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Analysis of the Main Architectural and Structural Design Considerations in Tall Timber Buildings

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Abstract: Tall timber buildings represent an emerging and highly promising sector due to their potential to yield significant environmental and economic advantages throughout their entire life cycles. Nonetheless, the existing body of literature lacks a comprehensive exploration of the primary architectural and structural design considerations for such sustainable towers. To address this gap and to enhance our understanding of emerging global trends, this study scrutinized data from 49 tall timber building case studies from around the world. The key findings revealed the following: (1) Europe stood out as the region boasting the highest number of tall timber buildings, with North America and Australia following behind; (2) residential applications were the most preferred function for tall timber buildings; (3) central cores were the predominant choice for core configuration; (4) prismatic forms were the most prevalent design preferences; (5) composite materials were notably widespread, with timber and concrete combinations being the most prominent; (6) structural systems primarily featured shear–frame systems, especially shear-walled frames. By unveiling these contemporary characteristics of tall timber buildings, this research is expected to provide valuable insights to architects, aiding and guiding them in the design and execution of future sustainable projects in this field.

Keywords: timber; tall timber building; core planning; function; form; structural system; structural material

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1. Introduction

Given their efficient land utilization and high population density, tall structures have emerged as a potentially sustainable response to the challenges posed by rapid population expansion and urban sprawl [1,2]. Timber is recognized as an asset in combatting the climate crisis due to its environmentally friendly attributes, such as minimal carbon emissions during processing and carbon sequestration [3]. It is positioned as a key element in advancing European climate policy objectives [4,5].

Engineered wood products (EWPs) have seen an increasing application as structural materials in the pursuit of sustainable construction [6,7] as in the case of the 18-story and 85-meter-high Mjøstårnet in Brumunddal, Norway [8], and the 14-story and 48-meter-high Lighthouse Joensuu in Joensuu, Finland [9]. Mass timber products, a subset of EWPs, are typically fabricated by laminating smaller boards or lamella into larger structural components, boasting exceptional load-bearing capabilities that enable the construction of intricate timber structures [10]. The global production of mass timber panels is projected to more than double by 2025 when compared to the 2019 levels, which stood at 1.44 million m^3, according to [11].

Cross-laminated timber (CLT) constitutes the predominant share of this production capacity [12]. CLT is a prefabricated EWP that is crafted by bonding at least three layers of boards together using adhesive application under pressure [13]. In addition to CLT, the roster of EWPs utilized in construction encompasses laminated veneer lumber (LVL), formed by the bonding of thin vertical softwood veneers with their grain oriented parallel to the section's longitudinal axis using heat and pressure [14]. Glue-laminated timber (GLT), another EWP, is fashioned by adhering multiple graded timber laminations with their grain aligned parallel to the section's longitudinal axis [15], and parallel strand lumber (PSL) is produced by slicing long, slender strands from timber veneers [16]. Given that these figures can fluctuate based on the manufacturer, manufacturing process, specific product formulations, and the wood species used, the production pressures for CLT, LVL, and GLT are generally within the ranges of 0.7 to 3.5 MPa [17–19].

EWPs, such as CLT, are increasingly finding application in progressively more demanding contexts, responding to the imperative of sustainable construction [20]. This expansion owes its success to substantial global research and development efforts since its inception in the 1990s [21]. The numerous merits of CLT encompass its capacity for low carbon emissions, high thermal insulation, exceptional in-plane and out-of-plane strength, a favorable strength-to-weight ratio, and structural stability [22]. These attributes have facilitated the construction of large-scale and taller buildings [23]. Consequently, advancements in EWP manufacturing techniques and innovations in connection systems have played a pivotal role in elevating timber's structural performance to a level that can rival steel and concrete, enabling its application in towering structures [24].

Multi-story and tall timber structures constitute a nascent and highly promising sector [25]. Beyond their potential to generate significant environmental and economic benefits throughout their life cycles, these buildings possess the capacity to advance social sustainability across multiple stages of their existence. This includes fostering sustainability within the primary production and processing of materials, with a particular emphasis on their integral role within wood-based value chains. In essence, these buildings serve as catalysts for a more sustainable and interconnected bioeconomy, shaping a future where ecological, economic, and social considerations harmoniously coexist.

The design and implementation of tall timber buildings represent a culmination of advancements in materials science, structural engineering, and sustainable architecture [26]. Leveraging engineered wood products, such as CLT and GLT, these structures attain unprecedented heights while maintaining structural integrity. Computational tools, including finite element analysis and advanced modeling techniques, play a pivotal role in predicting and optimizing the complex behavior of tall timber buildings under various loads and environmental conditions. In-depth considerations for fire resistance, acoustic performance, and seismic resilience are crucial aspects of the design process, requiring sophisticated engineering solutions to meet stringent safety standards. Sustainable forestry practices, including responsible timber sourcing and afforestation initiatives, are fundamental to ensuring a renewable supply chain for these tall timber constructions. The implementation of tall timber buildings not only addresses the pressing need for urban densification but also aligns with global efforts to mitigate the environmental impact of the construction industry, offering a viable alternative to traditional high-rise structures with a significantly reduced carbon footprint. As a result, the integration of tall timber buildings into urban landscapes not only exemplifies the technical prowess of modern construction but also underscores a commitment to environmentally conscious and resilient urban development.

It is worth noting that designing and building large timber-framed buildings poses several scientific and engineering challenges rooted in the unique properties of wood as a construction material [27–29]. The difficulties arise from various factors such as:

(1) Material properties (anisotropy): Wood is an anisotropic material, meaning its mechanical properties vary along different directions. The variability in strength, stiffness, and other properties requires careful consideration in the design process to ensure structural integrity and load distribution.
(2) Structural considerations:
    (a) Size and scale: Large timber-framed buildings demand a meticulous understanding of structural dynamics and load-bearing capacities. Timber's limitations in terms of span length and load-carrying capabilities necessitate innovative engineering solutions to address the challenges posed by the scale of the structure.

   (b) Connection design: Joinery and connection details become critical in large timber structures. Properly designing connections to accommodate loads and allow for the natural movement of wood due to moisture changes is challenging, requiring advanced engineering techniques.

(3) Environmental factors:

   (a) Moisture and dimensional changes: Wood is hygroscopic and undergoes dimensional changes with variations in moisture content. Large timber structures are particularly susceptible to these changes, requiring comprehensive moisture management strategies to prevent warping, swelling, or shrinking that could compromise structural integrity.
   (b) Durability: Exposure to the elements and the potential for decay or insect infestation are critical considerations. Preserving the structural integrity of large tim-ber buildings requires effective measures to protect against environmental deg-radation over time.

(4) Regulatory compliance (building codes): Compliance with building codes and standards is essential for ensuring the safety and performance of structures. The codes may not always provide specific guidelines for large timber buildings, necessitating a thorough understanding of timber behavior and innovative design solutions to meet or exceed regulatory requirements.
(5) Fire safety concerns (combustibility): Timber is inherently combustible, and fire safety is a major concern. Designing large timber structures necessitates implementing fire-resistant treatments, developing effective evacuation strategies, and ensuring compliance with fire safety regulations.
(6) Cost and construction challenges:

   (a) Material costs: While timber is renewable, the cost of high-quality, large-section timber can be a limiting factor in the economic feasibility of large timber struc-tures.
   (b) Construction complexity: Building large timber structures often involves intricate construction processes, specialized equipment, and skilled labor. Coordinating these elements can be challenging, and construction complexity may in-crease the likelihood of errors if not managed carefully.

(7) Innovative design approaches (interdisciplinary collaboration): Successfully designing and building large timber-framed structures requires collaboration between architects, structural engineers, material scientists, and other professionals. An interdisciplinary approach is crucial to integrating diverse expertise and overcoming the challenges associated with large-scale timber construction.

Over the recent years, there has been a discernible upswing in the fervor for progressing toward the construction of mass timber buildings of increased height in the context of urban landscapes [30]. This growing interest is underpinned by a significant shift toward more sustainable and environmentally conscious architectural practices. Notably, numerous projects in this category display a composite/hybrid construction approach, characterized by the adept integration of diverse building materials [31]. This amalgamation of materials, which may encompass steel, concrete, and other elements, underscores a multifaceted strategy that combines the strength and versatility of various construction components to enhance the structural integrity and architectural potential of these increasingly vertical timber buildings. This development reflects a commitment to both eco-friendly urbanization and the pursuit of innovative solutions in contemporary construction.

The analysis of the main architectural and structural design considerations in tall timber buildings is a crucial research topic due to several key factors rooted in both environmental sustainability and structural engineering principles.

(1) Sustainability and environmental impact:

(a) Carbon sequestration: Timber is a renewable resource that has the ability to sequester carbon throughout its lifecycle. Tall timber buildings act as carbon sinks, storing carbon dioxide and mitigating the environmental impact of traditional construction materials like concrete and steel.
(b) Reduced embodied energy: Timber has lower embodied energy compared with traditional construction materials, contributing to a reduction in greenhouse gas emissions associated with building construction. Investigating design considerations ensures the optimal use of timber resources for sustainable construction.

(2) Renewable resource utilization:
(a) Timber as a renewable material: Timber is a renewable material that can be sourced sustainably. Analyzing design considerations allows for the efficient use of timber resources, promoting responsible forestry practices and minimizing environmental impact.
(b) Forest management practices: Research in this area can contribute to the development of guidelines for responsible forest management, ensuring that the sourcing of timber aligns with the principles of sustainability and biodiversity conservation.

(3) Structural performance and safety:
(a) Material strength and durability: Understanding the structural behavior of tall timber buildings is critical to ensure that the materials used possess the necessary strength and durability to meet safety standards and withstand environmental factors.
(b) Fire safety: Addressing concerns related to fire safety is crucial, as timber is combustible. Research in this area focuses on developing fire-resistant treatments and designing structures that adhere to stringent safety regulations.

(4) Innovation and advancements:
(a) Technological advancements: Investigating architectural and structural design considerations facilitates the exploration of innovative technologies and construction methods. This can lead to the development of new materials, construction techniques, and building systems that enhance the overall performance of tall timber structures.
(b) Multi-disciplinary collaboration: This research involves collaboration between architects, engineers, material scientists, and other experts, fostering a multidisciplinary approach to design. This collaboration is essential for developing holistic solutions that consider both aesthetic and structural aspects.

(5) Urban development and land use: Vertical urbanization: Tall timber buildings contribute to the vertical expansion of urban spaces, promoting sustainable urban development. Analyzing design considerations helps optimize land use and provides alternatives to traditional building materials, addressing the growing demand for urban infrastructure.

In conclusion, the analysis of the main architectural and structural design considerations in tall timber buildings is a vital research topic that aligns with the global imperative for sustainable construction practices, environmental responsibility, and the advancement of structural engineering knowledge. It offers a pathway to creating resilient, environmentally friendly, and aesthetically pleasing structures for the future.

The currently available literature does not provide a thorough examination of the main architectural and structural design factors concerning sustainable skyscrapers. To bridge this knowledge gap and improve our insight into the evolving worldwide patterns, this research analyzed information from 49 instances of tall timber building projects across the globe.

This study concentrated on three crucial elements with the objective of identifying the emerging trends in the construction of tall timber buildings. These facets encompassed general particulars (inclusive of building name, geographic location, height, number of stories, and completion date), architectural design elements (including function, core configuration, and form), and structural design elements (encompassing the structural system and the choice of structural materials), as seen in Appendix A. While it is acknowledged that social factors contribute to the enduring viability and sustainability of tall structures, as emphasized by [32], it is important to note that these aspects do not constitute the primary emphasis of this paper. This study exclusively focused on contemporary tall timber buildings and did not include an examination of historical tall timber buildings, such as those in China and Japan, which utilized a combination of masonry central cores and timber exceeding 50 m in height. In this research, the building terms "low-rise", "multi-story", "mid-rise", and "tall" are specified to refer to structures with one to two stories, more than two stories, three to eight stories, and more than eight stories, respectively.

By shedding light on the present characteristics of contemporary tall timber constructions, it is expected that this research will offer valuable insights to assist and guide architects in the conceptualization and implementation of future tall timber building projects.

The article's subsequent sections are structured as follows: Initially, a comprehensive examination of tall timber buildings in the existing literature is presented. Subsequently, this paper discusses the research materials and methods utilized. Following this, it presents the results derived from an in-depth analysis of 49 case study buildings. This is succeeded by a comprehensive discussion section with potential future studies and the research's limitations. Lastly, the conclusions are presented.

2. Literature Review

Due to the increasing interest in timber-based structural systems and significant progress in the construction industry, extensive research has been conducted to investigate the technological, ecological, social, and economic aspects of EWPs in various building applications [33–35]. However, there is a notable lack of research focusing on global trends and classifications related to architectural and structural design factors in tall timber constructions.

Fink et al. [36] adopted a collaborative and interdisciplinary approach in designing taller multi-story timber structures, considering various aspects such as statics, dynamics, fire resistance, acoustics, and human health concurrently, rather than in isolation. They emphasized the importance of interdisciplinary analysis and collaboration as crucial for formulating a comprehensive set of design guidelines. Tuure and Ilgın [37] examined spatial efficiency in 55 mid-rise timber residential buildings in Finland, revealing that square floor plans predominantly featured a central core, and the study sample exclusively used prismatic building forms with a shear wall system as the sole structural system.

Zahiri [38] investigated current trends in tall timber buildings in the Scandinavian region, highlighting preferences for prefabrication, modular building, technological innovations, tall timber structures, and environmentally sustainable designs. Ilgın et al. [39] analyzed data from 13 case studies of tall residential timber buildings, finding that central cores and prismatic shapes with straight-line layouts were favored architectural designs, pure timber construction was preferred over hybrid methods, and the shear wall system was the most frequently used structural system. González-Retamal et al. [40] conducted a comprehensive review of over 250 scholarly articles, categorizing advancements and limitations in multi-story wooden structures based on sustainability, design, and engineering sciences. Most papers focused on engineering disciplines, with 25% addressing sustainability and 5% addressing collaborative design aspects. Santana-Sosa and Kovacic [41] assessed existing protocols for timber constructions in Austria using 15 in-depth interviews, offering recommendations to promote wood utilization in multi-story structures. Their outcomes were categorized into planning and production, construction, and further subcategorized into hindrances and potential avenues. Svatoš-Ražnjević et al. [42] analyzed architectural variety and spatial potential in multi-story timber buildings, classifying design concepts based on load-bearing systems and materials using a dataset of 350 contemporary case studies. Žegarac Leskovar and Miroslav [43] scrutinized architectural and structural design strategies in European multi-story timber constructions from 2007 to 2021, identifying shifts in architectural design, especially in building exteriors, and a transition from solid panel systems to composite load-bearing systems. Salvadori [44,45] performed a comparative analysis of over 190 multi-story timber structures, focusing on structural classification in one study [44] and providing a more comprehensive examination of various building component materials and design aspects in the broader thesis [45]. Tupėnaitė et al. [46] conducted a comparative analysis of towering modern timber structures, revealing greater efficiency in economic and environmental dimensions for taller timber constructions attributed to advanced lightweight EWPs and prefabricated elements. Kuzmanovska et al. [47] comprehensively investigated emerging patterns in tall timber applications, covering structural, envelope, and architectural aspects in 46 multi-story structures. Their findings included a growing preference for post and beam structures with CLT slab floors and a decline in load-bearing external walls. Salvadori [48] examined 40 case studies of completed and proposed projects exceeding seven stories in height, comparing mass timber structures with concrete counterparts. The study highlighted public acceptance of wood as a significant challenge rather than a technological impediment. Smith et al. [49] identified the primary benefits of off-site solid timber production, including speed, adaptability to varying weather conditions, raw material utilization, and carbon emissions reduction. The drawbacks included considerations related to knowledge and labor, logistics, planning, acoustic properties, and vibration control. Perkins and Will [50] surveyed 10 case studies of timber buildings exceeding five stories, while Holt and Wardle [51] explored the market context and justification for utilizing timber in high-rise construction. Their results emphasized the viability of using timber in taller structures as a construction approach capable of substantially mitigating the adverse environmental impacts of buildings.

The literature review above indicates a consensus on key themes in tall timber structures. Interdisciplinary collaboration is consistently emphasized, with studies like Fink et al. [36] stressing its importance in considering various aspects simultaneously. Common design elements, such as central cores, prismatic shapes, and the shear wall system, are prevalent in tall timber buildings, as highlighted by multiple studies, including Tuure and Ilgın [37] and Ilgın et al. [39]. Pure timber construction is favored over hybrids, and sustainability trends like prefabrication and modular building are noted by Zahiri [38]. Challenges, including public acceptance and technological impediments, are identified by Salvadori [44], Smith et al. [49], and others. Overall, the literature converges on the importance of interdisciplinary collaboration, common design elements, structural preferences, and the environmental advantages of utilizing timber in tall buildings.

3. Materials and Methods

Case studies were used to gather, compile, and synthesize data pertaining to contemporary tall timber structures, enabling a comprehensive exploration and analysis of their architectural and structural aspects. The case study approach is commonly used in evaluations related to the built environment [52,53]. This study encompassed a total of 49 tall timber buildings completed or under construction ((all timber buildings 9-story and above listed on the Council on Tall Buildings and Urban Habitat (CTBUH)) [54], spanning diverse locations, including 28 from Europe (7 in Norway, 6 in Sweden, 4 in France, 3 in the Netherlands, 2 in Finland, 2 in Germany, 2 in Switzerland, 1 in Austria, and 1 in Italy), 8 from North America (5 in Canada and 3 in the United States) and 1 from Asia (Singapore) as well as 7 in Australia and 5 in UK, as seen in Appendix A.

In the realm of timber towers, decision-making is predominantly driven by architectural and structural necessities, along with the primary purpose of the building. These same characteristics also exert an influence on decision-making for a variety of other building categories. The key attributes are outlined as follows [37]:

Within the realm of architectural characteristics, the following factors play a significant role:

- The intended function of the building.
- Planning of the (service) core, which can affect the arrangement of vertical circulation and, in specific scenarios, the distribution of shafts.
- The building form can influence the dimensions and geometry of floor slabs.

Regarding structural attributes:

- Structural material preferences can affect the dimensions of the structural elements.
- The structural system can impact the layout and dimensions of the structural components.

Typically, when categorizing tall buildings based on their intended purpose, they are classified as either dedicated for single-use or mixed-use purposes. In the realm of tall building design, the primary functions often encompass hotel, residential, office, and educational spaces. Hence, in this paper, the analysis of functionality is predicated on the following configurations: (a) hotel, (b) residential, (c) office, (d) educational, and (e) mixed-use.

Furthermore, the core classification introduced by [55] is used due to its more expansive framework, which includes the following categories: (1) central core, (2) atrium core, (3) external core, and (4) peripheral core.

In this research, the classification of tall building forms is determined by the following configurations (Figure 1) [56]:

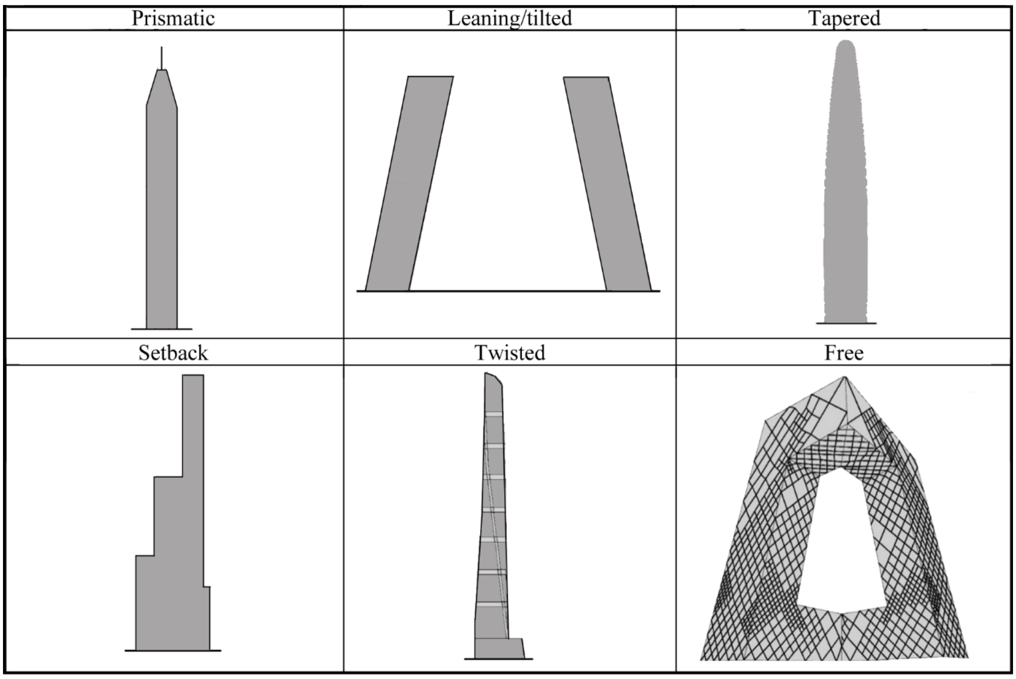


Figure 1. Tall building forms (figure by author).

(1) *Prismatic forms* pertain to buildings where both ends exhibit similarities, equality, and parallel geometrical figures, with identical sides and vertical axes, specifically perpendicular to the ground. This concept is exemplified in buildings like Mjøstårnet (Figure 2) and Lighthouse Joensuu (Figure 3).

Figure 2. Mjøstårnet: 18 stories and 85 m high. (photo by author).

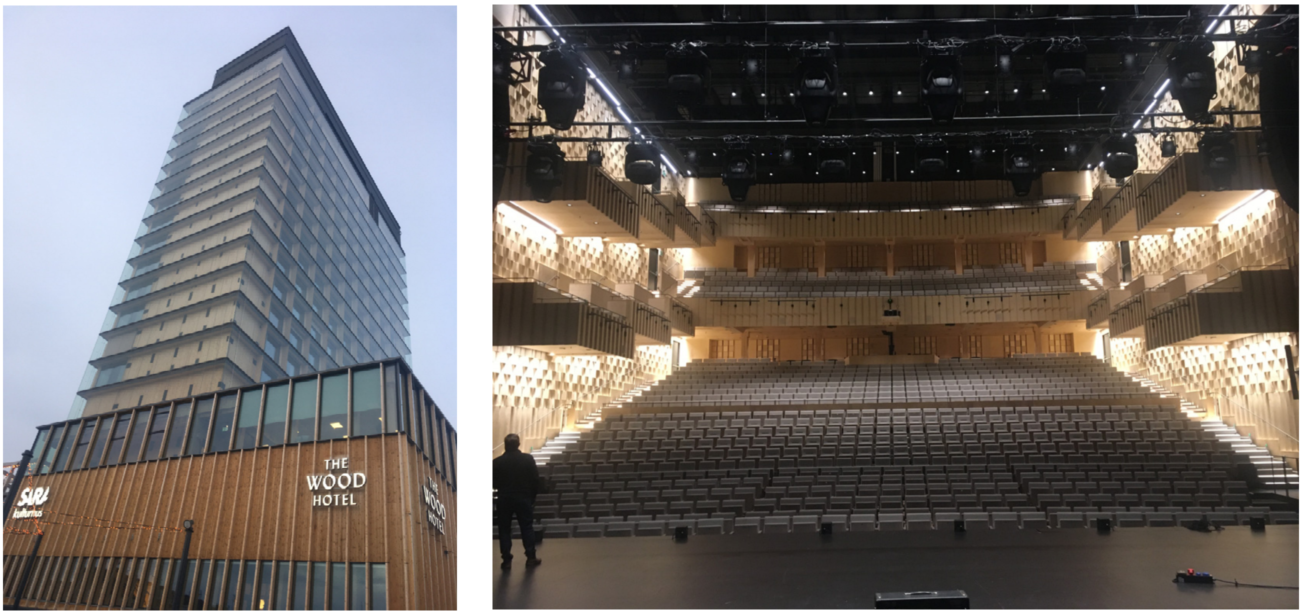
Figure 3. Lighthouse Joensuu: 14 stories and 48 m high (photo by author).

(2) *Leaning forms* describe buildings with an inclined architectural shape.
(3) *Tapered forms* are characteristic of buildings that exhibit a narrowing effect as they ascend, achieved by reducing floor plans and surface areas, resulting in either linear or non-linear profiles.
(4) *Setback forms* are observed in buildings featuring horizontally indented segments along the building's height. This characteristic can be seen in structures like *36–52 Wellington*.
(5) *Twisted forms* are indicative of buildings in which the floors or façade undergo gradual rotation as they extend upward along a central axis, incorporating a twist angle.
(6) *Free forms* pertain to buildings that do not adhere to the aforementioned configurations. This concept is exemplified in buildings like *HAUT* and *Hyperion*.

Structural materials can be categorized into two main groups: (1) "timber" or "all-timber" and (2) composite or hybrid, which encompass combinations like timber with concrete, timber with steel, or timber with concrete and steel. In this context, this paper is focused on primary load-bearing elements, which include columns, beams, shear trusses, and shear walls, with the exclusion of floor slabs. Additionally, it is important to note that the material composition of the load-bearing structures on the first floor does not modify the classification of the overall structural system.

According to this structural material classification, in more detail, for a structure to be classified as "timber", it is necessary that both its main vertical and lateral structural components are made entirely from timber [54]. It is worth noting that a "timber" structure can incorporate non-timber connections in specific areas between the timber elements. Even if a building is predominantly constructed from timber but features a floor system consisting of concrete planks or a concrete slab placed on top of timber beams, it remains categorized as a "timber" structure because the concrete elements do not serve as the primary load-bearing framework. An illustrative instance that is widely recognized is Mjøstårnet in Norway, as depicted in Figure 2.

On the other hand, in composite or hybrid sub-classification featuring timber, a significant portion of the vertical or lateral load-bearing system consists of materials other than timber, specifically steel, concrete, or a combination of both. For instance, in structures that combine timber and concrete, it is common to find a concrete core that supports a timber framework, as exemplified by HoHo in Vienna, Austria, standing at 84 m with 24 stories. Conversely, when it comes to structures combining timber and steel, a substantial portion of the vertical or lateral load-bearing system relies on steel. This often includes components like steel-framed cores, buckling-restrained braces, perimeter frames, or exoskeletons, as exemplified by Sara Kulturhus in Skellefteå, Sweden (Figure 4). Similarly, hybrid structures that incorporate timber, concrete, and steel use a combination of all three materials to bear primary loads. A typical configuration involves a concrete core working alongside steel beams and columns, while timber is used for flooring and partition walls. The tallest known building using concrete, steel, and timber in a hybrid manner is De Karel Doorman in Rotterdam, Netherlands, reaching a height of 71 m with 22 stories.



(**a**) (**b**)

Figure 4. Sara Kulturhus: (**a**) an exterior view and (**b**) an interior view (photos by author).

In the context of providing lateral support to tall buildings, specifically for addressing forces such as wind and seismic loads, various structural systems and classifications have been used in practical applications and have been a subject of discussion in the existing literature (for instance, [47]). In this study, the author opted to utilize the structural system classification presented by [57] due to its comprehensive nature (Figure 5):

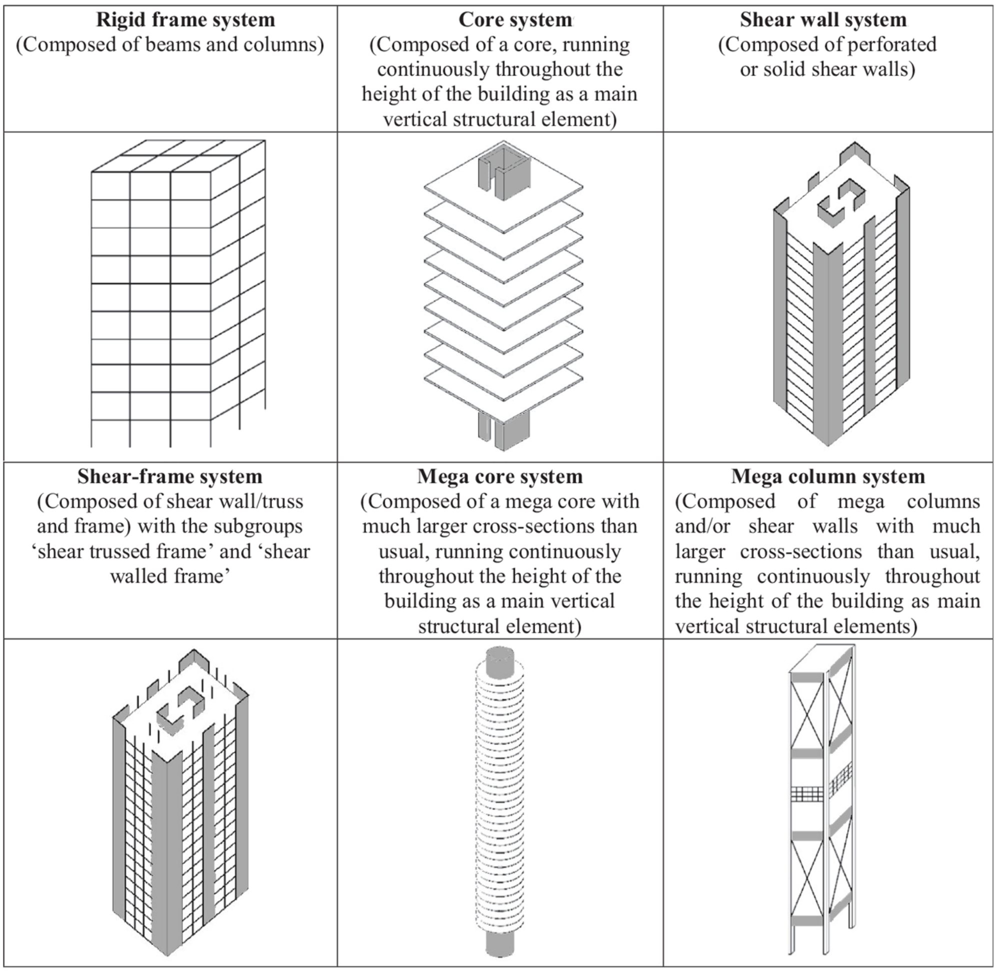


Figure 5. Tall building structural systems (figure by author).

It is also important to note that an outriggered frame, various tubular systems (including framed-tube, diagrid-framed-tube, trussed-tube, and bundled-tube systems), and buttressed-core systems are primarily used in supertall buildings exceeding 300 m in height, as they offer efficient and cost-effective solutions. Consequently, these structural systems were not considered for inclusion in this study, given its focus on tall buildings. Nevertheless, as demonstrated by Mjøstarnet (Figure 1) and Treet in Norway, there are limited instances of tall wooden structures that incorporate systems like tubular structures.

When it comes to defining tall buildings, there remains a lack of a universally accepted standard regarding their height or the number of stories, and even the characterization of "tall" in the context of timber constructions remains subject to debate. Smith and Frangi [58] proposed that tall timber buildings could be described as timber structures with approximately 10 to a maximum of 20 stories. On the other hand, the Wood Solutions Technical Design Guide [59] defines mass timber high-rises as buildings having an effective height of 25 m or more above ground level, or, in the absence of such data, structures exceeding 8 stories.

In the context of this research, a "tall timber building" is defined as a structure with more than 8 stories [39]. Additionally, this height criterion aligns with the current maximum allowable height for the "P2 class" solution for wooden construction in certain European countries, such as Finland, as specified in the National Building Code of Finland [60]. Historically, "fire" has played a pivotal role in the technical delineation of "building height", serving as a fundamental height limitation, especially in North America and various other regions [61].

While lightweight, timber-framed, multi-story housing of up to 4 or 5 stories is prevalent in many regions globally, this study exclusively addresses tall timber buildings, defined as those surpassing 8 stories, in which the primary load-bearing structure primarily comprises timber or (timber-based) composite/hybrid materials as described above. This category encompasses both post-and-beam construction (comprising rigid frame or shear-walled frame systems) and panelized or honeycomb construction (involving shear wall systems).

4. Results

Europe, taking on the role of an early innovator in the realm of mass timber technology, enjoys several advantages that position it as the preeminent global hub for the construction of tall timber structures. This preeminence can be attributed to a combination of factors. First, Europe is endowed with meticulously managed forests, ensuring a sustainable and reliable source of timber, which is a fundamental element for mass timber construction [62]. Moreover, the region boasts a comprehensive framework of stringent environmental regulations, emphasizing a commitment to eco-friendly building practices and resource conservation [63]. Given these conducive circumstances, it is hardly surprising that Europe commands a remarkable 56 percent share of the total within the context of tall timber buildings, a representation vividly illustrated in Figure 6. This dominant position underscores the region's status as a frontrunner in the global transition toward timber-based high-rise construction.

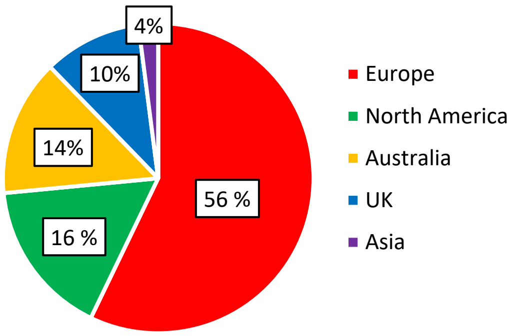


Figure 6. Tall timber buildings by location.

Within Europe, the Nordic nations, namely, Norway, Sweden, and Finland, have a strong historical affinity for wood-centered construction [64]. The tall timber structures in this region exemplify a distinctive regional character that draws from cultural heritage, design aesthetics, and a seamless integration with the surrounding natural landscape. Consequently, this region saw the construction of 15 tall timber buildings, representing over 50% of the total European inventory.

Next in line is North America, a region distinguished by its possession of the world's most extensively managed forests. North America also has a long-established tradition of wooden construction [65], although it is important to note that this tradition primarily pertains to traditional wood construction rather than the specialized category of mass timber. Nevertheless, these factors contribute to North America's representation at 16 percent within this context.

Similarly, Australia, accounting for 14 percent of the overall figure, boasts a notable presence in the realm of tall mass timber buildings, exemplified by renowned early projects such as Forte in Melbourne and 25 King in Brisbane. This achievement is particularly noteworthy when considering that Australia maintains a comparatively modest timber industry [66], relying on the transportation of most materials over vast distances from Europe, thousands of kilometers away.

Within the sample group, five tall timber towers located in the UK represent a proportion equivalent to 10 percent of the total buildings. While the UK has a rich history of timber-based construction techniques, the advent of mass timber technology has opened new horizons for tall timber structures. The UK's embrace of tall timber structures is indicative of a broader global shift toward timber as a viable and environmentally friendly alternative to traditional construction materials, contributing to the nation's ongoing efforts to address climate change and promote sustainable urban development, as in Europe [67].

In the dataset, Asia is positioned at the lower end with a mere count of only one building, Eunoia Junior College in Singapore. However, there is a strong anticipation that this figure will experience significant growth in the years to come. The region shows significant potential for expanding its collection of tall timber buildings, indicating a promising trend toward increased adoption of this construction methodology [68].

As seen above, tall timber buildings are experiencing widespread construction activity in various regions worldwide, with a pronounced surge in Europe, where demand and appreciation for them are on the rise. The following discussion provides an in-depth examination of the pivotal architectural and structural design factors that hold significant sway in the development of these structures.

4.1. Analysis of Architectural Design Considerations

This section provides an in-depth analysis of architectural design considerations for a total of 49 tall timber buildings, which are either completed or currently under construction. These considerations encompass:

- Function;
- Core planning;
- Building form.

Each of these three parameters is individually elaborated upon in the subsequent discussions.

4.1.1. Function

Figure 7 emphasizes a notable trend within the dataset comprising 49 tall timber buildings. It reveals that residential applications represent the predominant choice, constituting a substantial 65% of the total, with office usage following as the second most prevalent function, amounting to 19% of the overall distribution.

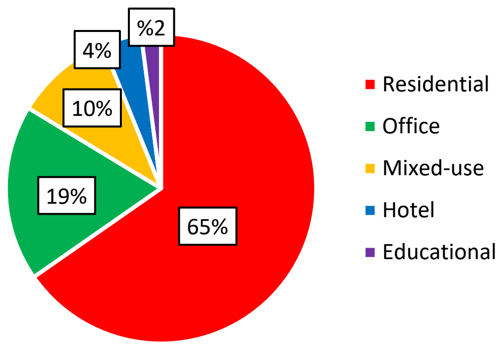


Figure 7. Tall timber buildings by function.

The dominance of residential use in tall timber towers can be justified based on several key factors: (a) Sustainability and environmental benefits: Timber is a renewable and sustainable building material, which aligns with global efforts to reduce carbon emissions and promote eco-friendly construction [69]. Residential use, with its relatively stable and long-term occupancy, maximizes the environmental benefits of using timber. (b) Psychological and health benefits: Studies have shown that exposure to wood and natural elements within residential spaces can have positive psychological and physiological effects on occupants [70]. Wood's warm and natural aesthetics create a comforting and stress-reducing environment, contributing to the overall well-being of residents. (c) Market demand and economic viability: Studies show a significant demand for residential spaces, especially in urban areas [71]. Tall wooden towers can economically meet this demand while aligning with sustainability goals, making them an attractive investment option.

On the other hand, tall timber building construction exhibits a reduced propensity for selecting hotels and educational facilities as their intended functions. This is indicative of a preference for alternative uses or purposes within the domain of tall timber structures, reflecting considerations related to architectural, operational, and regulatory factors that influence the choice of building function. Hotels and educational facilities have specific functional requirements that may not align well with the architectural and structural characteristics of tall wooden towers. Hotels, for example, require a high level of flexibility in interior design, larger common spaces, and specific infrastructure for accommodating guests [72], which may be more challenging to achieve in tall timber structures. Futhermore, hotels and educational buildings demand rigorous noise control measures, both within and between rooms or spaces [73,74].

4.1.2. Core Planning

Observing Figure 8, it becomes evident that the central core configuration, accounting for over 60% of cases, is the predominantly adopted core arrangement. It is trailed by the peripheral core arrangement, representing one-third of the samples, whereas external cores are infrequently used.

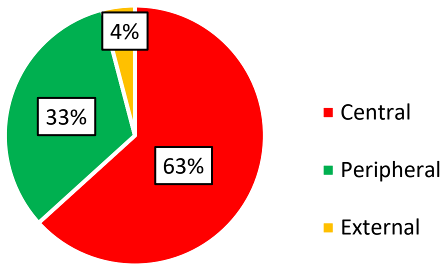


Figure 8. Tall timber buildings by core planning.

The benefits associated with a central core configuration are multifaceted and significantly influence its prevalent adoption [75]:

1. Structural integrity: A central core provides robust structural support to a tall timber building, enhancing its stability and load-bearing capacity. The core's central positioning ensures efficient load distribution and resists structural deformations, thereby contributing to the building's overall structural integrity and safety.
2. Compact design: Central cores are typically designed to occupy a minimal footprint within the building, allowing for more efficient use of the available space. This compact design maximizes the net usable floor area, making it an attractive choice for optimizing space within the structure.
3. Facilitation of open spaces: Central cores play a pivotal role in creating open and unobstructed spaces along the building's exterior façade. This arrangement enables an abundance of natural light to penetrate the interior and provides panoramic views, enhancing the overall quality of the living or working environment.
4. Enhanced fire safety: Central cores often serve as a key component of a building's fire safety strategy. Their location provides a centralized and controlled pathway for fire escape, facilitating safe evacuation in the event of an emergency. This enhanced fire safety feature is crucial for occupant well-being and compliance with safety regulations.

These combined advantages of structural stability, efficient use of space, promotion of open and well-lit environments, and improved fire safety measures may contribute to the central core configuration being the most preferred choice in tall timber building design.

Several of the structures within the sample group were characterized by rectangular floor plans. In scenarios where a building's dimensions are constrained, particularly when it assumes a narrow and rectangular shape, an architectural strategy involving the placement of the core near the outer edge of the structure emerges as a prominent practice. This strategic placement of the core serves the primary purpose of optimizing the overall efficiency of the floor plan, which justifies why peripheral core configurations are the second most preferred choice within this specific context. This approach ensures that the available interior space is maximally utilized, allowing for more flexibility in space allocation and usage, which can be especially beneficial in buildings with constrained dimensions.

Conversely, external core configurations present certain limitations [76] that are characterized by diminished efficiency in space utilization. This decline in efficiency arises from several factors, notably the introduction of longer circulation pathways within the building's layout. These extended pathways necessitate more time and effort for occupants to navigate the premises, potentially affecting the overall functionality and convenience of the space. Moreover, external core arrangements can introduce challenges related to fire safety, particularly in terms of escape distances. The extended distances required for fire evacuation routes may pose a higher degree of risk and difficulty for occupants during emergency situations, underscoring a notable drawback associated with such configurations.

4.1.3. Form

Following the morphological classification system for tall timber buildings, prismatic form, comprising 67% of cases, emerges as the prevailing design choice, with free forms constituting 31% of the total, as depicted in Figure 9.

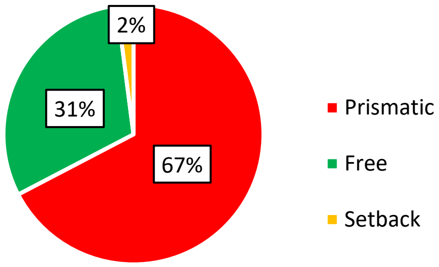


Figure 9. Tall timber buildings by building form.

The prevalence of prismatic forms as a prominent architectural choice can be elucidated through several favorable properties associated with this design approach. These attributes are instrumental in shaping the popularity of prismatic forms, particularly in tall timber building construction [37]:

1. Simpler construction: Prismatic forms are known for their straightforward and uncomplicated construction. Their geometric simplicity reduces the complexity of building processes, from structural design to material handling and assembly. This streamlined construction approach enhances efficiency and cost-effectiveness, making it an appealing choice for many projects.
2. Practicality: The practicality of prismatic forms is another key factor in their widespread adoption. These designs align well with conventional construction practices, which often results in lower labor and material costs. Moreover, the practicality of prismatic forms makes them suitable for a variety of building functions, enhancing their versatility.
3. Efficient space utilization: Prismatic forms, particularly when paired with rectangular floor plans, excel in terms of interior space utilization. The simple, orthogonal layouts of such designs maximize usable space, minimizing wasted areas and promoting a more efficient allocation of rooms, corridors, and amenities. This efficiency is of value in residential and office spaces where effective space utilization is crucial.
4. Cost-effectiveness: Prismatic forms, due to their simplicity and compatibility with standardized construction techniques, often translate into cost savings for developers and builders. The minimized complexity of the design reduces the likelihood of errors or delays during construction, further contributing to cost-effectiveness.

The increased prevalence of free forms within tall timber building design can be ascribed to architects' ardent pursuit of inventive and distinct architectural configurations. Architects, driven by a desire for creative expression and the establishment of iconic and visually striking structures, are increasingly drawn to the realm of free forms [77]. These forms, characterized by their departure from traditional rectilinear or prismatic geometries, provide a canvas for imaginative and pioneering architectural concepts.

4.2. Analysis of Structural Design Considerations

This section offers an examination of structural design aspects for the set of 49 tall timber buildings. These factors encompass:

- Structural material;
- Structural system.

4.2.1. Structural Material

Figure 10 highlights a significant prevalence of the composite approach (over 60%), with timber following, representing 39% of the dataset that encompasses 49 tall timber structures. The strategic incorporation of timber alongside these materials holds a crucial position in the pursuit of a multitude of substantial goals. These objectives encompass not only the mitigation of carbon emissions but also the augmentation of construction efficiency and the expeditious creation of vital housing solutions for a swiftly urbanizing global population. This synergy of materials serves as a cornerstone in addressing the pressing challenges of sustainability, resource utilization, and meeting the burgeoning housing demands of our ever-expanding urban communities.

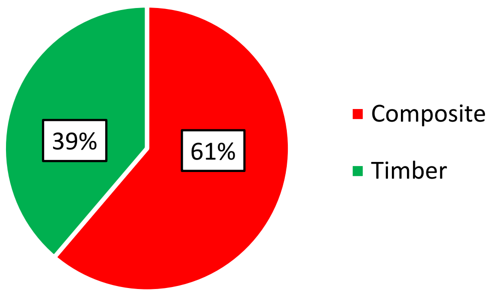


Figure 10. Tall timber buildings by structural material.

In the context of tall timber structures in Europe, a preference exists for utilizing timber rather than composite structures, as seen in Appendix B. Timber constructions across Europe can be attributed, in part, to factors such as the proximity of timber forests to construction sites [78], a commitment to environmental goals centered around reducing carbon footprints [79], or a concentration of projects that fall within the lower height range considered in this study.

Figure 11 presents composite structures categorized by the combination of structural materials. Notably, timber combined with concrete stands out as the most prominent choice, accounting for over 75% of the cases, followed by timber combined with both concrete and steel, representing 17%. Timber combined with steel is the least common, being observed in only two instances.

In composite structures, the decision to use concrete in the core can be attributed to several factors: firstly, it enhances the overall lateral stiffness and strength of the structure; secondly, it leverages concrete's innate fire resistance; and thirdly, it takes advantage of concrete's superior ability to dampen wind-induced swaying, a common challenge encountered in tall buildings [80].

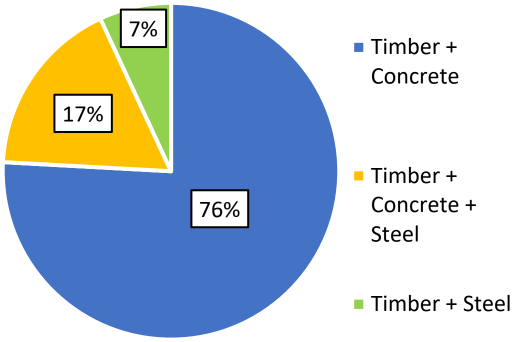


Figure 11. Composite tall timber buildings by structural material combination.

As notable instances of timber and concrete composite construction, both in HoHo [81] and HAUT [82], reinforced concrete core plays a crucial role in enhancing their lateral stiffness. Furthermore, it was observed that the inclusion of concrete cores in the design, as exemplified in the case of Brock Commons Tallwood House, streamlined the process of project approval [83]. This expeditious regulatory approval can be attributed to the fact that concrete cores are commonly featured in conventional high-rise buildings, regardless of the materials used. Notably, in this specific case study, the fire escape stairs were positioned within the concrete cores, ensuring their non-combustible construction.

It is important to emphasize that in taller buildings, the management of building sway poses a significant challenge that impacts both structural safety and the building's usability [84]. This challenge is applicable across different building materials. Controlling building sway is a crucial task for designers to ensure the comfort of building occupants, especially during turbulent weather conditions like windstorms. Maintaining building sway within acceptable limits is essential, particularly for reducing the discomfort experienced by occupants on the uppermost floors.

Furthermore, modern tall buildings, including tall timber towers, tend to be lighter than their predecessors [85]. Consequently, they exhibit increased susceptibility to lateral drift due to low damping, making wind-induced building sway a prominent concern in their design. In this context, the use of concrete can be advantageous as it provides the necessary mass to counteract wind loads in tall timber towers. For example, in Mjøstårnet, the top six floors incorporate 300 mm thick concrete slabs to augment the structure's self-weight, thus meeting the necessary serviceability standards [86].

The use of timber and steel hybrid structures can, in part, be attributed to the adaptability and effectiveness of steel in the face of seismic challenges [87], particularly in regions with robust timber industries like the Pacific Northwest in the United States and British Columbia in Canada [88]. Timber and steel hybrid structures leverage the benefits of both timber, including its low density and ease of construction, and steel, known for its high ductility and capacity to dissipate energy [89]. Timber typically exhibits brittle failure characteristics [90], limiting its ability to absorb seismic energy, while steel possesses a high ductility capacity. The synergy of these two materials enables an effective response to seismic forces, resulting in the desired structural performance during earthquakes.

It is important to highlight that in the case studies, the ground floor was constructed using reinforced concrete, often referred to as a concrete podium. Utilizing a concrete podium structure offers several advantages [91], including the integration of amenities and services at ground level, the creation of spacious and well-lit public areas with large openings, and the establishment of fire-resistant zones for accommodating extensive mechanical and electrical services and equipment [92].

4.2.2. Structural Systems

As illustrated in Figure 12, shear-frame systems (with the subgroups of "shear walled frame" and "shear trussed frame" as depicted in Figure 5) are the dominant preference, with a utilization rate of 69%, followed by the tube system, which constitutes 25%. It is worth noting that among shear–frame systems, the dominant choice in the case study samples was shear-walled frame systems, accounting for 94% of the towers. The shear wall system exhibits the lowest adoption rate among structural systems for tall timber buildings.

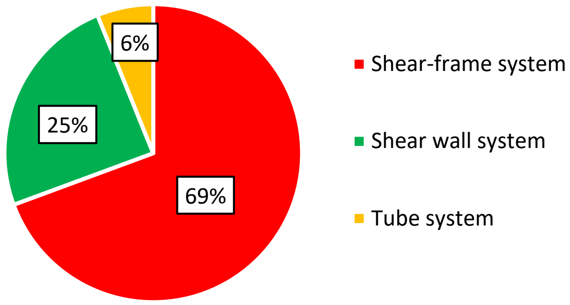


Figure 12. Tall timber buildings by structural system.

In shear–frame systems, which encompass shear-trussed frame and shear-walled frame systems, the drawbacks of a rigid frame in comparison with a shear truss or wall, as well as the limitations of a shear truss or wall when contrasted with a rigid frame, are mutually mitigated when these elements are used in conjunction [93]. In such scenarios, the frame augments the shear truss or wall in the upper levels, whereas the shear truss or wall enhances the performance of the frame in the lower levels. Consequently, shear–frame systems demonstrate highly effective resilience against lateral forces, endowing the structure with greater rigidity than if it were solely comprised of a "shear wall" or a "rigid frame" system, as observed in cases like Ascent, the world's tallest timber building, and HoHo [94]. This characteristic could serve as an explanation for the prevalence of shear–frame systems.

The intrinsic cantilever behavior exhibited by shear wall systems leads to a notable increase in the inter-story drift—the horizontal displacement between adjacent floors—in the upper levels when contrasted with the lower levels [95]. This occurrence remains consistent regardless of the specific building materials used in construction. This observed phenomenon can be considered a significant underlying reason behind the infrequent utilization of shear wall systems in the construction of tall timber towers.

In addition to its structural efficiency, the utilization of tube systems offers several advantages [96], including an expansion of the net usable area within the building while concurrently diminishing the dimensions of the structural elements situated in the core. This is made possible by the presence of an outer tubular frame that bears the entire lateral load. This rationale could elucidate the preference for using tube systems in the construction of tall timber towers.

Furthermore, the introduction of braces on the exterior of a framed-tube system brings it closer to achieving a nearly pure tubular cantilever behavior, resulting in heightened structural stiffness and effectiveness, along with a reduction in the adverse impact of "shear lag" caused by the flexibility of the spandrel beams [97]. In contrast, the trussed-tube system permits an increase in the structure's height by allowing for wider column spacing, as exemplified by the cases of Mjøstårnet and Treet.

5. Discussion

The main objective of this research is to methodically collect and combine extensive data pertaining to 49 modern tall timber buildings. This study primarily centers on the architectural and structural aspects of these buildings. The goal is to enhance our comprehension of the complexities inherent in the design and construction of tall structures, thereby making a valuable contribution to the existing body of knowledge in this field.

The outcomes presented in this paper reveal both commonalities and distinctions when compared with prior investigations, including the research conducted by, e.g., [37,98]. The key findings derived from this study can be succinctly summarized as follows:

(1) Europe was prominently recognized as the region with the greatest concentration of tall timber buildings, with North America and Australia following in succession.
(2) In terms of function, residential applications were the most frequently selected.
(3) Central core was the prevailing choice for core configuration.
(4) Prismatic form stood out as the predominant design preference.
(5) There was a notable prevalence of composite materials observed. Among composite construction, the combination of timber and concrete emerged as the most prominent choice.
(6) Shear–frame systems, especially shear-walled frame systems, were mostly used in structural systems.

In the realm of vertical architecture, a consistent pattern emerges as tall structures reach skyward amidst wooden towers or non-timber skyscrapers. The preference for central cores is prominently evident, as underscored by research conducted on various building typologies. In the context of mid-rise timber apartment buildings in Finland, a distinct inclination toward square-shaped floor layouts was found to favor the central core space, emphasizing the efficiency and functional optimization of such configurations [37]. Extending beyond timber constructions to encompass tall and supertall buildings made from non-timber materials, a prevailing trend toward central core dominance emerged, as highlighted by a series of studies [99–101]. This pattern is further corroborated by Oldfield and Doherty's comprehensive examination, wherein an overwhelming 85% of tall buildings constructed from non-timber materials featured central core configurations [73]. These findings collectively illuminate a widespread architectural inclination toward central core design, transcending material boundaries and underscoring its integral role in shaping the spatial efficiency and organizational dynamics of towering structures.

In the realm of tall timber buildings, a recurrent design trend manifests in the widespread adoption of prismatic shapes characterized by rectilinear layouts and consistent extrusions. This architectural preference is substantiated by Tuure and Ilgın's research, where an extensive observation of 55 mid-rise wooden residential buildings revealed a prevalent use of such straightforward configurations [37]. This inclination toward prismatic shapes extends beyond timber constructions, as evidenced by the comprehensive findings presented by Kuzmanovska et al. [47], which underscore the predominance of prismatic forms in multi-story structures. Building upon this trend, a study examining 93 supertall non-timber residential buildings, as documented by [98], revealed that prismatic shapes constituted the majority, accounting for over 44% of the studied structures. Moreover, in the realm of contemporary supertall residential buildings primarily constructed with reinforced concrete, the prevalence of prismatic forms remains noteworthy, as highlighted by [100]. This collective body of research underscores the enduring appeal and widespread adoption of prismatic shapes, transcending construction materials and reflecting a prevailing design ethos in the realm of tall and supertall structures.

A notable trend in contemporary construction lies in the substantial integration of composite materials, with the amalgamation of timber and concrete emerging as the predominant choice in composite construction. This strategic combination not only underscores the versatility of composite materials but also capitalizes on the unique strengths of both timber and concrete, resulting in structures that exhibit a harmonious blend of sustainability, durability, and structural integrity. The prevalence of composite construction extends its reach into the domain of supertall building projects, as elucidated by [98]. The widespread adoption of composite materials in these ambitious undertakings is attributed to the manifold benefits they confer, including enhanced load-bearing capacity, seismic resilience, and the efficient utilization of each material's distinct properties. This indicates a paradigm shift in modern construction practices, where the synergy of timber and concrete in composite construction emerges as a key driver in achieving structural innovation, durability, and sustainability in the evolving landscape of tall and supertall buildings.

Within the domain of structural systems for timber buildings, a discernible hierarchy has materialized, shaped by the variable of building height. Tall timber structures, in particular, have seen the ascendancy of shear-walled frame systems, emerging as the predominant and preferred choice. This predilection is underscored by the system's ability to efficiently distribute lateral forces and ensure stability in the face of height-induced challenges. Conversely, for mid-rise timber edifices, a prevailing inclination toward shear wall systems has been noted, setting them apart from their taller counterparts and reflecting a nuanced response to the structural demands associated with moderate building heights [37]. However, in the context of constructing supertall buildings, a paradigm shift occurs, with outriggered frame systems assuming a commonplace role. This distinctive trend signifies a deliberate departure from conventional choices, highlighting the unique structural considerations that come into play when engineering exceptionally tall structures [102,103].

The study's available empirical data are restricted to buildings that are both completed and under construction and are over eight stories tall. Due to the limited number of tall timber buildings in the world, further categorization with 49 specific tall timber buildings is not possible, as this could lead to biased results. However, given the significant rise in the number of buildings within this study's scope over the past decades, there may be a more substantial pool of buildings for sub-categories in the future. Additionally, future studies could encompass timber buildings below nine stories to include a broader range of lower-height structures in the sample set.

Potential future studies could include: (1) Conducting a thorough economic analysis to assess the cost-effectiveness of tall timber buildings compared with traditional materials like steel and reinforced concrete. Considering factors such as initial construction costs, maintenance expenses, and long-term financial benefits. (2) Investigating the adaptability of tall timber buildings for future uses. Assessing the potential for renovating and repurposing existing tall timber structures and exploring the design considerations and structural modifications needed for such adaptive reuse projects. (3) Studying the energy performance of tall timber buildings, focusing on heating, cooling, and insulation properties. Evaluating the effectiveness of different insulation materials, window designs, and HVAC systems in tall timber buildings to optimize energy efficiency. (4) Exploring how the use of timber in tall building construction impacts the cultural and social aspects of urban environments. Studying public perceptions, community acceptance, and potential psychological and aesthetic benefits of timber structures. (5) Expanding the dataset of tall timber building case studies to include a broader geographic and temporal scope. Analyzing how design considerations and structural choices may vary in different regions and cultures, considering local resources, traditions, and regulations.

6. Conclusions

This research significantly contributes to the existing knowledge of tall timber buildings, presenting a comprehensive analysis of 49 case studies from around the world. This study sheds light on various architectural and structural design considerations, revealing noteworthy trends that shape the emerging sector of sustainable architecture. Notably, the prevalence of tall timber structures in Europe, their primary utilization in residential applications, and the prominence of central cores and prismatic forms in design are key findings. Additionally, the widespread use of timber composite materials, particularly timber and concrete combinations, underscores the multifaceted nature of sustainable tall timber buildings.

This research further highlights the revelation that shear–frame systems, specifically shear-walled frames, dominate as the preferred structural choice. This insight adds a critical dimension to our understanding of the engineering principles used in environmentally friendly towers. By encapsulating these contemporary characteristics, this study serves as a pivotal resource for architects, providing valuable insights to inform and guide the design and implementation of future sustainable projects in the realm of tall timber buildings. Consequently, this research lays the groundwork for future advancements in sustainable architecture, fostering continued innovation and progress in this promising field.

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Data Availability Statement: The data presented in this study are available in this article.

Conflicts of Interest: The author declares no conflicts of interest.

Appendix A

Table A1. Tall Timber Buildings.

#	Building Name	Country	City	Height (Meters)	# of Stories	Completion Date	Function
1	Ascent	United States	Milwaukee	87	25	2022	R
2	Mjøstårnet	Norway	Brumunddal	85	18	2019	M
3	HoHo	Austria	Vienna	84	24	2020	M
4	HAUT	Netherlands	Amsterdam	73	22	2022	R
5	Sara Kulturhus	Sweden	Skellefteå	73	19	2021	H
6	De Karel Doorman	Netherlands	Rotterdam	71	22	2012	R
7	55 Southbank	Australia	Melbourne	70	19	2020	M
8	Roots Tower	Germany	Hamburg	65	19	UC	R
9	36-52 Wellington	Australia	Melbourne	63	15	UC	O
10	Abro	Switzerland	Risch-Rotkreuz	60	15	2019	O
11	Kaj16	Sweden	Göteborg	60	15	UC	M
12	Brock Commons Tallwood House	Canada	Vancouver	58	18	2017	R
13	Eunoia Junior College	Singapore	Singapore	56	12	2019	E
14	Hyperion	France	Bordeaux	55	16	2021	R
15	Rundeskogen Hus B	Norway	Sandnes	55	16	2013	R
16	Albizzia	France	Lyon	53	17	UC	M
17	Ngytan Koriayo	Australia	Greater Geelong	52	12	UC	O
18	503 on Tenth	United States	Portland	50	10	2023	O
19	Treet	Norway	Bergen	49	14	2015	R
20	Lighthouse Joensuu	Finland	Joensuu	48	14	2019	R
21	25 King	Australia	Brisbane	47	10	2018	O
22	2150 Keith Drive	Canada	Vancouver	45	10	UC	O
23	Cederhusen	Sweden	Stockholm	44	13	UC	R
24	Hoas Tuuliniitty	Finland	Espoo	44	13	2021	R
25	Palazzo Nice Meridia	France	Nice	44	10	2019	O
26	T3 Bayside	Canada	Toronto	42	10	UC	O
27	Tallwood 1 at District 56	Canada	Victoria	42	12	UC	R
28	Origine	Canada	Quebec	41	13	2017	R
29	INTRO Residential Tower	United States	Cleveland	40	9	2022	R
30	Monterey	Australia	Brisbane	39	12	2021	R
31	Sensations	France	Strasbourg	38	11	2019	R

Table A1. *Cont.*

#	Building Name	Country	City	Height (Meters)	# of Stories	Completion Date	Function
32	Rundeskogen Hus C	Norway	Sandnes	38	11	2013	R
33	Trafalgar Place	UK	London	36	10	2015	R
34	Aveo Bella Vista	Australia	Sydney	36	11	2018	R
35	Suurstoffi 22	Switzerland	Risch-Rotkreuz	36	10	2018	O
36	Kringsja Studentby	Norway	Oslo	34	10	2018	R
37	Hotel Jakarta	Netherlands	Amsterdam	34	9	2018	H
38	Rundeskogen Hus A	Norway	Sandnes	34	10	2012	R
39	SKAIO	Germany	Heilbronn	34	10	2019	R
40	Dalston Works	UK	London	34	10	2017	R
41	The Cube Building	UK	London	33	10	2015	R
42	Forte	Australia	Melbourne	32	10	2012	R
43	Botanikern	Sweden	Uppsala	31	9	2019	R
44	Cenni di Cambiamento	Italy	Milan	31	9	2013	R
45	Kajstaden	Sweden	Vasteras	31	9	2019	R
46	Press House	UK	London	31	9	2017	R
47	Vallen	Sweden	Vaxjo	31	9	2015	R
48	Stadthaus	UK	London	29	9	2009	R
49	Moholt 50/50	Norway	Trondheim	28	9	2016	R

Note on abbreviations: "M" indicates mixed-use; "H" indicates hotel use; "R" indicates residential use; "O" indicates office use; "E" indicates educational use; "UK" indicates United Kingdom; "UC" indicates under construction.

Appendix B

Table A2. Tall Timber Buildings by Core Type, Building Form, Structural System, and Structural Material.

#	Building Name	Building Form	Core Type	Structural System	Structural Material
1	Ascent	Prismatic	Central	Shear-walled frame	Composite (T + C)
2	Mjøstårnet	Prismatic	Peripheral	Trussed tube	Timber
3	HoHo	Prismatic	Central	Shear-walled frame	Composite (T + C)
4	HAUT	Free	Peripheral	Shear-walled frame	Composite (T + C)
5	Sara Kulturhus	Prismatic	Peripheral	Shear-walled frame	Composite (T + S)
6	De Karel Doorman	Prismatic	Peripheral	Shear-walled frame	Composite (T + C + S)
7	55 Southbank	Free	Peripheral	Shear-walled frame	Composite (T + C + S)
8	Roots Tower	Prismatic	Central	Shear-walled frame	Composite (T + C)
9	36-52 Wellington	Setback	Central	Shear-walled frame	Composite (T + C)
10	Abro	Prismatic	Central	Shear-walled frame	Composite (T + C)
11	Kaj16	Free	Central	Shear-walled frame	Composite (T + C)
12	Brock Commons Tallwood House	Prismatic	Peripheral	Shear-walled frame	Composite (T + C)

Table A2. *Cont.*

#	Building Name	Building Form	Core Type	Structural System	Structural Material
13	Eunoia Junior College	Free	Central	Shear-walled frame	Composite (T + C)
14	Hyperion	Free	Central	Shear-walled frame	Composite (T + C + S)
15	Rundeskogen Hus B	Free	Central	Shear-walled frame	Composite (T + C)
16	Albizzia	Prismatic	Central	Shear-walled frame	Composite (T + C)
17	Ngytan Koriayo	Prismatic	External	Shear-walled frame	Composite (T + C)
18	503 on Tenth	Prismatic	Central	Shear-walled frame	Timber
19	Treet	Prismatic	Peripheral	Trussed-tube	Timber
20	Lighthouse Joensuu	Prismatic	Central	Shear wall	Timber
21	25 King	Prismatic	External	Shear-trussed frame	Timber
22	2150 Keith Drive	Free	Peripheral	Framed tube	Composite (T + C)
23	Cederhusen	Prismatic	Central	Shear wall	Timber
24	Hoas Tuuliniitty	Prismatic	Peripheral	Shear wall	Timber
25	Palazzo Nice Meridia	Prismatic	Peripheral	Shear-walled frame	Composite (T + C)
26	T3 Bayside	Prismatic	Central	Shear-walled frame	Timber
27	Tallwood 1 at District 56	Prismatic	Central	Shear-trussed frame	Composite (T + S)
28	Origine	Free	Central	Shear wall	Timber
29	INTRO Residential Tower	Prismatic	Peripheral	Shear-walled frame	Composite (T + C)
30	Monterey	Free	Peripheral	Shear-walled frame	Composite (T + C + S)
31	Sensations	Free	Central	Shear-walled frame	Timber
32	Rundeskogen Hus C	Free	Central	Shear-walled frame	Composite (T + C)
33	Trafalgar Place	Prismatic	Peripheral	Shear wall	Timber
34	Aveo Bella Vista	Free	Central	Shear-walled frame	Composite (T + C)
35	Suurstoffi 22	Prismatic	Central	Shear-walled frame	Composite (T + C)
36	Kringsja Studentby	Prismatic	Central	Shear-walled frame	Timber
37	Hotel Jakarta	Prismatic	Peripheral	Shear-walled frame	Composite (T + C)
38	Rundeskogen Hus A	Free	Central	Shear-walled frame	Composite (T + C)
39	SKAIO	Prismatic	Central	Shear-walled frame	Composite (T + C)
40	Dalston Works	Prismatic	Central	Shear wall	Timber
41	The Cube Building	Free	Central	Shear-walled frame	Composite (T + C + S)
42	Forte	Prismatic	Central	Shear wall	Timber
43	Botanikern	Prismatic	Peripheral	Shear frame	Timber
44	Cenni di Cambiamento	Free	Central	Shear wall	Timber
45	Kajstaden	Prismatic	Peripheral	Shear wall	Timber
46	Press House	Prismatic	Central	Shear-walled frame	Timber
47	Vallen	Prismatic	Central	Shear-walled frame	Composite (T + C)
48	Stadthaus	Prismatic	Central	Shear wall	Timber
49	Moholt 50/50	Prismatic	Central	Shear wall	Timber

Note on abbreviations: "(T + C + S)" indicates composite/hybrid structures combining timber and concrete and steel; "(T + C)" indicates composite/hybrid structures combining timber and concrete; and "(T + S)" indicates composite/hybrid structures combining timber and steel.

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