on embodied carbon assessment. The evaluation primarily employs a cradle-to-grave LCA approach while also incorporating preliminary findings from a cradle-to-cradle perspective to highlight the potential benefits of material reuse and recycling. Additionally, the impact of using renewable concrete materials is assessed.

2.1. Structural System Development and Analysis

Five structural systems for a typical sixty-story office building were proposed, and a static structural analysis was conducted for each. Figure 1 illustrates the overall dimensions of the office building used in this study. The primary objective of the analysis was to develop the most efficient structure for each of the five systems based on an acceptable drift ratio criterion. Structural efficiency in this context is measured by the minimum weight, designated in PSF (kN/m^2).

2.1.1. Steel Structural Systems

Several steel structural lateral systems are commonly used in practice, including the frame/braced tube, tube-in-tube, diagrid, and moment frames. In this study, three distinct steel systems were carefully selected and developed to represent varying levels of structural efficiency. These systems include the frame tube (Steel 1), tube-in-tube (Steel 2), and moment frames (Steel 3). The details of the three systems are illustrated in Figure 2.

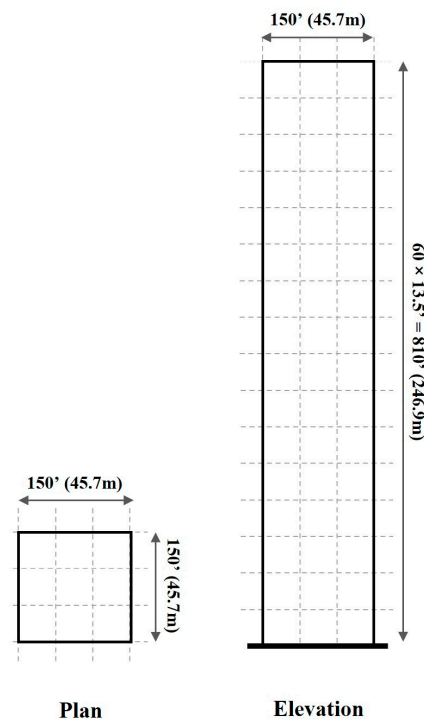


Figure 1. The dimensions of a sixty-story office building.

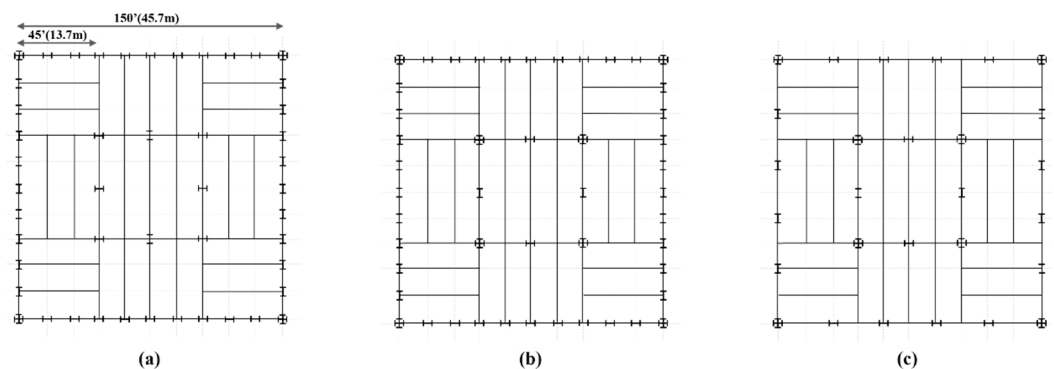


Figure 2. Floor plans of steel structures: (a) Steel 1: frame tube, (b) Steel 2: tube-in-tube, and (c) Steel 3: moment frames.

The following sections present the analysis results, including member sizing and structural performance evaluation.

Steel 1: Frame Tube System

The weight of the frame tube columns and spandrel beams

$$15 \text{ PSF} = 0.7185 \text{ kN/m}^2$$

The weight of the floor framing

$$6 \text{ PSF} = 0.2874 \text{ kN/m}^2$$

The weight of the interior columns

$$1 \text{ PSF} = 0.0479 \text{ kN/m}^2$$

Total weight of the structure

$$22 \text{ PSF} = 1.0538 \text{ kN/m}^2$$

Sizing of members:

(a) Tube columns and beams are given the same section properties.

Length of columns = 40×800

$$32,400 \text{ ft}$$

Length of beams = $4 \times 150 \times 60$

$$36,000 \text{ ft}$$

Total length

$$68,400 \text{ ft}$$

Total floor area = $150 \times 150 \times 60$

$$1,350,000 \text{ ft}^2$$

Weight of lateral system = $15 \times 1,350,000$

$$20,250,000 \text{ Pounds}$$

Cross-sectional weight = $20,250,000/68,400$	296 PLF
The section used for LCA	282 PLF
(b) Floor framing	
Length of beams per floor = 150×9	1350 ft
Total length of floor beams = 1350×60	8100 ft
Total weight of floor beams = $1,350,000 \times 6$	8,100,000 ft
Cross-sectional weight = $1,350,000 \times 6/60 \times 1350$	100 PLF
The section used for LCA	89 PLF
(c) Cross-sectional weight of interior columns	
Cross-sectional weight of interior column = $1 \times 1,350,000/8 \times 800$	211 PLF
The section used for LCA	282 PLF

Steel 2: Tube-in-Tube System

The weight of the outer frame tube	13.5 PSF = 0.6467 kN/m^2
The weight of the inner frame tube	13.5 PSF = 0.6467 kN/m^2
The weight of the floor framing	13.5 PSF = 0.6467 kN/m^2
Total weight of the structure	24.0 PSF = 1.1497 kN/m^2

Sizing of members:

Tube columns and beams are given the same section properties.

Outer tube as in Steel 1, section size = $13.5 \times 296/15$	267 PLF
The Section used for LCA	W36 $\times$ 282
Inner tube section weight is = $5 \times 1,350,000/20,880$	323 PLF
The section used for LCA	W40 $\times$ 297
Floor framing outside the inner tube Section size = $5.5 \times 1,350,000/60 \times 8.25 \times 150$	100 PLF
The section used for LCA	W16 $\times$ 89

Steel 3: Moment Frame System

The weight of the outer frame beams	8.0 PSF = 0.3832 kN/m^2
The weight of the outer frame columns	6.5 PSF = 0.3114 kN/m^2
The weight of the inner frame beams	7.0 PSF = 0.3353 kN/m^2
The weight of the inner frame columns	2.0 PSF = 0.0958 kN/m^2
The weight of the gravity floor framing	3.0 PSF = 0.1437 kN/m^2
Total weight of the structure	26.5 PSF = 1.2694 kN/m^2

Sizing of members:

The outer frame beam section = $8 \times 1,350,000/600 \times 60$	300 PLF
The section used for LCA	W40 $\times$ 297
The outer frame column section = $6.5 \times 1,350,000/810 \times 20$	541 PLF
The section used for LCA	W40 $\times$ 503
The inner frames beam section = $7 \times 1,350,000/5 \times 150 \times 60$	210 PLF
The section used for LCA	W27 $\times$ 194
The inner frames column section = $2 \times 1,350,000/8 \times 810$	400 PLF
The section used for LCA	W40 $\times$ 397
The gravity floor framing beam size = $3 \times 1,350,000/600 \times 60$	112 PLF
The section used for LCA	W16 $\times$ 89

2.1.2. Reinforced Concrete (RC) Structure

For the RC structure, a frame tube lateral system was chosen, paired with a typical flat slab/plate gravity system as shown in Figure 3. Figure 4 illustrates the steel reinforcement

within the RC structural elements. These systems are among the most efficient available for RC construction and provide a strong representation of RC structural performance.

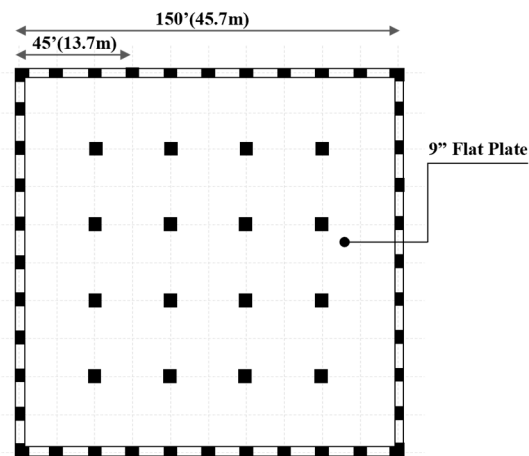


Figure 3. Frame tube reinforced concrete structural system.

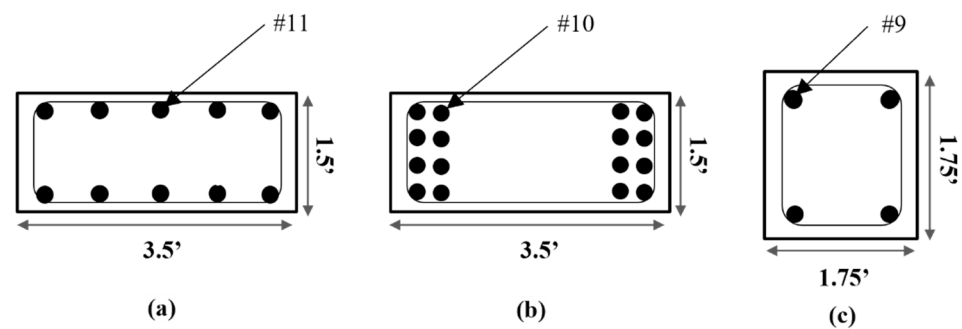


Figure 4. Steel reinforcement sections: (a) tube column, (b) tube beam, and (c) interior column. #9, #10, and #11 indicate the rebar sizes used in each structural element.

The following sections present the analysis results, including member sizing and structural performance evaluations.

Quantities:

(a) Tube columns

$$\text{Length of column} = 40 \times 810 \quad 32,400 \text{ ft}$$

$$\text{Volume} = 32,400 \times 1.5 \times 3.5 \quad 170,100 \text{ ft}^3$$

(b) Tube beams

$$\text{Length of beam} = 4 \times 150 \times 60 \quad 36,000 \text{ ft}$$

$$\text{Volume} = 36,000 \times 1.5 \times 3.5 \quad 189,000 \text{ ft}^3$$

$$\text{Total floor area} \quad 1,350,000 \text{ ft}^2$$

$$\text{Weight/ft}^2 = (170,100 + 189,000) \times 150 / 1,350,000 \quad 40 \text{ PSF}$$

(c) Steel reinforcement

$$\text{Columns} = 15.6 \times 32,400 \times 3.4 / 1,350,000 \quad 1.27 \text{ PSF}$$

$$\text{Beams} = 21.0 \times 36,000 \times 3.4 / 1,350,000 \quad 1.9 \text{ PSF}$$

$$\text{Total} \quad 3.17 \text{ PSF}$$

(d) Gravity system

$$\text{Slab} = 9/12 \times (150 \times 150 \times 150 \times 60) / 150 \times 150 \times 60 \quad 112.5 \text{ PSF}$$

$$\text{Reinforcement} = 2/100 \times 144 \times 3.4 \quad 7.3 \text{ PSF}$$

2.1.3. Composite Structure (CP)

For the CP system, a single system was selected, as this is considered the most efficient in this study. The system consists of a core shear wall combined with steel outrigger trusses at levels 44–46. The gravity floor system follows a typical steel framing approach, similar to the steel structural options. Figure 5 illustrates the reinforced concrete core shear wall with steel outrigger trusses in the proposed CP system. As later demonstrated through the LCA in this paper, the composite system ultimately proved to be the most efficient among all the systems analyzed.

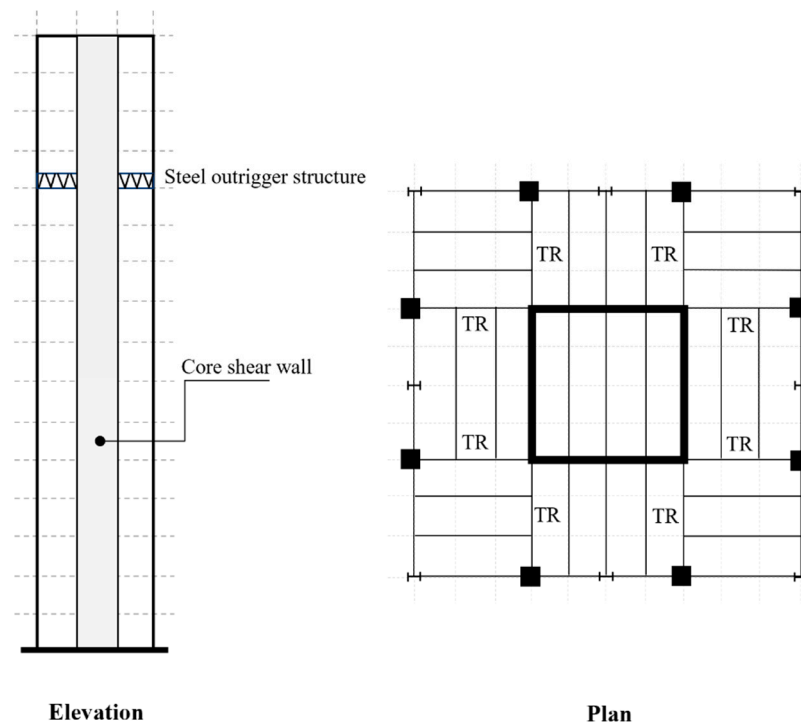


Figure 5. Composite structure with core shear wall and steel outrigger trusses at levels 44–46.

The following sections present the analysis results, including member sizing and structural performance.

Quantities:

(a) Core shear wall

$$\text{Concrete} = (2 \times 60 \times 4 \times 810 \times 0.85 \times 150) / 1,350,000 = (60 \times 4 \times 810 \times 150 \times 1.7) / 1,350,000 \quad 36.7 \text{ PSF} = 1.758 \text{ kN/m}^2$$

$$\text{Steel reinforcement} = [(2 \times 1.5) / 100] \times [(60 \times 4 \times 810 \times 0.85 \times 490) / 1,350,000] = (1.5 \times 490 \times 1.7 \times 120 \times 810) / 135,000,000 \quad 1.8 \text{ PSF} = 0.08622 \text{ kN/m}^2$$

(b) Steel outrigger trusses

$$\text{Steel outrigger trusses} = (8 \times 45 \times 288 \times 2) / 1,350,000 \quad 0.15 \text{ PSF} = 0.0072 \text{ kN/m}^2$$

$$\text{Floor beams as in structure} \quad 6 \text{ PSF} = 0.2874 \text{ kN/m}^2$$

Beam size

100 PLF

The section used for LCA

W16 × 89

(c) Exterior columns

$$8 \text{ RC columns} = 3.5 \times 3.5 = 12.25 \text{ ft}^2, \text{ Weight} = (12.25 \times 810 \times 8 \times 150) / 1,350,000 \quad 8.8 \text{ PSF}$$

$$8 \text{ Steel columns, Weight} = 1.5 \text{ PSF, Weight of a column} = 1.5 \times 810 / 8 \quad 152 \text{ PLF}$$

The section used for LCA

W14 × 150

2.2. Life Cycle Assessments (LCAs) Focusing on Embodied Carbon

The second method of this study investigates the environmental impact of the five proposed tall building structural systems. A Building Information Modeling (BIM)-LCA integrated method is employed to analyze and compare the environmental impacts of these structural design approaches. The study aims to provide reliable information to support the structural design of tall buildings using concrete and steel during the early design stage. To isolate the effects of the structural elements and avoid confounding impacts from other building components, such as facades and interior partitions, the analysis is limited to the structural elements. Among various impact indicators in the LCA, a key objective and expected outcome of this study is the assessment of greenhouse gas emissions, primarily embodied carbon, measured in kilograms of carbon dioxide equivalent ($\text{kg CO}_2\text{-eq.}$), as this study focuses on the life cycle-based impact of material use for structural systems on global warming.

As illustrated in Figure 6, the analysis consists of four stages. Five structural alternatives were developed and computationally modeled using Autodesk Revit 2023, a well-established BIM software. These alternatives include three steel structures, including frame tube (Steel 1), tube-in-tube (Steel 2), and moment frame (Steel 3) systems, as well as a frame tube lateral RC structure (RC) and a composite system with a core shear wall combined with steel outrigger trusses (CP), as introduced earlier. The BIM models were then utilized to calculate the weight of the structural elements in each model. Figure 7 illustrates the developed BIM models, and Table 1 summarizes the structural elements used. Detailed structural elements, such as steel framework joints, were excluded from the analysis.

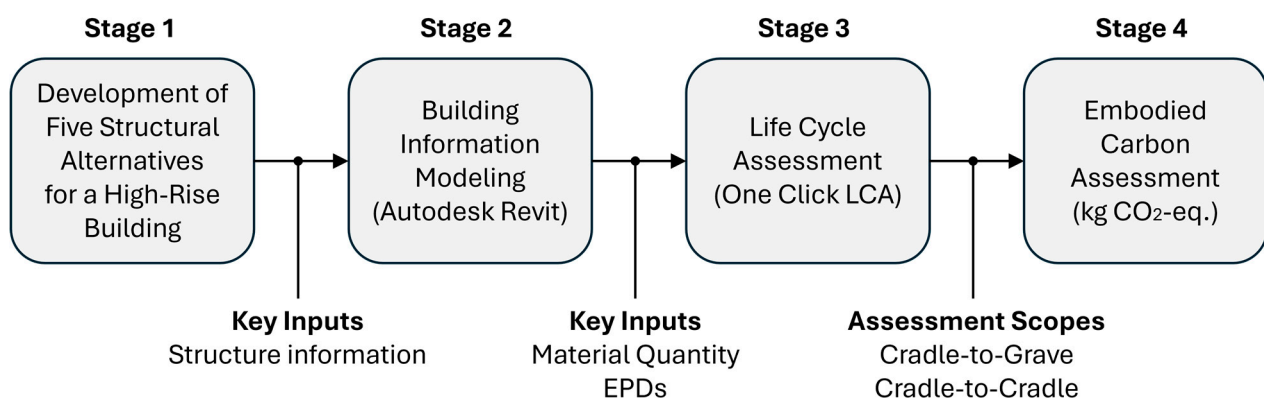


Figure 6. Workflow diagram for LCA and BIM integration.

Material quantity and environmental impact assessments were conducted using One Click LCA [40], an LCA software with strong interoperability with Autodesk Revit through a directly integrated plugin. The tool has been used in more than 170 countries, and its database includes Environmental Product Declarations (EPDs) in accordance with EN 15804+A2 [41] and ISO 14040 [42], verified through a process reviewed by the Building Research Establishment.

The LCA was conducted using both the cradle-to-grave and cradle-to-cradle approaches, as illustrated in Figure 8. Since the analysis primarily focused on material consumption during the construction phase and its associated environmental impacts, the product stage is the most critical. Consequently, substages A1 to A3, which correspond to the cradle-to-gate phase and account for embodied emissions during the material production, were included in the assessment. Substage A4 (transportation to the building site) calculates the environmental impacts associated with transporting building materials

from manufacturing sites to construction sites. As the study does not specify a particular construction site location, the default average transportation distance values and methods recommended for concrete and steel by One Click LCA were used. Substage A5 includes emissions associated with material losses, waste processing, and disposal during construction.

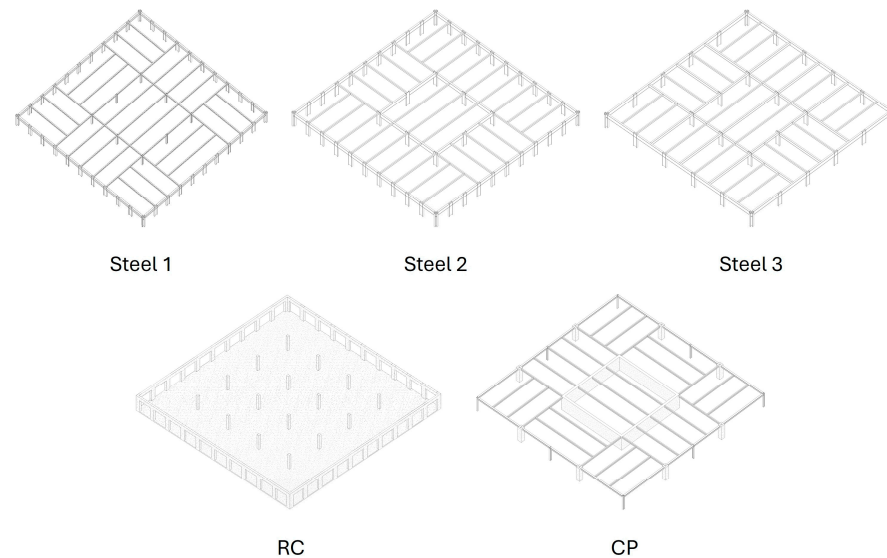


Figure 7. 3D BIM model diagrams for five structural options.

Table 1. Dimensions of structural elements in five structural cases.

Steel Options	Vertical Structure		Horizontal Structure	
	Exterior Column	Interior Column	Exterior Frame	Interior Frame
Steel 1	W36 × 282	W14 × 283	W36 × 282	W16 × 89
Steel 2	W36 × 282	W40 × 297	W36 × 282	W40 × 297 W16 × 89
Steel 3	W40 × 503	W40 × 397	W40 × 297	W27 × 194 W16 × 89
RC Options	Exterior Column	Interior Column	Exterior Frame	Structural Slab
RC and RC-R	18 × 42 RC column	21 × 21 RC column	18 × 42 RC beam	9" RC slab
Composite Options	Exterior Column	Shear Core Wall	Exterior Frame	Interior Frame
CP and CP-R	3'-6" composite column W14 × 145	2' RC wall	W14 × 145	27' × 250 outrigger truss W16 × 77

The use stage (B1–B7), which primarily addresses building operational emissions, is excluded, as this study focuses solely on the environmental impact of building structures. Additionally, substages C2 and C3, which account for emissions from waste processing and transportation during demolition, are included. However, substages C1 (deconstruction or demolition) and C4 (disposal) are excluded due to insufficient data to accurately predict their impacts. While the LCA primarily focuses on substages A1 to A5 and C2 and C3 for the cradle-to-grave assessment, Stage D, which accounts for the environmental impacts of material reuse and recycling, is also considered under the cradle-to-cradle approach. It is important to note that Stage D in this study primarily relies on EPD data, serving as a preliminary investigation into the potential benefits of material recycling and reuse. In this analysis, all steel structural elements are assumed to be theoretically reusable.

Product Stage A1–A3			Construction Process Stage A4–A5		Use Stage B1–B7							End-of-Life Stage C1–C4				Benefits and loads beyond the system boundary D		
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D

Figure 8. Life cycle stages considered in the study: Gray-highlighted cells represent the modules included in the cradle-to-grave approach, and orange-highlighted cells indicate additional modules included in the cradle-to-cradle approach.

Additionally, low-carbon-intensive concrete materials are considered. Concrete with a 20% recycled binder in cement is applied to the RC slabs, while a 10% recycled binder in cement is used for the RC columns, beams, and shear walls. These ratios of recycled binder in cement are commonly used as average values for RC structures. Beyond the five structural cases introduced earlier, two additional options incorporate recycled binder-based concrete: one for RC, referred to as RC-R, and another for CP, referred to as CP-R.

A detailed summary of the EPDs used in this study is provided in Table 2. It is important to note that the EPDs were selected from the database available in One Click LCA, which includes average EPDs that comply with relevant standards to represent typical cases. Since this study does not specify a particular building region or the origin of materials. The results may vary if different EPDs or software are used. However, all the processes and data utilized in this study have been validated.

Table 2. List of EPDs and their details used in the study.

EPD Descriptions	Material Types	EPD Numbers	EPD Programs	Years	Standard
Hot-rolled steel coil	Structural steel	EPD-441	ASTM	2023	ISO 14040 [42]
Hot-rolled steel reinforcement bar	Reinforcement for concrete (rebar)	EPD-801	ASTM	2024	ISO 14040 [42]
Ready-mix concrete, normal-strength, generic, C40/50 (5800/7300 psi)	Ready-mix concrete for structures	-	One Click LCA	2018	EN 15804+A1 EN 15804+A2 [41]
Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 psi)	Ready-mix concrete for external walls and floors	-	One Click LCA	2018	EN 15804+A1 EN 15804+A2 [41]
Ready-mix concrete, normal-strength, generic, C40/50 (5800/7300 psi), 10% recycled binders in cement	Ready-mix concrete for structures	-	One Click LCA	2018	EN 15804+A1 EN 15804+A2 [41]
Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 psi), 20% recycled binders in cement	Ready-mix concrete for external walls and floors	-	One Click LCA	2018	EN 15804+A1 EN 15804+A2 [41]

After setting up the seven structural models, One Click LCA was used to calculate the material quantities and their environmental impacts using the appropriate EPD database. Figure 9 illustrates an example of this process.

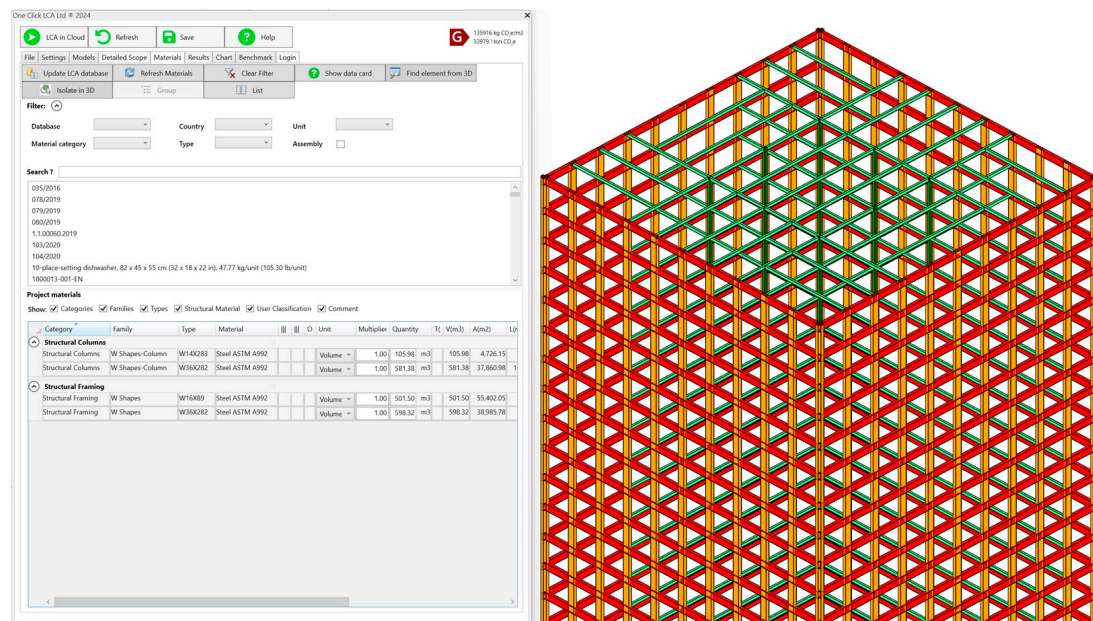


Figure 9. Example of an LCA process using One Click LCA and Revit.

For calculation purposes, the expected service life of the building is set at 50 years. However, this input does not affect the analysis results, as the structural components in this study are assumed to require no replacements or maintenance.

3. Results and Discussion

The LCA results are organized into separate sections based on the cradle-to-grave and cradle-to-cradle approaches. These sections include discussions on the environmental impacts of the materials, material weight changes due to the structural design, the influence of the horizontal and vertical structural elements, and the role of the materials in reuse and recycling in embodied carbon emissions.

3.1. Results of the Cradle-to-Grave Approach

This section summarizes the results of life cycle stages A1 to A5, C2, and C3. Table 3 presents and compares the embodied carbon emission results of the seven structural cases across the life cycle stages considered in this study. The embodied carbon results, expressed in kg CO₂-eq., are normalized by the total gross floor area to determine the cumulative embodied carbon per unit floor area over the entire building life.

Table 3. Embodied carbon emission results by life cycle stage (unit: kg CO₂-eq./m²).

Life Cycle Stages	Module	Steel 1	Steel 2	Steel 3	RC	RC-R	CP	CP-R
Production Stage	A1–A3	130.9	143.2	157.3	142.8	135.0	108.3	105.2
Construction Process Stage	A4 Transportation	1.4	1.6	1.7	11.9	11.9	4.6	4.6
	A5 Installation	4.6	5.0	5.5	7.0	6.7	4.5	4.2
End-of-Life Stage	C2–C3 Waste transport and processing	4.8	5.3	5.8	4.3	4.3	3.4	3.2
Total		141.7	155.1	170.3	166	157.9	120.8	113.9

In general, the steel frame structural options exhibited lower embodied carbon emissions compared to the RC options. The total embodied carbon intensities of Steel 1 and Steel 2 were 141.7 kg CO₂-eq./m² and 155.1 kg CO₂-eq./m², respectively, both of which were lower than that of Steel 3. The structural analysis results in Section 2.1.1 indicated that Steel 3 was the least effective option, Steel 1 was the most efficient, and Steel 2 fell in between. This suggests that optimizing material weight while maintaining structural performance is a critical factor in reducing environmental impacts.

However, while Steel 1 and Steel 2 had lower total embodied carbon than RC, which measured 166 kg CO₂-eq./m², Steel 3 had an embodied carbon intensity of 170.3 kg CO₂-eq./m², which was 4.3 kg CO₂-eq./m² higher than RC, despite RC having a significantly greater total material weight. This discrepancy arises primarily from the embodied carbon per unit volume during the material production stage in the EPDs. Steel has significantly higher embodied carbon than concrete due to its high-temperature processing requirements, which results in greater embodied energy and carbon emissions. Consequently, this study highlights the importance of considering both total material weight and the impact of the material production processes when assessing environmental impacts. Further details on material weight will be discussed in later sections.

All the CP options produced the lowest embodied carbon emission results, indicating that an optimized composite structural design incorporating both concrete and steel can reduce carbon emissions compared to mono-material structural designs. Additionally, the use of recycled materials in concrete further reduced emissions. The embodied carbon emissions of the RC-R decreased to 8.1 kg CO₂-eq./m² compared to the RC, while the values for the CP-R decreased to 7 kg CO₂-eq./m² compared to the CP, representing reductions of 4.9% and 5.7%, respectively.

The emissions from substages A4 and A5 were highly influenced by the predominant materials used in each structural option. The options with higher concrete consumption exhibited higher embodied carbon emission results in these two substages compared to the steel frame structures. The differences in results become more pronounced when analyzed across individual life cycle stages. Figure 10 presents a comparative analysis of the embodied carbon emission results for the seven structural cases, expressed as a percentage (%) of the total embodied carbon emission for each option. This approach highlights the relative impact of each stage within the analysis framework.

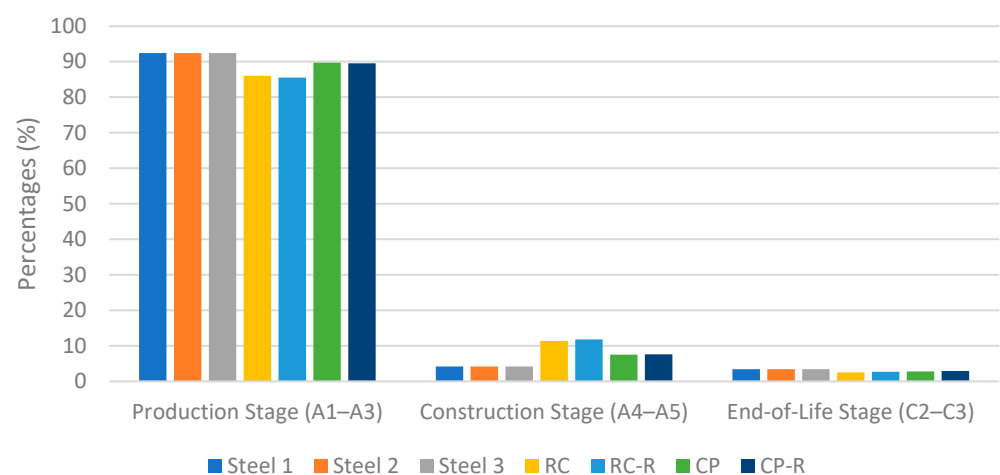


Figure 10. Comparative analysis of embodied carbon emission results across life cycle stages.

The results clearly indicate that the material production stage constitutes the largest share of total embodied carbon across all cases. The emissions from the production stage accounted for more than 90% of the total embodied carbon in all three steel frame structural

cases, while the RC cases showed slightly lower values at 85.5% and 86%. The CP cases exhibited marginally lower percentages than 90%, with values of 89.5% and 89.7%. These variations were influenced by the emissions from the construction stage, particularly the transportation stage (A4) from the material production site to the construction site. In the RC options, the emissions from this stage accounted for 11.4% to 11.8% of the total embodied carbon, whereas the steel options contributed less than 5% of the total embodied carbon.

The end-of-life stage showed very similar percentage distributions across all the structural options, with its impact being marginal compared to other stages, based on the assumptions in this study.

The study also focused on analyzing the impact of each horizontal and vertical structural element on the embodied carbon emissions. Table 4 summarizes the total embodied carbon emissions of all the structural options based on the structural classifications. The emissions are categorized into vertical and horizontal elements. The vertical elements include all the structural columns and vertical shear walls in the CP options, while the horizontal elements consist of all the horizontal steel beams, RC beams, and RC slabs.

Table 4. Embodied carbon emission results by structural classification (unit: kg CO₂-eq./m²).

Structural Classification	Steel 1	Steel 2	Steel 3	RC	RC-R	CP	CP-R
Vertical elements	54.5	54.9	56.7	29.8	28.3	69.2	65.8
Horizontal elements	87.2	100.2	113.6	136.2	129.6	51.6	48.1
Total	141.7	155.1	170.3	166	157.9	120.8	113.9

With the exception of the CP cases, all the steel frame and RC structures indicated that the horizontal structural elements were the primary contributors to the embodied carbon. Notably, the horizontal elements in the RC cases exhibited a significantly higher share of the embodied carbon emissions compared to the vertical elements.

In contrast, the CP cases showed that the vertical elements contributed more to the embodied carbon emissions. This is primarily due to the vertical RC shear walls and the outrigger truss system implemented between levels 44 and 46, which significantly reduced the weight of the horizontal steel beams.

Figure 11 presents a comparative analysis of the embodied carbon emissions across all the analyzed structural cases, expressed as percentages of the total embodied carbon based on structural classifications. As noted earlier, due to the total weight of the RC slabs in the RC cases, the horizontal structural elements accounted for 82% of the total embodied carbon in these cases. Similarly, the steel cases indicate that 61.54% to 66.72% of the embodied carbon was attributed to the horizontal structural elements. However, in the CP cases, only approximately 42% of the total embodied carbon was associated with the horizontal elements.

Among the steel frame cases, the embodied carbon emissions increased as the structural weight increased. Therefore, the material quantity is a significant factor contributing to environmental impacts. However, the absolute total weight of the materials used does not solely determine the level of embodied carbon emissions.

Figure 12 presents the total mass of the materials used for all the cases, showing that the RC cases had approximately 83,200,000 kg of total material mass—656% higher than that of the Steel 3 case, which exhibited the highest embodied carbon emissions among the seven structural cases. This discrepancy arises because the global warming potential (GWP) data for stages A1 to A3 in the steel EPD used in this analysis is 1.17 kg CO₂-eq./kg, whereas the GWP for the mixed concrete EPD is 0.161 kg CO₂-eq./kg. This significant difference is due to the fact that concrete is primarily composed of abundant natural mate-

rials, including water, sand, and aggregate, which have lower energy-intensive extraction processes. Additionally, steel requires very high-temperature processing, typically reaching up to 1500 °C, resulting in higher embodied energy during the production stage.

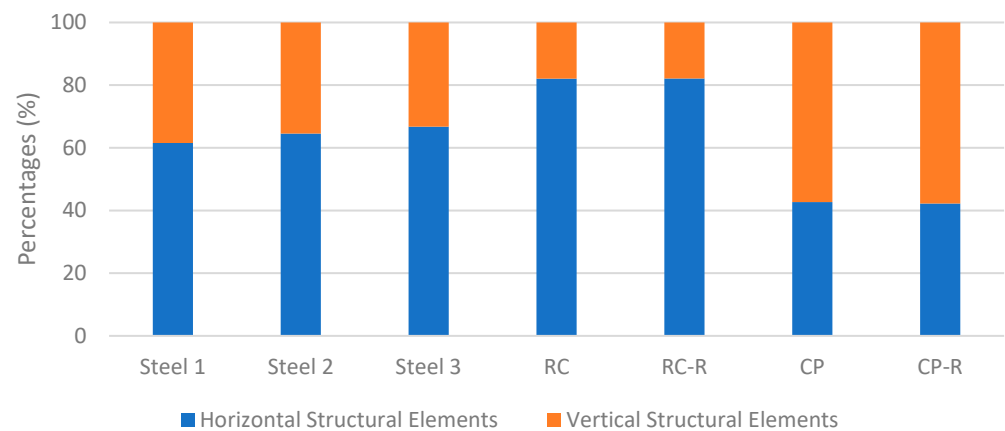


Figure 11. Comparative analysis of embodied carbon emission results by structural classification.

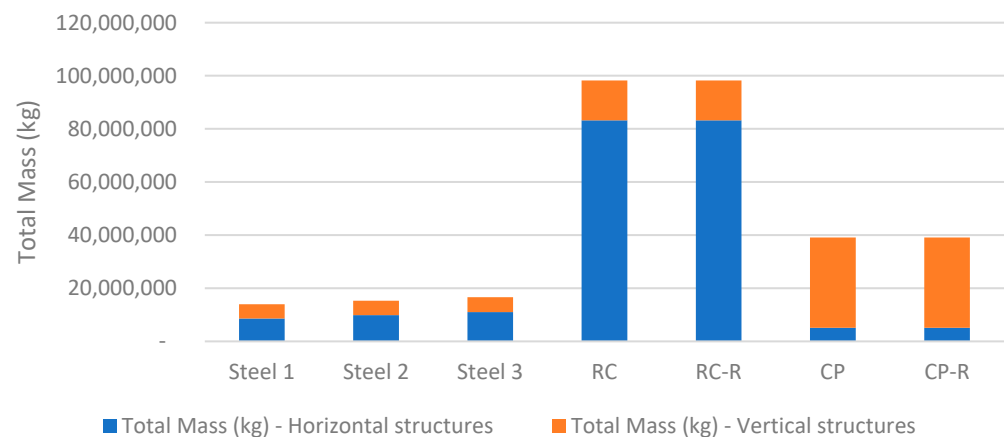


Figure 12. Total weight of materials used in the structural options.

Due to the disparity in environmental impact between the two materials, although the total material quantity of the CP cases is higher than that of the steel cases, the total embodied carbon emission intensity of the CP was 20.9 kg CO₂-eq./m² lower than that of Steel 1, which had the lowest embodied carbon emissions among the steel cases. In the CP cases, the total mass of the vertical structures accounted for 87% of the total material mass, while the emissions from these vertical structures contributed to 42% of the total embodied carbon. This discrepancy is attributed to the presence of vertical shear walls in these cases.

Figure 13 presents a comparative summary of the total embodied carbon emissions, expressed as percentages, ranging from the highest-emission case, Steel 3, to the lowest emission case, CP-R. While Steel 3 exhibited the highest environmental impact, exceeding even the RC cases, Steel 1 and Steel 2 demonstrated reductions of 16% and 8.9%, respectively, compared to Steel 3. The CP cases showed the greatest reductions, with a 29.8% decrease when conventional concrete was used and a 33.1% decrease when concrete containing 10% and 20% recycled binders in cement was used.

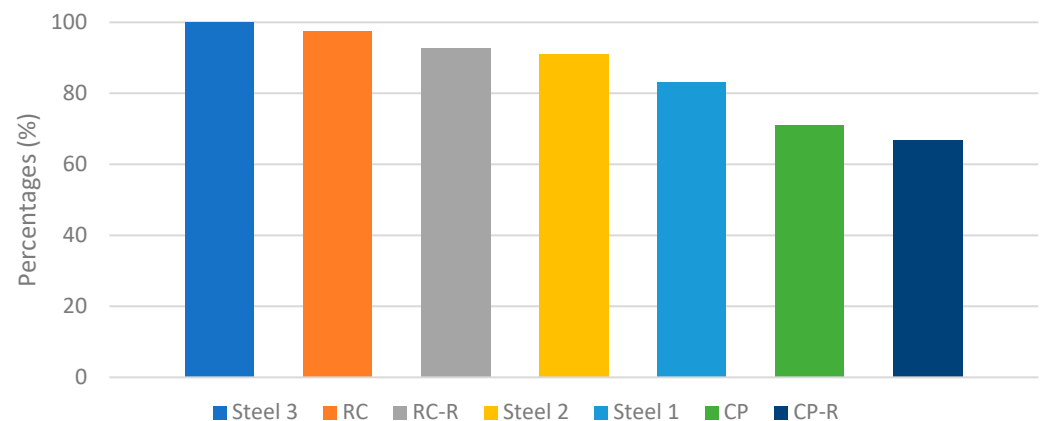


Figure 13. Comparative analysis of total embodied carbon emissions based on the cradle-to-grave approach.

3.2. Results of the Cradle-to-Cradle Approach

Both concrete and steel can be recycled and reused. Although concrete has a lower potential for recycling and reuse compared to steel, both materials can significantly reduce their environmental impact when repurposed. To assess their benefits within the cradle-to-grave approach, an additional LCA was conducted, incorporating Module D, which accounts for benefits and loads beyond the system boundary.

As previously mentioned, this assessment relied on Module D data from the EPDs used in this study. Therefore, this section assumes a theoretical recycling or reuse scenario for preliminary assessment purposes. A benefit of 2.15 kg CO₂-eq./kg was applied when steel materials were recycled or reused, while 0.0039 kg CO₂-eq./kg was applied to Module D for concrete materials.

Figure 14 illustrates the total embodied carbon intensity based on the cradle-to-grave approach, the embodied carbon benefits from recycling and reuse, and the projected embodied carbon intensity under the cradle-to-cradle approach for all seven cases. When recycling and reuse were theoretically fully applied, all the steel cases exhibited significant carbon-negative results, indicating that more carbon could be removed from the atmosphere than was emitted during construction.

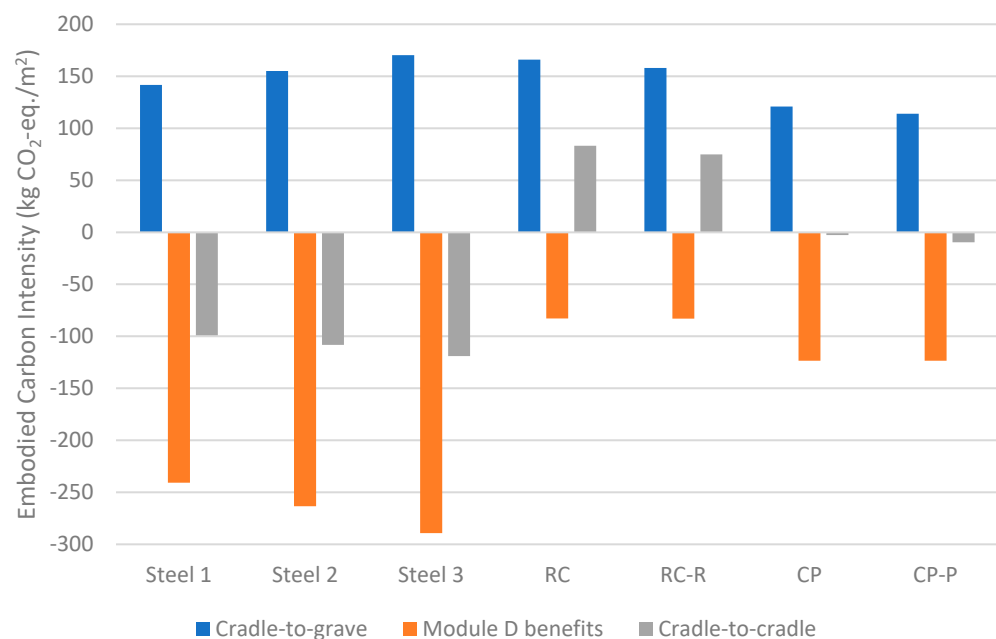


Figure 14. Embodied carbon results based on the cradle-to-grave and cradle-to-cradle approaches.

While the concrete continued to emit carbon after recycling due to its lower recycling potential compared to the steel, the results still showed significant improvement. The CP cases demonstrated carbon-neutral potential.

4. Conclusions

This study explores the potential of concrete and steel, traditionally high-carbon materials, as environmentally effective structural options for tall buildings through optimal design. Five structural systems for a 60-story building were analyzed: three steel systems (frame tube, tube-in-tube, moment frames), a reinforced concrete (RC) frame tube system, and a composite (CP) system with a core shear wall and steel outrigger trusses.

Using LCAs with a focus on embodied carbon, the study supports evidence-based decision-making in tall building design. The cradle-to-grave LCA revealed that optimizing structural weight reduces the environmental impact. Among the steel systems, the frame tube design had a 17% lower embodied carbon intensity than the moment frame. While reducing material mass is crucial, embodied carbon per unit volume also plays a key role. Despite consuming over 600% more material than the least efficient steel system, the RC case had less than 20% higher embodied carbon, as steel requires significantly more energy in material processing.

The CP system had the lowest embodied carbon, reducing emissions by 29.8% compared to the highest emission case, primarily due to a lighter horizontal steel structure and the lower carbon impact of concrete in vertical elements.

The cradle-to-cradle LCA results showed that the fully reused steel systems became carbon-negative, while the RC systems still had positive emissions due to lower recycling potential, though significantly reduced. The CP system achieved carbon neutrality, and the use of recycled cement further reduced the emissions. These findings suggest that advancements in non-cementitious materials are making reinforced concrete a more sustainable option.

However, it is important to note that LCA results may vary depending on the software and EPDs used, as they influence nearly all the LCA stages. Therefore, if the process is replicated using different LCA software or EPDs, the results may differ. Although the method introduced in this study is reliable and the EPDs used were sourced from a validated database, the authors acknowledge the limitations that may arise from data variability and software differences.

Lastly, the study did not consider several significant factors contributing to embodied carbon emissions. First, structural foundations, primarily composed of concrete and steel, were excluded from the analysis. Additionally, factors such as the construction period, detailed energy and material usage, and disposal processes during construction were not considered. Including these critical aspects would provide a more comprehensive understanding of environmental impacts and should be addressed in future studies.

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