REGENERATIVE APPROACH THROUGH CIRCULAR DESIGN: POTENTIAL OF BIO–BASED CARBON FIBER COMPOSITES IN STRUCTURAL SYSTEMS OF TALL BUILDINGS

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Abstract

Carbon fiber composites have gained popularity in various industries, including aerospace, automobile, and sports, for their high strength and performance. In recent years, their unique aesthetic and superior structural properties have made them a desirable building material, leading to discussions around mechanical properties, production techniques, construction methods, recycling potential, and environmental impact in the construction industry. However, the highly sophisticated production methods and specific raw materials required for carbon fiber composites, such as polyacrylonitrile (PAN), pose significant challenges to their widespread acceptance due to high embodied energy. To address the environmental impact of carbon fiber composites, there have been efforts to search for alternative raw materials to produce bio-based carbon fibers. Bio-based carbon fibers are made from lignin, a natural compound found in trees and a waste byproduct of the paper manufacturing industry. Bio-based epoxy resin is also made from biodegradable sources such as linseed oil. These raw materials have proven to be viable candidates for producing carbon composites with high mechanical properties.

This paper investigates the application of bio-based carbon fiber composites as a structural material in tall buildings, focusing on material performance, reuse, and recycling as part of the circular design strategy for tall building structures. Simulation-based studies are conducted on a tall building structural system using carbon fiber composites made with bio-based carbon fiber. Parametric design simulations are performed for selected structural systems to quantify the performance of carbon fiber composites. Finite element analysis (FEA) for structural components investigates the material strength and stiffness requirements, which are used to identify potential applications of recycled carbon fiber composites within the structural systems. The results of the simulations reveal potential ways of using bio-based composites in tall building structural systems. The FEA studies on structural components provide specific opportunities to utilize recycled bio-based carbon fibers with reduced mechanical properties, resulting in a lower embodied carbon for the building structure.

In summary, this paper highlights the potential of bio-based carbon fiber composites as a sustainable alternative to traditional carbon fiber composites in tall building construction. The study provides valuable insights into the material performance, reuse, and recycling potential of bio-based carbon fiber composites in tall building structures, offering designers and engineers new ways to reduce the environmental impact of building materials.

Introduction

With rapid urbanization and increased construction, the global CO2 emissions rate has drastically increased. In order to control and reduce CO2 emissions, a more sustainable and resilient design of tall buildings is desired. Most of the current research is focused on building energy consumption, especially in terms of heating and cooling demands, building envelope optimization, and the use of efficient mechanical equipment. Another well-researched area related to the sustainability of the built environment is the embodied energy of building materials which gives a comprehensive and holistic picture of energy consumption. The design of tall buildings is a highly collaborative effort. The structure and architecture of a tall building are closely interconnected and can impact the overall performance of the building (Elnimeiri & Gupta, 2009). Successful collaboration between architects and engineers is highly desirable from the early design stages to develop energy-efficient tall buildings.

The tall building design is a complex process requiring collaborative efforts from multiple disciplines. Structural engineering is one of the critical aspects of tall building design. The core principle of structural engineering is to predict the applicable forces on a building structure and design the structure to withstand those external forces, all while ensuring the occupant's comfort is maintained and the stresses in the material are under the defined limits. Tall buildings are subjected to different forces throughout their lifespan, such as gravity and wind loads. Depending on the geographical location and seismic activity, many tall buildings are also designed to account for earthquake forces.

Structural material for a tall building significantly impacts the system's overall performance. Steel and reinforced concrete are the two available materials widely used in the construction of tall buildings around the globe. Based on the primary material, the structural systems are classified into four categories: 1) Steel Construction, 2) Concrete Construction, 3) Composite Construction (Composite here means two materials acting together to resist the forces), and 4) Hybrid Construction (Hybrid means two materials acting independently to resist loads).

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 in 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 and fiber composites to reduce the carbon emissions of tall building structural systems.

Carbon Composites as a Structural Material

Carbon fiber is a synthetic fibrous material made from natural precursor fibers or chemical-based substances. Initially developed in 1880 by Thomas Edison to be used as filaments in light bulbs, carbon fibers have come a long way in their development and properties. Today, carbon fibers are one of the strongest materials for their superior tensile strength and comparatively lower weight (Windhorst, 1997).

Carbon Composites, or Carbon Fiber Reinforced Polymer (CFRP), are a particular type of material that consists of carbon fibers embedded in a polymer resin matrix (Liu et al., 2015). The fibers act as the reinforcement to the resin, giving it strength, hence the name. Figure 1 shows the typical composition of carbon composites. The resin polymer in the CFRP helps with fiber alignment and uniform stress distribution (Liu et al., 2015).

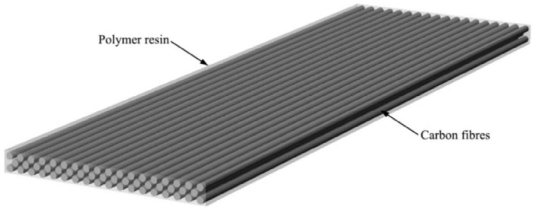


Figure 1: Typical Structure of Carbon Fiber Reinforced Polymer (CFRP). (Source: Liu et. al. 2015, CC-BY http://creativecommons.org/licenses/by/4.0/.)

	Mass Timber			
Material	Cross Laminated Timber (CLT)	Glued Laminated Timber (GLT)	Structural Steel (A572 Grade 50)	UD Carbon Composite (CFRP) (60% Fiber Fraction)
Density lb/ft^3 (kg/m^3)	32.1 (514.2)	31.8 (509.3)	499.7 (8,004.4)	96 (1,537.7)
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)	258,000 (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)	436,000 (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 ().34)	50,000 (344.7)	10,000 (68.9)

Table 1: Mechanical properties of structural mass timber, steel, and carbon fiber. (Source: Author.)

The low density of carbon fibers and resin matrix makes the material extremely lightweight compared to other materials, such as steel and aluminum. The high axial strength and stiffness of carbon fibers are the primary sources of strength for composite materials making the strength-to-weight ratio of CFRPs higher than that of structural steel. Table 1 documents the mechanical properties of mass timber, structural steel, and carbon composites.

Materials are classified into two categories based on mechanical properties: Isotropic and Orthotropic. Isotropic material has the same properties in all directions, while material properties vary based on different directions for orthotropic materials. Anisotropic materials are a subset of orthotropic materials whose properties depend on the direction in which they are measured (Campbell, 2010). Wood and Composite materials are examples of orthotropic materials. Since the mechanical properties of carbon composites are mainly dependent on the fibers, the orientation of these fibers governs the orthotropic behavior of CFRP. The strength of the CFRP part varies with the angle between the fiber direction and the direction of the applied load, as shown in Figure 2. Unlike wood, it is possible to control the orientation of the carbon fibers in the CFRP components giving flexibility in the manufacturing of the material and allowing for a specific layout of fibers depending on the applied loads and forces.

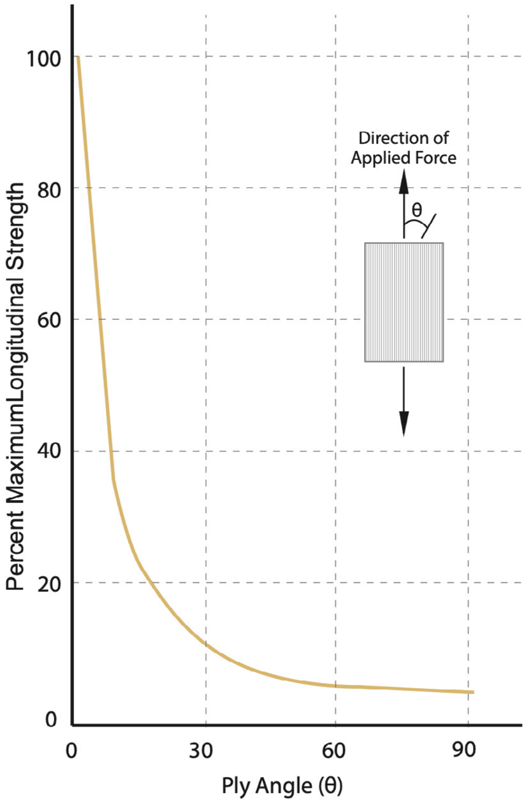


Figure 2: Longitudinal strength of carbon fiber composites vs. fiber orientation. (Adapted from Campbell, 2010. Source: Author.)

Bio-Based Composites

Bio-based carbon composites are composite materials manufactured from natural or renewable sources, such as plant-based fibers or biopolymers (Mehta et al., 2017). Unlike traditional carbon composites, which are made from petroleum-based materials, bio-based carbon composites offer the potential for reduced environmental impact and sustainability benefits.

A bio-based epoxy matrix is an epoxy resin derived from renewable plant-based materials such as soybean, linseed, or castor, rather than petroleum-based sources. The epoxy resin is typically combined with a hardener to create a high-performance matrix material that can be used to manufacture composite materials.

Bio-based epoxy matrices have several advantages over traditional petroleum-based epoxy resins. They are more environmentally friendly, as they are made from renewable resources and have a lower carbon footprint than petroleum-based resins. They also have the potential to reduce dependence on fossil fuels and contribute to a more sustainable manufacturing and construction industry (Fiorelli et al., 2020).

In addition to their environmental benefits, bio-based epoxy matrices also offer good mechanical properties, including high strength and stiffness, good adhesion to fibers, and excellent chemical resistance (Mohanty et al., 2021). These properties make them well-suited for various aerospace, automotive, and construction applications.

Carbon fibers made from lignin are bio-based carbon fibers derived from lignin, a natural polymer that is a byproduct of the paper and pulp industry. *Lignin* is a renewable and abundant raw material that can be obtained from various sources, such as wood, agricultural residues, and grasses. Producing carbon fibers from lignin involves extracting lignin from the raw material and then subjecting it to a series of chemical and thermal treatments to convert it into a carbon-rich material. This material is spun into fibers using conventional carbon fiber manufacturing processes (Saini et al., 2018).

Carbon fibers from lignin have several advantages over conventional carbon fibers derived from petroleum-based precursors:

- They are renewable and can be produced from a waste stream, making them an eco-friendly alternative to petroleum-based carbon fibers.
- They have a lower carbon footprint than conventional carbon fibers, as producing petroleum-based precursors involves significant energy consumption and emissions.
- They have excellent mechanical properties and can be used in various applications, including aerospace, automotive, and construction industries.

Despite their potential benefits, carbon fibers made from lignin are still in the early stages of development, and their commercial viability is yet to be established. Further research is needed to optimize their production process, improve their mechanical properties, and evaluate their suitability for various applications. However, with growing interest in sustainable materials and the circular design, lignin-based carbon fibers are expected to play an increasingly important role in the future of advanced materials.

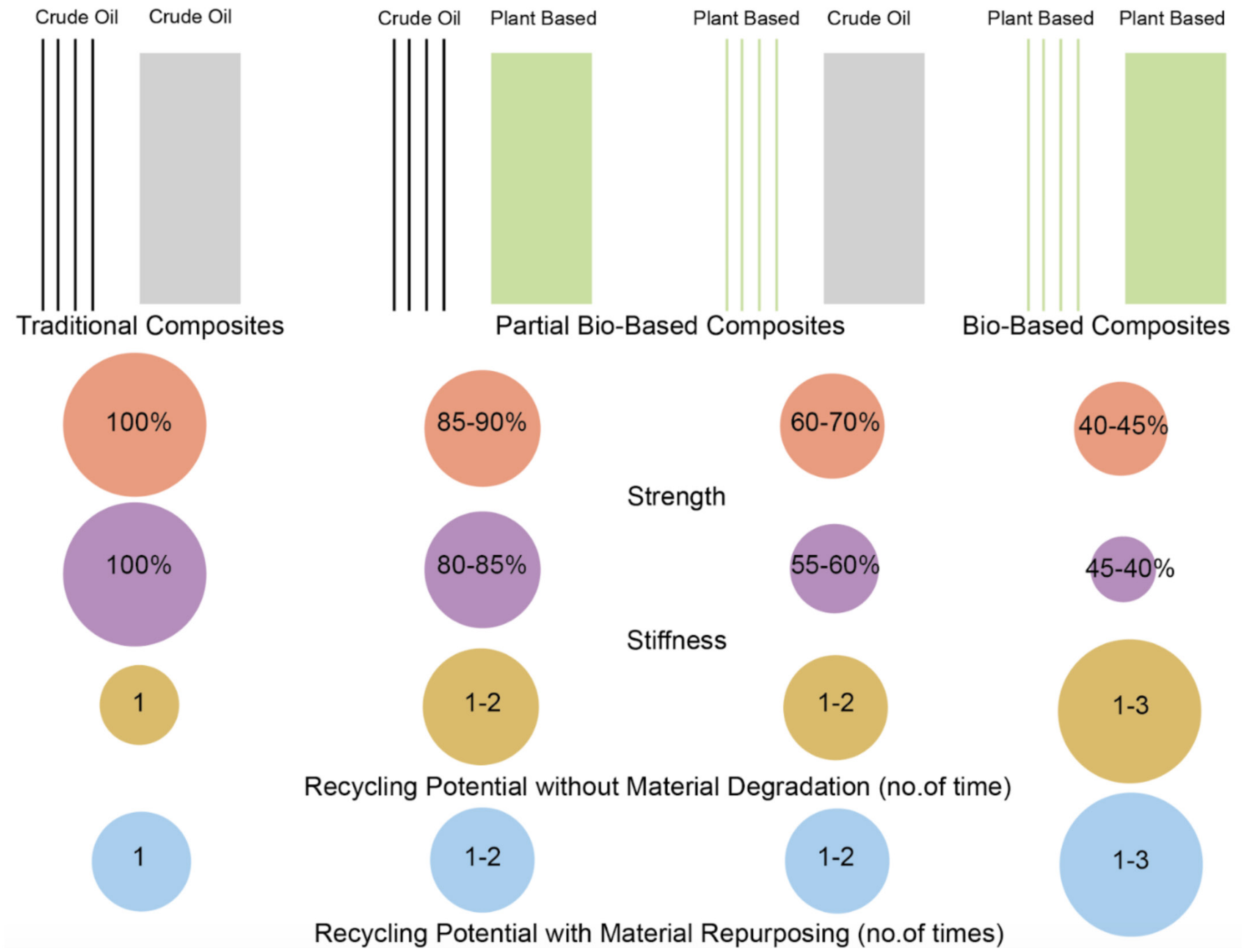


Figure 3: A comparative study of material properties and recycling potential for fossil fuel-based and bio-based composites. Data provided is based on available literature. (Source: Author.)

Based on the composition and raw materials used in manufacturing, bio-based composites can be classified into two categories, Partial Bio-Based composites, where at least one component is bio-based, and Fully Bio-Based composites, where both the fibers and polymer matrix is made from bio-based raw materials. Despite their environmental benefits, bio-based composites offer significantly lower strength and stiffness than fossil fuel-based composites. Figure 3 compares various properties of fossil fuel and bio-based composites. The data presented is based on the available literature.

Objectives

This research paper aims to identify the potential of bio-based carbon composites as a structural material in tall buildings. The research also examines the performance of carbon composites as a structural material in the construction industry. This research also aims to identify the opportunities for circular design within the construction industry using bio-based composites to reuse the material for as long as possible to reduce building structures' waste and environmental impact.

Methodology

Preliminary research related to the properties of bio-based carbon composites and the current structural applications of this material in the building industry reveals that the use of this material is limited in tall building structural design. Identified as the primary research gap, this provides a unique opportunity to research and understand the performance of tall building structural systems that utilize bio-based carbon fiber composites as the primary structural material.

The research is divided into two phases, where each phase undertakes simulation and analysis of a critical part of selected tall building structural systems. Figure 4 documents the research workflow, and the two phases are explained below.

PHASE 1 In this phase, the primary building form is generated using basic geometrical parameters. The native capabilities of Grasshopper, a parametric plugin and tool for computational design, are used to construct the selected building form. The visualization of the geometry is achieved with the help of Rhinoceros 3D, a graphics and CAD application software, which also acts as the native environment for Grasshopper. Once the basic parametric form of the building is constructed, the next step deals with the generation of discrete structural elements that constitute the design of the gravity system of the tall building, which represents the virtual model of the system.

The next step analyzes individual components and parametric models of gravity systems for structural behavior under simulated loading conditions. The structural simulations are performed with the help of Karamba3D. It is a parametric structural engineering tool that can provide an accurate analysis of various types of structural elements. Karamba3D works within the environment of Grasshopper.

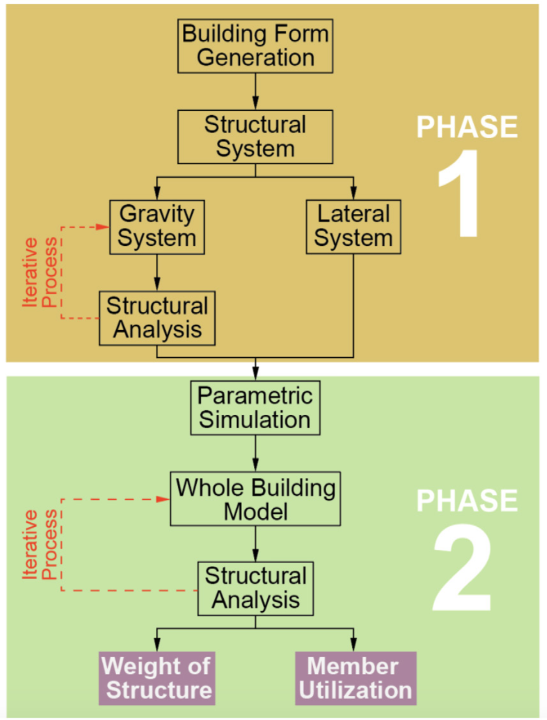


Figure 4: Schematic research workflow documenting the two phases. (Source: Author.)

PHASE 2 As the most crucial phase in the research, this phase is responsible for most simulations, including a whole building simulation where gravity and lateral load-resisting systems are combined and analyzed. The geometric information generated from Phase 1 simulates a combined structural model of selected building forms and structural systems. A structural analysis that incorporated the entire building structure, despite large quantities of structural members and longer computation times, was needed to holistically understand the material's behavior and performance of the structural systems.

Once again, Karamba3D was used as the primary tool to simulate the structural components, assign material and dimensional properties to individual structural elements, and simulate the applicable forces that included gravity, live, and wind loads. The native capabilities of Rhinoceros 3D allowed for visualizing results from structural analysis against the building geometry and helped understand the complex behavior of the structural systems.

Two results, the total weight of the structural system and internal forces in structural members were observed and documented from various simulations. While the weight of the structural systems serves as the prime indicator of its efficiency, the internal member forces provide opportunities for further analysis to calculate the utilization of material and stiffness contribution to document material efficiency. Figure 5 shows the schematic workflow for simulating the whole building system.

As part of this research, a regular square prismatic building form was selected for structural analysis. Analysis methods for such simple geometry are well established, and load application on the structural system is well defined in the available building design codes. After researching the material's structural properties and reviewing available literature on structural system analysis and the behavior under lateral loads, three different structural systems were selected as part of this study: 1) Braced Frame, 2) Diagrid System, and 3) Stressed Skin System. These structural systems transfer externally applied load with the help of

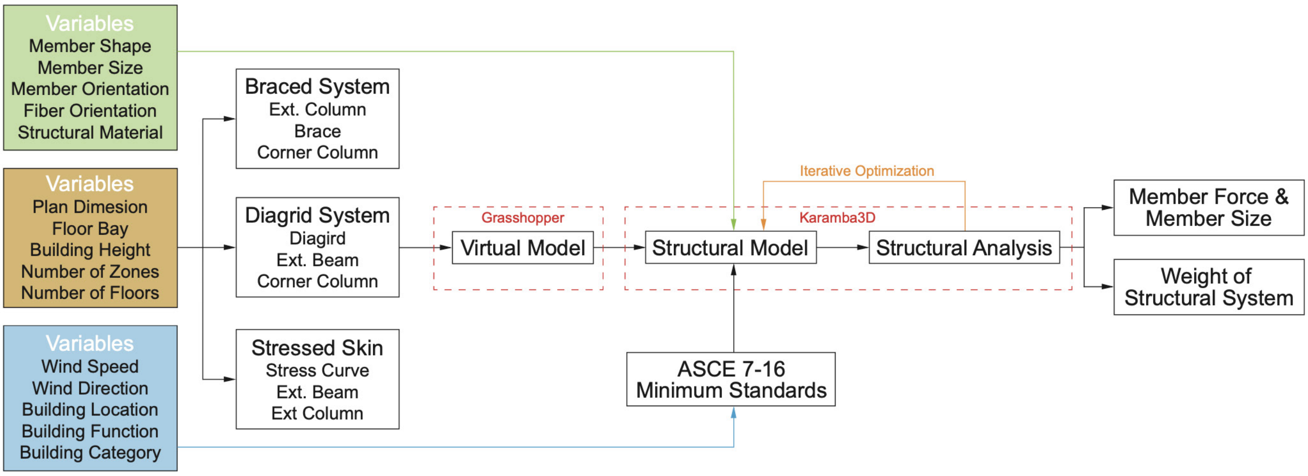
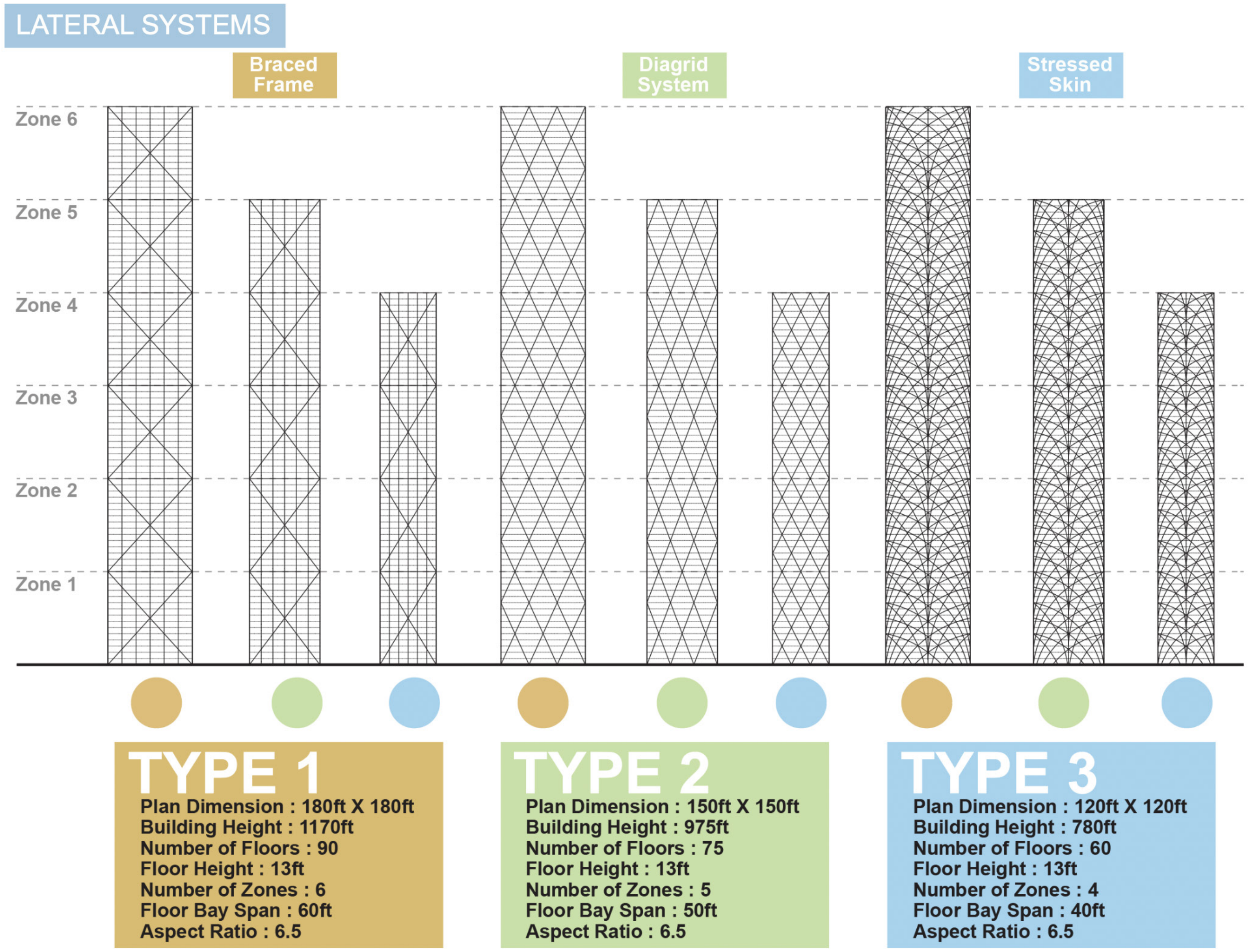


Figure 5: Schematic workflow for simulations of whole building structural system. (Source: Author.)



TYPE 1
Plan Dimension : 180ft X 180ft
Building Height : 1170ft
Number of Floors : 90
Floor Height : 13ft
Number of Zones : 6
Floor Bay Span : 60ft
Aspect Ratio : 6.5

TYPE 2
Plan Dimension : 150ft X 150ft
Building Height : 975ft
Number of Floors : 75
Floor Height : 13ft
Number of Zones : 5
Floor Bay Span : 50ft
Aspect Ratio : 6.5

TYPE 3
Plan Dimension : 120ft X 120ft
Building Height : 780ft
Number of Floors : 60
Floor Height : 13ft
Number of Zones : 4
Floor Bay Span : 40ft
Aspect Ratio : 6.5

Figure 6: Descriptions of the three types of lateral systems with three building heights for each system that were simulated and analyzed. (Source: Author.)

axially loaded members. While the first two are well-known, the stressed skin system mimics the stress flow pattern of a free-standing cantilever under lateral loads. Figure 6 shows the three structural systems studied in this research.

Results and Discussion

The discussion of simulations for structural systems is classified based on the system type. The results related to building weight, element utilization, and stiffness distribution for each system type were averaged across building heights to create graphical representations, called efficiency polygons, categorized by each element type. Figure 7 documents the results of the simulation studies.

BRACED FRAME SYSTEM The efficiency polygon indicated that, on average, 60 percent of the system weight and stiffness come from the exterior columns along the face of the building. Corner columns and braces account for almost 40 percent of stiffness distribution and 10 percent and 23 percent of system weight. While constituting 7 percent of system weight, interior columns do not offer any significant stiffness to the lateral system.

DIAGRID SYSTEM Regarding key performance indicators, the diagrid elements contribute to almost 80 percent of the stiffness and weight of the system, while the corner columns provide the remaining 20 percent of stiffness and 17 percent of weight. At the same time, the remaining system weight is attributed to the interior columns. Like the braced frame, the interior columns provide negligible stiffness to the system. The absence of corner columns results in lateral deflections beyond the acceptable limits, which increases the cross-section size of diagrid elements reducing the system efficiency.

STRESSED SKIN SYSTEM Almost 80 percent of the system weight comes from a combination of the stress curves, while the remaining 20 percent of weight is divided almost equally between the vertical elements of the system- corner columns, exterior columns, and interior columns. Corner columns contribute approximately 38 percent of system stiffness, while the stress curves contribute 23 percent each. The remaining stiffness contribution comes from the four exterior and interior columns. While almost equal stiffness distribution among the primary structural members may result in higher efficiency as the system height increases, the large number of structural members affects the system efficiency negatively at smaller building heights.

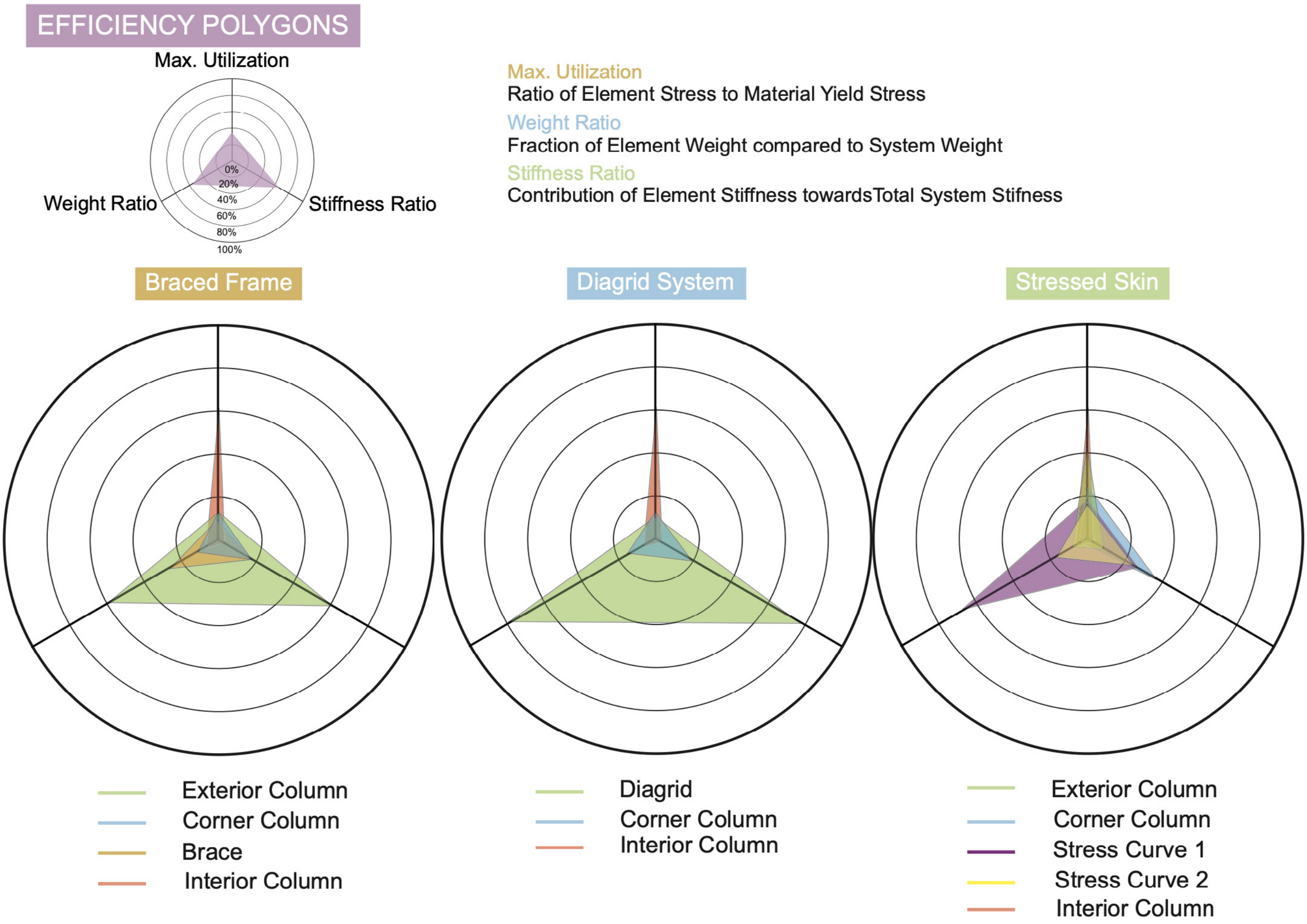


Figure 7: Results of the building simulations presented through the efficiency polygons. (Source: Author.)

The results clearly show that material utilization varies across system types and individual structural elements. This variation in member utilization presents a unique opportunity to substitute structural elements with low utilization and stiffness rates with bio-based composites or recycled composite members. The reduced stiffness and strength of bio-based composites make them the ideal candidate for use in secondary structural elements reducing the overall environmental impact of the structure. Bio-based composites are highly recyclable but suffer from degradation in strength and stiffness. Tertiary structural elements and non-structural components can be made with these recycled bio-composites where strength and stiffness criteria are less stringent. Figure 8 shows the potential material journey as part of a circular design strategy. Reusing and recycling bio-based composites in structural systems will reduce the carbon emissions and associated environmental impact of tall buildings.

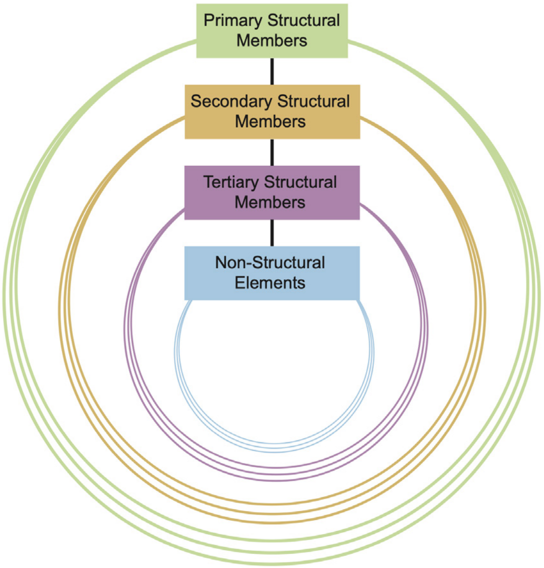


Figure 8: A schematic showing material journey of bio-based composites in the building industry. The decreasing diameter of circles represent reduced mechanical properties due to reuse and recycling. (Source: Author.)

Conclusion

Circular design is focused on creating a closed-loop system within the production and consumption cycle of products and materials. It focuses on designing products and materials to be reused, repaired, and recycled at the end of their lifecycle rather than discarded as waste. The circular design aims to create a “circular economy” where resources are used for as long as possible, and waste is minimized. Circular design can be seen as a tool or approach towards achieving regenerative design. It seeks to create closed-loop systems where waste is minimized and resources are used more sustainably. By designing products and materials for a circular economy, we can reduce the amount of waste generated and minimize the use of finite resources.

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