Comparing the Life Cycle Assessments of a high-rise Building: Concrete vs. Concrete-Timber Hybrid Construction

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Abstract

This study employs a comprehensive Life Cycle Assessment (LCA) to evaluate the environmental and structural performance of two construction methods for a 120 meters high-rise building. The first method features a conventional concrete structure, while the second proposes a hybrid system inspired by the Atlassian Central Tower in Sydney, incorporating cross-laminated timber (CLT) frames, reinforced concrete cores, and RC slabs. Parametric modelling techniques validate structural performance using Grasshopper with the Karamba plugin for structural modelling, loading, and analysis. This innovative design optimizes material distribution, reduces embodied greenhouse gas emissions (EGHGE), and enhances design flexibility. Findings highlight the hybrid system's potential to reduce emissions by nearly 35% while ensuring stability, contributing to sustainable high-rise design.

Keywords high-rise buildings; concrete structure; hybrid system; LCA assessment; parametric design; sustainable construction; embodied EGHGE emission; structural efficiency; slabs; walls

1 Introduction

The global building sector is expanding rapidly, with projections estimating that 230 billion square meters of new construction will be added over the next 40 years—equivalent to building a city the size of Paris every week [1] Tall buildings are often proposed as a sustainable solution to urban densification, maximizing land use efficiency. However, their sustainability is debated, as they typically have a significantly higher embodied carbon footprint than low-rise buildings. Therefore, optimizing material use and structural systems is critical to reducing their environmental impact.

Several studies have examined the impact of vertical structural systems on the environmental performance of tall buildings, emphasizing the need to integrate sustainable materials. Among various materials, timber offers a favourable environmental balance compared to steel and concrete, primarily due to its carbon sequestration properties [2]. However, to optimize timber's application in high-rise construction, hybrid technologies are increasingly being explored. These systems strategically combine materials to enhance overall performance, ensuring structural efficiency while minimizing embodied emissions. Hybrid systems not only improve the structural viability of timber but also expand its usability in modern construction [3].

One such hybrid approach is timber-concrete composite (TCC) systems, which have gained significant attention over the past five decades. Initially used primarily for refurbishing existing structures, TCC systems are now applied in diverse structural contexts, including new buildings and bridge construction. Since the early 1990s, TCC systems have been widely adopted across several European countries, both for renovating old timber floors and for new structural applications [4]. The continued evolution of these systems highlights their potential to balance structural performance with environmental sustainability, making them a viable solution for reducing embodied carbon in high-rise buildings.

A key aspect of sustainable high-rise construction is design flexibility, which ensures that buildings can accommodate future functional changes without excessive material waste or structural modifications. Structural flexibility is particularly relevant in hybrid systems, where modular components and adaptable layouts enhance long-term usability and resource efficiency [5].

Life Cycle Assessment (LCA) is a robust methodology for evaluating the environmental impact of materials and buildings, employing standardized metrics grounded in scientific principles [6] [7]. One of the most widely recognized metrics in LCA is Global Warming Potential (GWP), which quantifies the life-cycle carbon footprint of a building. Although LCA has been used for building performance evaluation since the late 1980s, it has gained significant traction as a research area in recent years, particularly in the context of sustainable construction and the urgent need to reduce greenhouse gas emissions in the building sector [1] [8]. The life cycle of a building encompasses several stages, each contributing to its overall environmental impact. These include the production stage (A1-A3), which involves raw material extraction, transportation, and manufacturing; the construction stage (A4-A5), covering material transportation to the site, on-site installation, and waste management; the use stage (B1-B5), which accounts for maintenance, repair, replacement, and refurbishment activities; and the end-of-life stage (C1-C4), which includes deconstruction, material sorting, transportation, and disposal [6] [9] [10].

In the context of high-rise buildings, which are often proposed as a sustainable solution to urban densification, the embodied carbon footprint of materials and construction processes is a critical concern. Tall buildings typically have a significantly higher embodied carbon footprint compared to low-rise structures, primarily due to the extensive use of energy-intensive materials like steel and concrete [1] [8]. However, the integration of sustainable materials, such as timber, and hybrid systems like timber-concrete composites (TCC), offers a promising pathway to reduce embodied emissions while maintaining structural efficiency [11] [12]. Recent studies have demonstrated that hybrid systems can reduce the embodied carbon of high-rise buildings by up to 40% compared to traditional reinforced concrete structures [13].

In this study, the focus is on embodied greenhouse gas emissions (EGHGE), also referred to as cradle-to-gate emissions, which occur during the production and construction stages. Operational emissions are excluded from the analysis, as they are considered negligible for the building typologies under investigation, particularly due to minimal maintenance and repair requirements over their lifecycle [14].

2 Acoustic and Fire Resistance Standards

Acoustic insulation and fire resistance are critical considerations in building design, particularly for high-rise structures. The NBN EN ISO 16283 series defines measurement standards for on-site acoustic performance, with ISO 16283-1 (2014) assessing airborne sound insulation between rooms through sound pressure measurements and ISO 16283-2 (2018) evaluating impact sound insulation from floors and stairs. European recommendations suggest a maximum impact sound level of $L'nT,w \leq 53\,dB$ for new constructions and a minimum airborne sound insulation of $Rw = 50\,dB$ for floors and $Rw = 52\,dB$ for walls between apartments to ensure privacy and comfort [15] [16].

Fire resistance, determined through standardized tests such as those by ASTM International and the International Building Code (IBC), measures how long a construction element can withstand fire while maintaining its structural or protective functionwrite [17] [18]. In Belgium, fire resistance requirements specify that floors in buildings exceeding 25 meters must withstand fire for 120 minutes, while walls between apartments must achieve a 60-minute fire rating [19].

3 Aims and Scope

This paper aims to investigate and compare the environmental and structural performance of two construction approaches for high-rise buildings: a traditional reinforced concrete system and a hybrid timber-concrete system. The case study focuses on a 120-meter-tall residential and office high-rise building. The tower, featuring 40 floors above ground with a floor height of 3 meters. The research employs life cycle assessments (LCA) to evaluate the embodied greenhouse gas emissions (EGHGE) and structural flexibility of the two approaches.

Several studies have analysed the relationship between vertical structural systems and the environmental impacts in high-rise buildings, highlighting the importance of optimizing materials and structural systems to reduce emissions. This research contributes to this body of knowledge by assessing two different slab systems—CLT timber, bubble deck—as well as two material options (CLT and brick) for partition, division, and exterior walls. Each system is evaluated for its finishing layers, fire resistance, and acoustic performance, ensuring compliance with Belgium's building standards.

The proposed designs are analysed using parametric modelling tools like Karamba 3D to simulate structural performance and optimize configurations for environmental and structural efficiency. The original rigid frame concrete structure of the Tower is compared to an alternative hybrid system inspired by the Atlassian Tower in Sydney, which features reinforced concrete cores and load-bearing structures with timber non-load-bearing elements distributed every 4 floors. By integrating digital tools and LCA methods, this study aims to present innovative solutions for reducing embodied greenhouse gas and improving the sustainability of high-rise construction. The building is simulated under Belgium's standards conditions.

The embodied greenhouse gas (EGHGE) emissions of the materials are calculated using Global Warming Potential (GWP) indicators from the ÖKOBAUDAT platform. This platform is publicly accessible LCA database includes datasets for building materials, construction processes, transport, energy, and disposal, all adhering to EN 15804+A2 standards. The datasets are derived from GaBi background data to ensure accuracy and consistency in emissions reporting [20].

4 Methods and materials

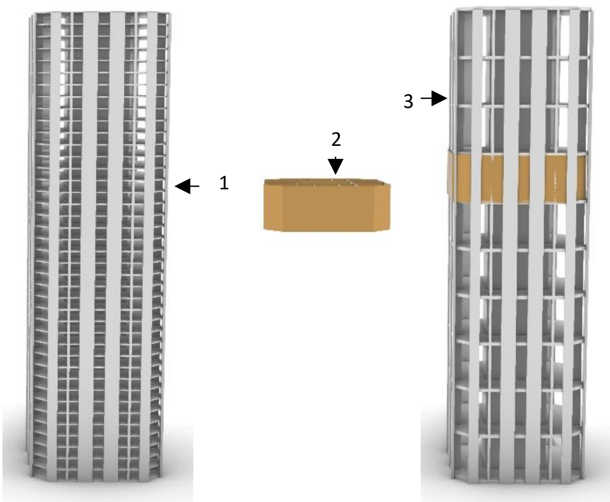
4.1 Structural system design

In the first approach a concrete rigid frame system with a concrete core is simulated

The proposed system consists of a "main structure + substructure" construction composed of two parts:

Main Structure: A concrete core and thick concrete slabs at every four floors.

Substructure: Cross-laminated timber (CLT) components, including walls in all floors and slabs in the substructure part. Figure1.



Figuer1.the initial concrete frame system building and the proposed hybrid timber-concrete system, 1. Initial building, 2. Proposed CLT part, 3. The proposed building

4.2 Slab systems

The concrete bubble deck slab, used in the initial building design and the concrete components of the proposed building, is compared with the timber CLT slab proposed for the timber elements of the building. The analysis focuses on material quantities, design processes, and the integration of finishing layers, which are included in the calculations of embodied greenhouse gas emissions and the total weight of the floor structures. These finishing layers also enhance acoustic performance and fire resistance. Specifications such as span range, thickness, weight, acoustic characteristics, and fire resistance were sourced from industrial brochures and producer websites, with consideration given to loading conditions and deflection limits appropriate for office buildings.

1. Cross-laminated timber (CLT), a mass timber product, is crafted by bonding layers of solid wood panels [21]. featuring 74dB airborne (and 49dB impact) sound insulation capability and a fire resistance duration of 2 hours. Figure2.

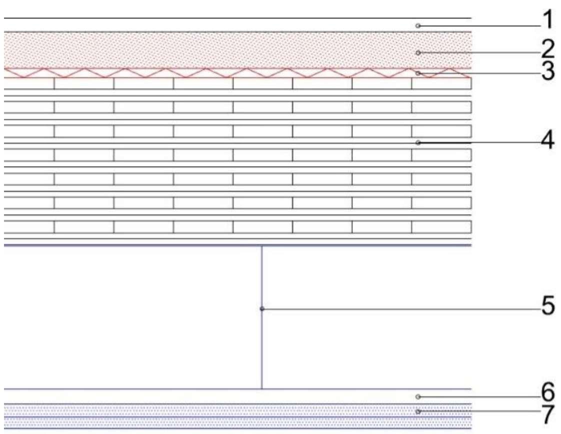


Figure 2. CLT slab system, 1. oak on-edge lamella parquetry (17,6mm), 2. Cement screed (38mm), 3. Closed cell foam (9,5mm), 4. CLT slab (200mm), 5. Metal grillage (150mm), 6. Additional acoustic hug ceiling (15,9mm), 7. 2 layers gypsum board ceiling (2×12,5mm)

2. The Bubble deck slab, [22] has a Rw 55 to 57dB is designed to provide a level of 72-74 dB airborne sound insulation and 120 minutes of fire resistance. Figure3.

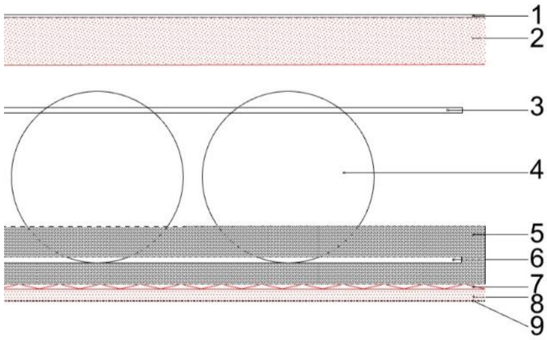


Figure 3: Bubble deck concrete slab, 1. Soft tiles Linoleum glued (2,5mm), 2. Cement screed, 50(mm), 3. Top reinforcement mesh (6mm), 4. Balls diameter (180mm), 5. Precast concrete (60mm), 6. Bottom reinforcement mesh (6mm), 7. Acoustic insulation (5 mm), 8. Thick coating, gypsum plaster(12,5mm), 9. Film coating, acrylic paint (0,1mm)

4.3 Wall systems

4.3.1 Interior walls

Brick interior partition walls, figure 4.

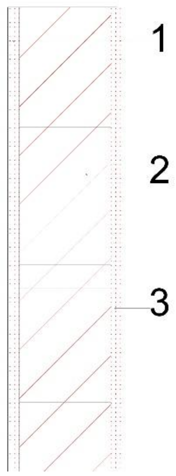


Figure 4. Brick partition wall, 1. Gypsum board (12,5mm), 2. Brick (100mm), 3. Gypsum board (12,5mm)

CLT interior partition walls, figure 5.

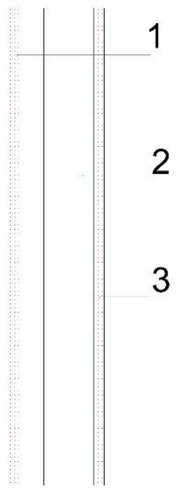


Figure 5. CLT partition wall, 1. Gypsum board (12,5mm), 2. CLT panel (90mm), 3. Gypsum board (12,5mm)

Brick division (between apartments) wall: with a Rw value of ~50-55 dB, the fire resistance achieving a 2-hour fire rating. Figure 6.

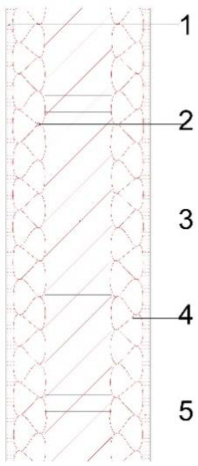


Figure 6. Brick division wall, 1. Gypsum board (12,5mm), 2. mineral wool insulation (50mm), 3. Brick work (100mm), 3. mineral wool insulation (50mm), 5. Gypsum board (12,5mm).

The proposed apartment division CLT wall has the same layering as the brick wall to be more compatible and ensures required fire resistance, with an estimated 120–180 minutes (REI 120-180). The wall achieves sound insulation, with a Rw value of 62–67dB. Additionally, its thermal performance is optimized, with an estimated U-value of 0.22–0.23 W/m²K, ensuring energy efficiency. Figure 7.

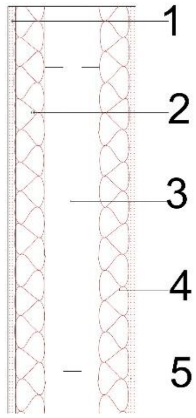


Figure 7. CLT division wall, 1. Gypsum board (12,5mm), 2. mineral wool insulation (50mm), 3. CLT core (90mm), 4. mineral wool insulation (50mm), 5. Gypsum board (12,5mm).

4.3.2 Exterior Walls

Brickwork System: This configuration meets building regulations with a U-value of 0.30 W/m²K and offers excellent thermal properties, aiding temperature regulation within the building [23]. The overall wall thickness is 225 mm, with a fire resistance of 120 minutes, and Rw 50-55dB making it suitable for buildings over 25 meters tall. Figure 8

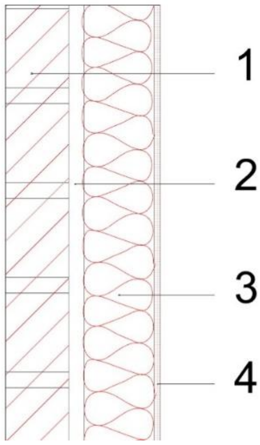


Figure 8. brick exterior wall. 1. Brick (100mm), 2. Air cavity (25mm), 3. Mineral wool insulation (110mm), 4. Gypsum plasterboard (10mm)

The CLT system: providing a 120-minute fire resistance to meet Belgian standards, and Rw 55–60 dB, ensuring effective sound insulation between interior and exterior spaces. Figure 9.

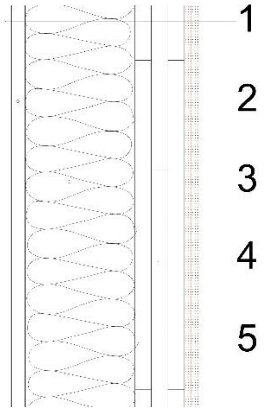


Figure 9. CLT exterior wall, 1. Cladding (20mm), 2. Air layer (25mm), 3. Mineral wool thermal insulation (200mm) 4. CLT panel (90mm), 5.2 layers gypsum plaster board (2×12,5mm)

4.4 Parametric modelling and Loads

The Grasshopper 3D plugin is selected for performing the parametric simulations, while the Karamba 3D plugin is used for the structural simulations. The simulation incorporates wind loads, live loads, and dead loads. Initially, a verification of the reinforced concrete structure is performed to ensure accuracy and reliability.

4.4.1 Dead load

Dead load is combination of slab loads and walls loads.

The weight of each slab is calculated using equations derived from graph that relate the slab's span to its weight [6]. Eqn. (1-2)

$$Weight\ CLT = 0{,}0927x^2 + 4{,}8545x + 144{,}86 \quad (1)$$

$$Weight\ bubble\ deck = 0{,}044x^3 - 1{,}2344x^2 + 28{,}228x + 522{,}64 \quad (2)$$

Where

$x = span\ (m)$

These calculated weights are then converted into loads acting on the beams using Karamba plugin. To simplify the calculations, the slabs are treated as beams in the model.

The formula used to calculate the loads on the load-bearing beams from the span weight is: Eqn. (3)

$$\text{Load}= \frac{(q \times A \times B)}{2 \times C} \quad (3)$$

Where

$A\ and\ B$ = dimensions of the rectangular slab (m)

$C = min\ (A, B), (m)$

q = slab weight (kg/m_2)

The weight of the walls is calculated according to Eqn.1 It is then distributed onto the hypothetical load-bearing beams in the same manner as the slab weights. Eqn. (4)

$$\text{wall weight} = \frac{\text{q} \times \text{H} \times \text{L}}{\text{A}} \quad (4)$$

q = the weight of the wall material per square meter $kg/m_2)$

H= height of the wall (m)

L= length of the wall (m)

A= area of the floor (m^2)

4.4.2 Live load

For live load, a load of 2 kN/m^2 is implemented. For the simulation, the same method used for slab loads is applied.

4.4.3 Loads on the central core

The central core of the building is modeled using beam elements. A concentrated force is implemented on the central core to consider permanent and service loads (dead and live loads).

4.4.4 Wind loads

The wind load acting on each floor of the tower is determined using equations based on European standards (European Union, 2010). The force applied at each floor level is given by Eqn. (5):

$$F_p = q_p \times (\frac{H \times B}{N_{nodes}}) \quad (5)$$

H = 3m (floor height)

B = 33,5m building's length, facing to the wind

N_{nodes}= 8 number of columns facing to the wind

$q_p(z)$ = peak velocity pressure at height z the peak velocity pressure is calculated as Eqn. (6):

$$q_p(z) = [1+7Iv(z)] \times \frac{1}{2}\rho v_m^2(z) \quad (6)$$

ρ = 1,25 $kg/m3$ (air density)

$Iv(z)$ = turbulence intensity

$v_m(z)$ = mean wind velocity at height z

The mean wind velocity is given by: Eqn. (7)

$$v_m(z) = C_T(z)C_T(z)V_b \quad (7)$$

Where:

$C_T(z) = k_r \ln(z/z_0)$ is the roughness factor

k_T = 0,2154, z_0 = 0,3m

V_b =25 m/s (basic wind velocity)

The turbulence intensity is: Eqn. (8)

$$I_v(z) = \frac{1}{C_0(z)}\ln(z/z_0) \quad (8)$$

Substituting these expressions, the peak velocity pressure simplifies to: Eqn. (9)

$$q_p(z) = [1+7\ln(\frac{z}{0{,}3})] \times \frac{1}{2} \times 1{,}25 \times [0{,}215\ln\left(\frac{z}{0{,}3}\right) \times 25]^2 \quad (9)$$

Finally, the wind load at each floor is: Eqn. (10)

$$F_p = q_p \times (\frac{3\times 33{,}5}{8}) \quad (10)$$

4.5 Beams dimensions

Initially, the load-bearing beams in Karamba were assigned a uniform dimension of 30 cm. However, their depths were later adjusted based on bending moments using the formula below.

To determine the depth of each beam, a width of 40 cm was assumed, and the required depth was calculated according to the bending moment in each beam. As a result, each beam has a different depth depending on its bending moment.

In general, mirror beams (beams with symmetric loading conditions) experience the same bending moments and, consequently, have the same depth.

The cross-sectional area of each beam was then determined by multiplying its length, width, and depth.

Finding the depth of the beams: Eqn. (11)

$$d = \sqrt{\frac{(M_{SD}\times 100\times 1{,}1)}{(0{,}9\times b\times f_{YD})}} \quad (11)$$

d = depth of the beam without considering the cover (mm)

M_{SD} = bending moment (Nmm)

b = width of the beam (mm) $400mm$

f_{YD}=resistance of the steel $435N/m^2$

4.6 Measuring the embodied green house gas emissions of entire building

The formula for total building EGHGE sums up the embodied greenhouse gas emissions (EGHGE) of all structural components, including slabs, walls, beams, and columns. Eqn. (12)

$$EGHGE_{building} = \sum_{ss=1}^{S}\sum_{m=1}^{M}(Q_{m,ss} \times EGHGE_m) \quad (12)$$

$EGHGE_{ss}$ = embodied greenhouse gas emission of structural system per unit area in $kgCO_2e/m^3$.

$Q_{m,ss}$ = quantity of material m per area in structural system SS.

$EGHGE_m$ = embodied EGHGE emissions coefficient of material m.

5 Results

The findings indicate that the hybrid system reduces embodied greenhouse gas emissions (EGHGE) by approximately 35% compared to the conventional concrete system. Table 1 summarizes the EGHGE contributions of each structural component. Table 1.

$EGHGE_{the\ initial\ building}$ =10767564 $kgco_2e$

$EGHGE_{hybrid\ building}$ = 7118618 $kgco_2e$

Table1. EGHGE of each structural system

EGHGE / SS	**Initial concrete frame tower** $[kgco_2e]$	**Hybrid timber-concrete tower** $[kgco_2e]$
slabs	5658400	3711200
beams	1529660	237445,1

columns	731060,2	731060,2
Concrete core	1370421	1370421
walls	1478023	1068492
total	10767564	7118618

6 Conclusions

This study analyzed the environmental and structural performance of two construction methods for a high-rise building: a traditional concrete system and a hybrid concrete-timber system. Through a life cycle assessment (LCA), it was found that the hybrid system significantly reduces embodied greenhouse gas emissions (EGHGE) by approximately 35%, primarily due to timber's carbon sequestration capabilities.

The results indicate that while concrete remains advantageous in terms of structural performance and durability, incorporating timber components in high-rise construction presents a viable strategy to reduce carbon footprint without compromising stability and design flexibility. However, considerations such as fire resistance, acoustic performance, and regulatory constraints must be addressed to ensure feasibility in large-scale applications.

Future research should focus on:

- Cost-benefit analysis of hybrid vs. traditional construction.
- Optimization of parametric design for enhanced efficiency.
- Comparing operational emissions beyond embodied carbon.

By integrating sustainable materials and advanced structural modeling techniques, this study contributes to the ongoing discourse on sustainable high-rise construction, highlighting hybrid systems as a potential pathway for reducing the environmental impact of urban development.

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