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Lightweight Floor Systems for Tall Buildings: A Comparative Analysis of Structural Material Efficiencies

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Abstract Typical floor systems in contemporary tall buildings consist of reinforced concrete or composite metal deck over framing members and account for a majority of the structural weight of the building. The use of high-density materials, such as reinforced concrete and steel, increases the weight of floor systems, reducing the system's overall efficiency. With the introduction of high-performance materials, mainly mass timber products, and fiber-reinforced composites, in the construction industry, designers and engineers have multiple options to choose from when selecting structural materials. This paper discusses the application of mass timber and carbon fiber composites as structural materials in floor systems of tall buildings. The research focused on a comparative analysis of the structural system efficiency for five different design options for tall building floor systems. Finite Element Analysis (FEA) method was adopted to develop a simulation framework, and parametric structural models were simulated to evaluate the structural performance under specific loading conditions. Simulation results revealed the advantages of lightweight structural materials to improve system efficiency and reduce material consumption. The impact of mechanical properties of materials, loading conditions, and issues related to fire engineering and construction were briefly discussed, and future research topics were identified in conclusion.

Keywords Carbon Fiber Reinforced Composites, Mass Timber, Tall Building Floor Systems, Structural Simulation, Parametric Design

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1. Introduction

The increasing rate of urban migration globally has caused a need for dense urban habitats. Tall buildings are at the forefront of this growth, and changing skyline of different cities around the globe is evident. The Structural system is an essential and critical component of any tall building and accounts for 20-30% of construction cost (Elnimeiri et al., 2009). Two primary structural systems components for any tall building are the lateral load-resisting system and the gravity system, where the function of the first one is to resist the forces generated by wind and earthquake, while the latter supports the forces due to gravitational pull of the earth. Many researchers have conducted considerable research on the structural design of tall buildings and have given significant attention to lateral load-resisting systems. However, accounting for almost 50% by weight of the total structural system, the gravity system of tall buildings is essential, and careful design of such systems can significantly impact the overall performance of the structure. The gravity system of tall buildings includes floor systems and columns. The floor system carries almost the same force per unit area of the building regardless of the structure's height (Ali et al., 2022) depending on the function of the space. As the building height increases, the column system experiences a linear increase in forces, provided the geometry and function of the building are consistent. A lightweight floor system can improve the performance of a structural system by reducing material consumption and embodied carbon.

Designers of contemporary tall buildings predominantly prefer to use two structural materials, reinforced concrete and structural steel, or a composite system (composite here means a combination of steel and reinforced concrete). A report published in 2020 by the Council on Tall Buildings and Urban Habitat (CTBUH) documents that 59% of tall buildings worldwide use a composite system, whereas the number for steel and reinforced concrete buildings is 8% and 29%, respectively. With the introduction of new materials, such as mass timber and advanced fiber

composites, along with newer manufacturing techniques in the construction industry, there has been a significant shift in the design thinking among architects and engineers. Researchers are looking at these alternatives to replace the traditional structural materials to achieve better performance for the structural systems of tall buildings. Embodied carbon is one of the driving forces behind this decision. Designers are looking for unique and creative ways of using bio-based materials such as mass timber to reduce the carbon emissions of tall buildings.

2. Performance and Weight of the Structural System

The performance of tall building structural systems is critical and needs to be accounted for when designing. Some key performance indicators include the deflection of structural components under applicable loads, ease of construction, and weight of the structural system. Structural engineers always try to reduce the weight of the systems while satisfying various deflection criteria. Materials such as mass timber and fiber composites weigh significantly less than reinforced concrete and structural steel, making them an ideal choice for structural systems. However, the structural properties of materials like mass timber are comparatively lower than that of steel or reinforced concrete resulting in larger structural elements and increased system weight. Table 1 shows the specific mechanical properties of various structural materials.

In the pioneering research on tall buildings, Dr. Fazlur Rahman Khan developed steel and concrete structural systems for tall buildings (Figure 1). Their research focused on lateral wind-resisting systems and the performance of structural material. Since then, considerable research has been done on lateral wind-resisting systems of tall buildings with a focus on material performance.

3. Isotropic vs. Anisotropic Behavior of Structural Materials

The structural performance of any material is dependent on the mechanical behavior of that material. In material science, materials are classified into two categories. Isotropic materials exhibit similar mechanical properties in all cardinal directions (X, Y, and Z), making the structural analysis straightforward. The classic examples of isotropic materials are steel and concrete. Orthotropic materials behave differently and showcase distinct properties in all three directions. Anisotropic materials are a subset of orthotropic material where the mechanical behavior of the material is dependent on the type of force (compression or tension) applied to the structural components. The structural analysis involving anisotropic materials is complex and often includes Finite Element Analysis (FEA). Mass timber and Fiber-reinforced Composites (Glass and Carbon Fiber) are anisotropic materials.

4. Research Problem and Objective

This paper focuses on the floor systems for tall buildings and aims to evaluate the performance of such systems. With different mechanical properties and analysis methods, selecting a structural material is often a complex task. To understand the performance of floor systems of tall buildings, one needs to account for variables related to material weight, mechanical properties, and other challenges related to fabrication and construction. The primary objective of this research is to present a quantitative

Table 1. Mechanical properties of structural materials

Material		Mass Timber		Structural Streel (A572Grade 50)	UD Carbon Composite (CFRP) (60% Fiber Fraction)
		Cross Laminated Timber (CLT)	Glued Laminated Timber (GLT)		
Density	lb/ft^3 (kg/m^3)	32.1 (514.2)	31.8 (509.3)	499.7 (8004.4)	96 (1537.7)
Longitudinal Modulus of Elasticity	Ksi (GPa)	1,700 (11.7)	2,132 (14.7)	29,000 (200)	18,900 (130.3)
Transverse Modulus of Elasticity	Ksi (GPa)	1,200 (8.3)	71 (0.48)	--	1,240 (8.55)
Longitudinal Compressive Strength	Psi (MPa)	1,800 (12.4)	4,500 (31.0)	50,000 (344.7)	2,58,000 (1,778)
Transverse Compressive Strength	Psi (MPa)	650 (4.5)	520 (3.5)	--	31,300 (215.8)
Longitudinal Tensile Strength	Psi (MPa)	1,375 (9.5)	3,770 (25.9)	50,000 (344.7)	4,36,000 (3,006)
Longitudinal Tensile Strength	Psi (MPa)	250 (1.7)	70 (0.48)	--	8,820 (60.8)
Shear Strength	Psi (MPa)	135 (0.93)	52 (0.34)	50,000 (344.7)	10,000 (68.9)

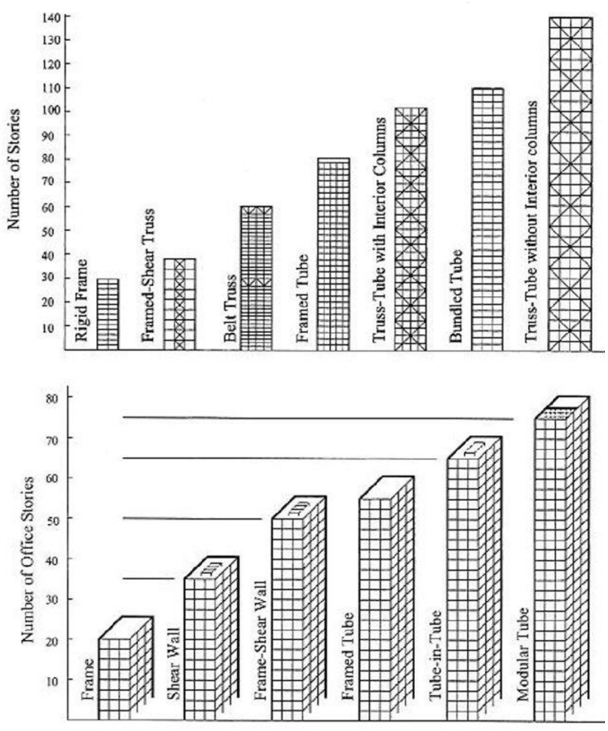


Figure 1. Lateral load resisting structural systems developed by Dr. Fazlur Khan. (Adopted from Ali et.al. 2007)

comparison of the performance of lightweight floor systems when utilizing different materials. The structural analysis results will also provide pathways for future work associated with the fabrication and construction of such floor systems. The framework of structural analysis developed in this research will provide designers with a tool to assess the performance of tall building structural systems and assist with better decision-making.

5. Methodology

Clear floor space with minimum vertical columns is desirable in tall buildings. A typical tall building consists of a core usually made up of reinforced concrete, in which all the building services and vertical transportation, such as elevators and stairs, are housed. The perpendicular distance from the core wall to the building facade is called the lease span. A minimum lease span of 35-45 ft is desirable for commercial buildings, whereas residential buildings need a lease span of 20-30 ft (Choi, 2002).

This research study consisted of two stages. A base case consisting of a square floor bay measuring 40ft X 40ft was developed in the first stage of the research and was simulated parametrically. Design parameters such as bay width, location of primary and secondary framing members, and member cross-section sizes were identified. Two framing options were identified for further analysis based on the spacing of secondary framing members reflecting common practices in the construction industry. Structural analyses for five design options were performed to evaluate the system's performance in the second stage to quantify the efficiency of the structural system. *Structural efficiency* was defined as the structural weight per unit floor area and calculated using the formula below.

The use of specific materials for individual structural components corresponds with five design options. Figure 2 shows the structural layouts considered in this study. Table 2 documents the material used for distinct structural components and the geometrical layout of the floor system for each design option.

A parametric model was generated using the digital modeling software - Rhinoceros 3D and Grasshopper. Figure 3 shows the grasshopper components used to generate the geometry. Finite Element Analysis (FEA) was selected as the preferred method of structural analysis to account for the anisotropic behavior of specific material options. A parametric structural simulation tool called Karamba3D was used to perform the computational structural analyses. The research workflow is adopted from the doctoral dissertation of the author titled "Efficiency of Carbon Fiber Composite Structural Systems for Tall Buildings: A Parametric Simulation Based Framework for Finite Element Analysis"

American Society of Civil Engineers (ASCE) standard 7-22 was used to determine applicable design loads, and material-specific design standards and codes were referred to satisfy various design criteria, such as strength and deflection of structural components. Table 3 documents the material-specific standards used to establish the design criteria. All simulations included in this research

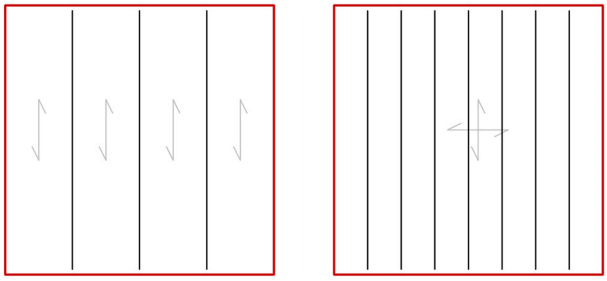


Figure 2. Framing layout option A (left) and option B (right) showing edge beams (red) and simply supported interior beams/joists (black) indicating primary span directions.

Table 2. Material details of five design options and structural layout

Design Option	Layout	Floor Slab	Exterior Beams	Interior Beams
Mass Timber	A	CLT	GLT	GLT
Structural Steel	B	Composite	Steel	Steel
Carbon Composite	B	Composite	CFRP	CFRP
Steel-Timber Hybrid	A	CLT	Steel	Steel
CFRP-Timber Hybrid	A	CLT	CFRP	CFRP

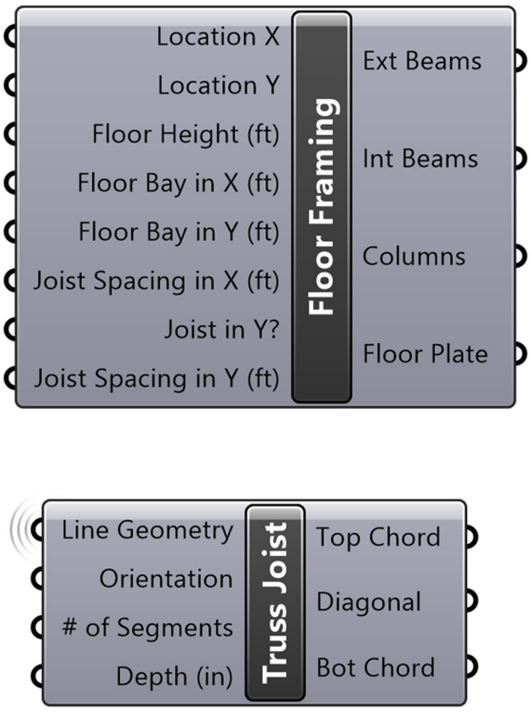


Figure 3. Custom Grasshopper components used for parametric design generation. Required inputs are shown on the left side and output geometry on the right side.

assumed an office function to determine minimum building loads. Additional loads, such as concrete topping on CLT floor panels to reduce vibrations, were also accounted for while analyzing the structural models.

Iterative simulations were performed to optimize for the minimum possible weight of the structural elements to satisfy design criteria. The efficiency of the floor system was calculated using the most optimized solution. Figure 4 and 5 show the schematic research work flow and the simulation framework using Grasshopper-Karamba3D, respectively.

During the structural simulations and analyses, careful consideration was given to the material-specific constraints, such as manufacturing limitations, construction issues, and mechanical properties. An example is the use of Cross Laminated Timber (CLT) as floor panels in structural systems. CLT panels are typically produced in widths of 10-13 ft. During the analyses, each panel was simulated individually to model the system as accurately as possible. Structural connections were assumed between panels for continuous diaphragm action.

Another consideration during simulation was done for the composite flooring in All-Steel, and Carbon Fiber options; only reinforced concrete is used to simulate a floor panel instead of a corrugated deck due to the modeling limitations of the Karamba3D tool. An equivalent thickness of concrete floor was assumed to calculate the system weight. Using reinforced concrete to model the floor panel does not significantly impact the performance of floor framing members. A rigid diaphragm action was assumed for all simulated floor systems.

6. Results and Discussion

The simulation results of this study are documented in Figure 6(a) and 6(b). Results include total deflection of the system to satisfy the serviceability criteria with

Table 3. Applicable Building Code/Standard used in the structural design process to satisfy strength and serviceability criteria

Category	Standard/ Building Code
Mass Timber	National Design Specification for Wood Construction, 2018
Structural Steel	Specification for Structural Steel Buildings, ANSI/AISC 360-16
Carbon Composite	Load and Resistance Factor Design (LRFD) for Pultruded Fiber Reinforced Polymer (FRP) Structures, ASCE/SEI 74-XX
Building Loads	Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-22

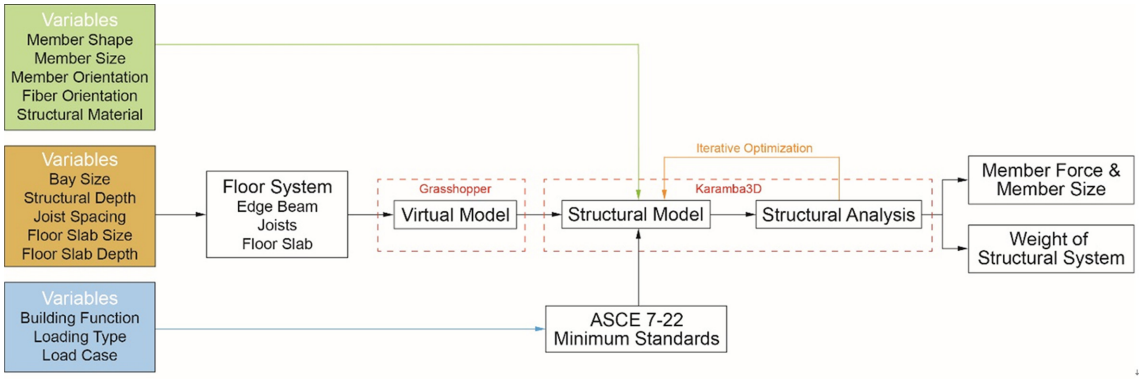


Figure 4. Schematic workflow of the research methodology. (Adopted from Khairnar. 2022)

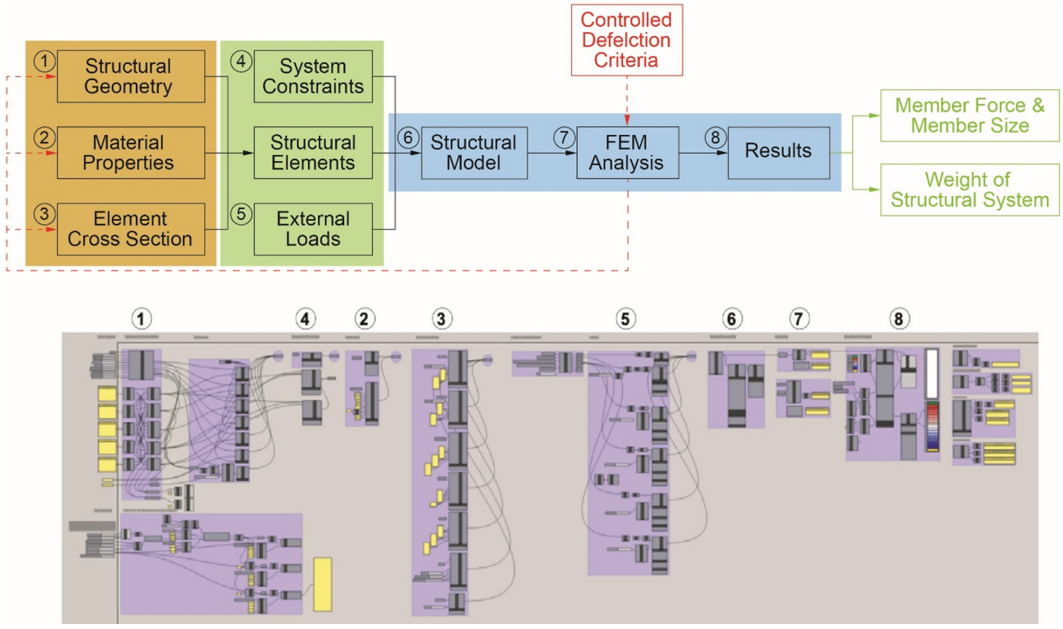


Figure 5. Schematic workflow of Karamba3D analysis (top) and screenshot of Karamba3D user interface (bottom). (Adopted from Khairnar. 2022)

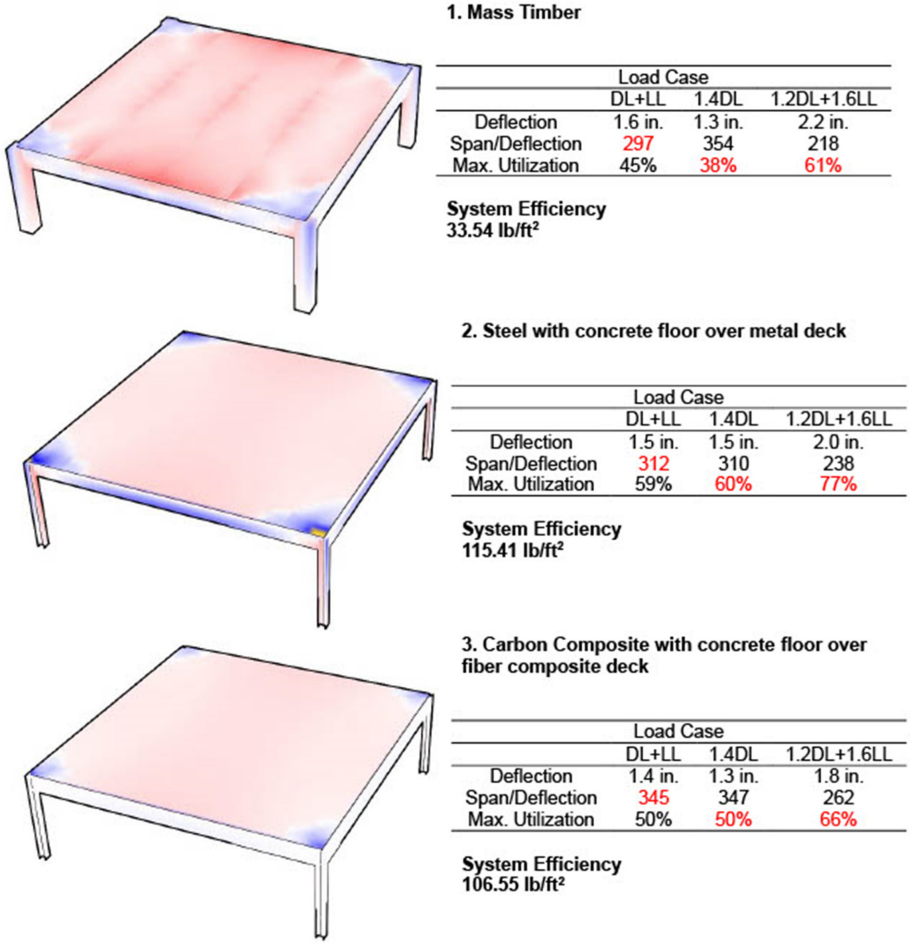


Figure 6(a). Analysis results for various design options. Image on the left shows visual result of member utilization. Values in red indicate the governing criteria for the specified load case

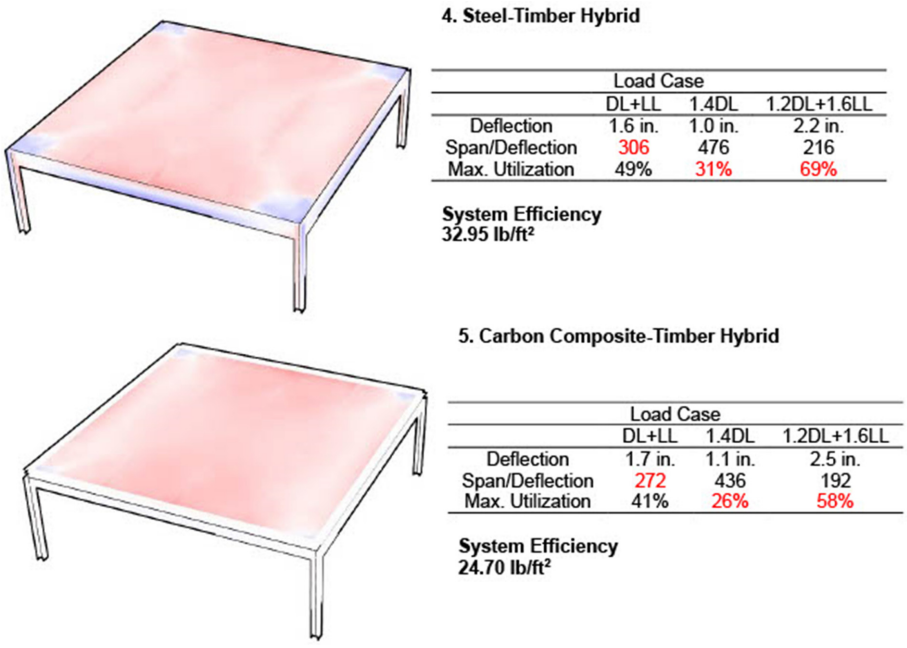


Figure 6(b). Analysis results for various design options. Image on the left shows visual result of member utilization. Values in red indicate the governing criteria for the specified load case.

minimum span to deflection ratio limit of 250. Member utilization (defined as the ratio of stress in structural members to the material's yield stress) was also documented to account for strength criteria under various load cases.

The structural system with the carbon composite-timber hybrid option has the least weight per unit area at 24.70 lb/ft2, making it the most efficient structure. This high efficiency is due to the high strength-to-weight ratio of carbon composites and lightweight CLT floor panels. Due to the high density and weight of materials, All steel system with composite concrete slabs weighs 115.41 lb/ft2, resulting in the least efficient system. The weight of the entire floor system, including the concrete slab, is considered when comparing to account for the use of CLT floor panels in mass timber systems. However, using lightweight materials such as mass timber and carbon composite results in a more efficient structural system; more than merely assessing performance based on system weight is needed. Other aspects of system performance are discussed below to understand the impact of material choice on structural systems.

6.1. Material Stiffness and Member Sizes

Stiffness can be defined as the ability of a material to resist the change in shape under applied loading. Thus a critical mechanical property to consider when assessing structures, such as floor systems, that undergo deformations. Mass timber and carbon composite materials exhibit lower stiffness than steel and reinforced concrete, resulting in higher deflections. If not carefully designed, mass timber and carbon composite structural members can easily exceed the deflection limits considered in serviceability criteria in building standards. The results of simulation studies show that structural systems with mass timber and carbon composite show higher deflections than structural steel under identical loading conditions. With a lower stiffness of mass timber and carbon composite as materials, structural members are often sized with more considerable depths, which results in a high structural depth of the system. When considering tall buildings, this deeper structural system may result in reduced floor-to-ceiling height, causing a low number of overall building floors reducing the economic value of the building.

6.2. Behavior under Lateral Loads

Although floor systems are considered a part of gravity systems, they provide significant advantages to the lateral load-resisting system. Tall building structures are subjected to high wind loads causing significant bending moments at the base and overall building deflections. Building floors account for a significant self-weight which resists the overturning bending moments induced due to wind forces. Having a floor system that weighs more makes much sense to avoid any net tension and uplift in the foundation of tall buildings.

Unlike wind loads, seismic loads induce inertial forces in building structures dependent on the system's weight. The higher the weight of the system, the higher will be the inertial forces causing more significant movement. Since floor systems account for most of the weight in tall buildings, having a lightweight floor system using materials such as mass timber and carbon composite will result in better seismic performance of tall building structures.

6.3. Fire Engineering

Fire protection in tall buildings is closely related to the structural material used during construction. Reinforced concrete typically does not require additional measures for fire protection, as the concrete cover provides the insulation for the steel reinforcement. In steel construction, spray-applied insulation is a common practice. In mass timber construction, fire protection is provided in two primary methods: to provide insulation by covering the mass timber elements with a gypsum board to achieve the required duration to resist fire or to overdesign the structural member to account for the char depth during a fire event. One of the reasons for using mass timber in tall buildings is the natural aesthetic appeal of the material. Many designers avoid gypsum covering and choose to expose the structural material. This results in prominent structural members causing increased structural weight and reduced system efficiency.

In the case of carbon composites, the resin matrix used is susceptible to high temperatures and loses its strength and stiffness in the event of a fire. Spray-applied insulation is a solution to provide required fire protection, but similar to mass timber, the unique aesthetic features of carbon composite may require that the structural materials be exposed. In such cases, a special coating of intumescent material is applied to the structural components, which expands and provides necessary protection to the structure in the event of a fire. Although this does not significantly impact the weight of the systems, it is crucial to consider when selecting a structural material.

6.4. Construction Process and Material Cost

The construction of tall buildings is a complex process, and structural systems account for 20-30% of the total construction cost (Elnimeiri et al., 2009). The construction cost of a structure is closely associated with the type of material and structural system. Some critical aspects considered during construction are the structure's weight, the number of crane lifts required, the curing period (in the case of concrete), the assembly of materials, and on-site construction vs. prefabrication.

One of the advantages of materials such as mass timber and carbon composites is their light weight. The reduced weight of the system directly relates to the speed of construction, on-site material installation, and labor costs. Lower material weight also means reduced cost of transportation from the manufacturing plant to the construction site resulting in fewer carbon emissions.

Another advantage of lightweight construction systems that use mass timber and carbon composite is the manufacturing quality. As both these materials require careful consideration for design and fabrication, the manufacturing process is highly controlled, resulting in high-quality products. The prefabrication process also reduces the on-site construction time and inspection costs.

The raw material and manufacturing costs for carbon composite materials are higher than steel or mass timber. This increased cost is partly due to sophisticated manufacturing and a need for more mass production. The reduced weight of the carbon composite structural system and associated construction benefits may counterbalance this high raw material cost.

7. Conclusions

It is clear from the results of this research study that high structural efficiencies can be achieved by using lightweight structural materials in floor systems of tall buildings. It is also understood that the design of floor systems of tall buildings does not happen in isolation, and structural design is only one of the criteria to assess the performance of such systems. In conclusion, this study identifies three areas of contribution and future research to the field, which are discussed below.

7.1. Whole Building Performance

The structural simulations presented in this study were performed on a square floor bay to showcase the impact of lightweight materials on system performance. A whole building simulation must be performed to identify areas of future research for lightweight floor systems and to assess the impact of these design decisions on the efficiency of the overall building structure. The research can be further expanded to include lateral load-resisting systems to explore potential applications of lightweight materials in tall buildings.

7.2. A Parametric Framework

The simulation framework developed in this research provides opportunities for engineers and designers to simulate various structural systems using parametric design. The framework can be easily applied to various building typologies and incorporate various building materials. The faster analysis results using the finite element analysis (FEA) adopted in the research allow for exploring multiple design options at the early stages of design.

This framework's computer-generated and simulated digital models can easily be integrated with the digital fabrication processes, reducing manufacturing bottlenecks. This use of computational design will allow for a quicker exchange of information between multiple stakeholders for a streamlined design-fabrication-construction process for buildings, resulting in a sustainable and economical design.

7.3. Environmental Impact of Structural Systems

The life cycle assessment (LCA) method for building systems requires precise material quantities to quantify the environmental impact of various materials and design decisions. The simulation results of this research provide detailed material quantities which can be further analyzed

for the environmental impact of the structural systems, providing opportunities to reduce the environmental impact of tall buildings by designing efficient floor systems with reduced weight.

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