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High-Rise Residential Timber Buildings: Emerging Architectural and Structural Design Trends

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Abstract: High-rise residential timber buildings (≥8 stories) are an emerging and promising domain, primarily owing to their capacity to deliver notable environmental and economic benefits over the entire span of their existence. However, it is worth noting that the current body of scholarly work falls short in providing a thorough examination of the key aspects related to architectural and structural design for these environmentally sustainable towers. In an effort to bridge this knowledge gap and deepen our comprehension of the evolving worldwide trends, this research delved into data collected from 55 case studies conducted across the globe. The primary findings unveiled the following: (1) Europe, particularly Nordic countries, stood out as the region boasting the highest number of high-rise residential timber buildings, with North America and the United Kingdom following suit; (2) central cores were the prevailing choice for the core configuration, with the peripheral type following as the second most common option; (3) prismatic forms were the most commonly favored design choices; (4) widespread prevalence of employing pure timber was observed, followed by timber and concrete composite combinations; and (5) structural systems were predominantly characterized by the utilization of shear walled frame and shear wall systems. This research aims to reveal the current attributes of high-rise residential timber buildings, with the expectation that it will offer architects valuable knowledge to assist and steer them in planning and implementing forthcoming sustainable projects within this domain.

Keywords: timber/wood; high-rise; residential; high-rise residential timber building; core planning; form; structural system; structural material

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Citation: Ilgın, H.E. High-Rise Residential Timber Buildings: Emerging Architectural and Structural Design Trends. *Buildings* **2024**, *14*, 25. https://doi.org/10.3390/buildings14010025

Academic Editor: Thomas Tannert

Received: 15 November 2023
Revised: 16 December 2023
Accepted: 20 December 2023
Published: 21 December 2023

1. Introduction

As per targeted projections, it is expected that more than 66% of the world's population will choose urban habitats as their place of residence by the year 2050 [1]. This notable shift toward urban living underscores the practicality of erecting tall structures within these metropolitan zones. In the context of this accelerating urbanization trend, the construction of high-rise buildings emerges as a highly pragmatic response to accommodate the increasing population [2].

In recent years, the construction industry has witnessed a notable resurgence of interest in timber as a primary building material [3]. This resurgence can be primarily attributed to the advent of advanced engineered timber products [4], including but not limited to glued laminated timber (glulam), laminated veneer lumber (LVL), and cross-laminated timber (CLT). These sophisticated timber materials have revolutionized the construction landscape by rendering timber, a renewable and abundant natural resource, a feasible choice for erecting high-rise structures [5] as in the cases of the 87 m high Ascent in Milwaukee in the United States (Figure 1) and the 48 m high Lighthouse Joensuu in Joensuu, Finland (Figure 2). Traditionally, such construction endeavors were predominantly the domain of steel and reinforced concrete.

Figure 1. Ascent (image courtesy of Jason Korb, Korb + Associates Architects).

Figure 2. Lighthouse Joensuu (photo by author).

The impetus behind this shift in construction technology is grounded in the growing recognition of the environmental impact of the concrete and steel industries [6]. These industries, which have played a pivotal role in shaping modern cities and their towering skyscrapers, are characterized by significant energy consumption and are significant contributors to global carbon emissions [7]. As environmental concerns escalate and the world experiences rapid urbanization, with an ever-increasing proportion of the global population choosing to reside in urban areas, the allure of mass timber solutions gains momentum [8].

What sets mass timber solutions apart from their concrete and steel counterparts is their intrinsic sustainability. Mass timber not only serves as a structurally sound building material but also actively participates in carbon sequestration, thereby mitigating the environmental issues currently at the forefront of our global agenda [9,10]. This means that as timber grows, it absorbs carbon dioxide from the atmosphere, effectively locking away this greenhouse gas [11]. When used in construction, the carbon remains sequestered within the timber products, reducing the overall carbon footprint associated with building construction and providing a tangible and proactive means of combatting climate change.

Visionary architectural designs that embrace the potential of this pioneering building approach have foreseen a future urban landscape characterized by timber skyscrapers soaring to heights of 350 m [12]. While the current state of timber technology falls short of rivaling the towering grandeur of steel and concrete skyscrapers, there are active plans in motion to construct timber towers spanning a range of 18 to 25 stories [13]. This endeavor is underpinned by the continuous evolution of engineered timber technology, coupled with ongoing research that sheds new insights on structural solutions, fire safety strategies, and construction methodologies [14]. As this technological and research-driven progress unfolds, timber tower designs will persistently challenge the established boundaries of height, unlocking new possibilities for vertical urban development.

Crucially, it is imperative to view mass timber construction not merely as a series of technical problems to be surmounted but as an entirely fresh architectural typology [15]. This typology carries the potential to harness the intrinsic attributes of timber as a building material, rather than merely emulating the conventional techniques and aesthetics associated with brick, steel, and concrete construction that have dominated in the past. In doing so, it fosters a paradigm shift in architectural thinking, recognizing timber as a versatile and eco-friendly medium that can not only match but also transcend the structural and aesthetic capabilities of traditional construction materials. This transformation paves the way for the emergence of innovative architectural designs that seamlessly integrate timber's unique characteristics, marking a departure from architectural conventions and fostering sustainable, forward-thinking approaches to urban development.

Overall, this emerging architectural trend is driven by a confluence of factors, including the need to reduce carbon emissions, decrease the consumption of non-renewable resources, and create healthier and more livable urban environments [16,17]. Timber, a renewable and carbon-sequestering material, has gained considerable attention as a viable alternative to conventional construction materials such as concrete and steel, which have significant environmental impacts. High-rise residential timber buildings, often referred to as 'plyscrapers' due to their tall and slender profiles, have become a focal point in the pursuit of sustainable urban living [18].

It is worth noting that designing high-rise residential timber buildings poses several challenges that need to be addressed to ensure structural integrity, safety, and compliance with building codes. Here are some of the key challenges associated with the architectural and structural design of high-rise residential timber buildings:

1. Vertical load and stability [19–21]: Timber has a lower strength-to-weight ratio compared to traditional materials like steel and concrete. Ensuring the building's stability and ability to support vertical loads over multiple floors requires careful consideration of load distribution and structural design.
2. Fire safety [22–24]: Timber is combustible, and fire safety is a significant concern. The design must incorporate fire-resistant materials, sprinkler systems, and other fire protection measures to meet stringent safety regulations for high-rise buildings.
3. Moisture and durability [25–27]: Timber is susceptible to decay and deterioration when exposed to moisture. Designing effective moisture barriers, proper ventilation, and choosing durable timber species are essential to ensure the longevity and structural integrity of the building.
4. Code compliance [28–30]: Building codes and regulations may not have specific provisions for high-rise timber structures. Designers need to work closely with authorities to ensure that the design meets or exceeds existing codes and may need to advocate for or adapt regulations to accommodate innovative timber construction.
5. Connection design [31–33]: Ensuring robust connections between timber elements is crucial. The proper detailing and design of connections are essential to prevent issues such as creep, shrinkage, and other factors that can affect the long-term performance of the structure.
6. Vibration control [34–36]: Timber buildings may be more prone to vibrations compared to traditional materials. Designing effective damping systems and ensuring that the building can withstand dynamic forces, such as wind-induced vibrations, are critical for occupant comfort and safety.

7. Construction and assembly challenges [37–39]: Building tall timber structures may pose logistical challenges during construction. Issues related to transportation, on-site assembly, and the need for specialized construction techniques must be addressed to ensure efficient and cost-effective construction processes.
8. Acoustic performance [40–42]: Timber structures may have different acoustic properties compared to conventional materials. Designing for adequate sound insulation and acoustic performance between floors is important to provide a comfortable living environment.
9. Economic viability [43–45]: The cost of high-quality timber and the need for specialized construction techniques can impact the economic viability of high-rise timber buildings. Balancing cost considerations with the desire for sustainable and innovative construction is a key challenge.
10. Public perception and acceptance [46–48]: Convincing stakeholders, including the public, investors, and insurers, of the safety and viability of high-rise timber buildings is a challenge. Building trust and addressing concerns related to fire safety and structural stability is essential for the widespread acceptance of timber construction in high-rise buildings.

Addressing these challenges requires collaboration among architects, engineers, builders, and regulatory bodies to advance the field of high-rise timber construction and ensure the safety and success of such projects.

The current state of the scientific literature falls short in providing an in-depth investigation into the dynamic architectural and structural design parameters within the realm of high-rise residential timber buildings, a prominent subset of tall timber construction. In an effort to bridge this substantial void in this collective understanding and gain deeper insights into the shifting global dynamics, this research undertook a comprehensive analysis by scrutinizing data derived from a wide-ranging selection of 55 high-rise residential timber building projects spanning the globe.

The study focused its attention on three fundamental components with the aim of identifying the emerging trends in the construction of high-rise residential timber buildings. These components included a comprehensive range of information (such as the building's name, geographical location, height, number of stories, and completion date), architectural design aspects (including core configuration and form), and structural design elements (encompassing structural system and structural materials), all of which are detailed in Sections A and B. It is important to acknowledge that while social factors, as emphasized by Gifford [49], undoubtedly play a role in the long-term viability and sustainability of high-rise structures, this paper primarily underscores the technical aspects and does not delve deeply into the social factors.

By shedding light on the prevailing characteristics and qualities of contemporary high-rise residential timber constructions, this research is poised to offer invaluable insights that can serve as a guiding beacon for architects, facilitating their creative vision and the successful execution of these projects in the future. These understandings are expected to enhance the architects' ability to conceptualize, plan, and bring to fruition upcoming high-rise timber construction endeavors.

The article is organized as follows: It begins with a thorough review of the existing literature on high-rise timber buildings. Next, it outlines the research materials and methods employed in this paper. It then presents the findings from an extensive analysis of 55 case study towers. This is followed by a comprehensive discussion section that addresses potential avenues for future research and acknowledges the study's limitations. Finally, the article concludes with a summary of its findings.

2. Literature Review

Due to the increasing interest in timber-based structural systems and the remarkable progress in the construction industry, substantial research efforts have been made to examine the technological, environmental, social, and economic aspects of engineered wood products

(EWPs) in various building applications, as documented in previous studies [50–52]. However, there is a notable scarcity of research specifically addressing the global trends and categorizations related to architectural and structural design elements in high-rise timber constructions. The following literature review delves into a comprehensive analysis of case studies focused on the architectural and structural design aspects of multi-story and tall wooden structures.

In their work, Fink et al. [53] adopted a collective and interdisciplinary approach when addressing the design of taller multi-story timber structures. Instead of examining individual aspects in isolation, they simultaneously considered static, dynamic, fire safety, acoustic performance, human health, and various other factors. They emphasized the significance of interdisciplinary analysis and collaboration as the critical pathway to establish a comprehensive set of design guidelines.

Tuure and Ilgın [54] performed an investigation into space efficiency in 55 mid-rise timber apartments located in Finland. The key findings of their study indicated that: (a) square floor layouts predominantly incorporated a central core; and (b) the sample of buildings exclusively adopted prismatic architectural designs and relied solely on the shear wall system as the structural framework.

Zahiri [55] conducted a study to explore the contemporary developments in tall timber buildings in the Scandinavian region. The prevailing trends in timber construction in the Nordic area can be summarized as follows: (i) the use of prefabrication and modular construction techniques, (ii) integration of technological advancements, (iii) the construction of tall timber edifices, (iv) the adoption of multifunctional designs, and (v) a focus on environmentally sustainable building practices.

Ilgın et al. [56] investigated by analyzing data obtained from 13 case studies of tall residential timber buildings, with the objective of enhancing our understanding of the evolving global trends in this field. The primary results of their research were as follows: (1) central cores and prismatic forms with linear layouts were the most favored architectural designs; (2) a clear preference for pure timber construction over hybrid approaches was evident; and (3) the shear wall system stood out as the most frequently used structural system.

González-Retamal et al. [57] performed an extensive examination of over 250 academic articles archived in the Web of Science, encompassing the period from 2017 to 2022. Their study was primarily aimed at pinpointing significant progress and constraints in the development and implications of multi-story timber buildings. These articles were categorized based on their focus areas, including sustainability, design, and engineering sciences. The results revealed that the majority of the papers highlighted innovations and limitations primarily associated with engineering disciplines, with 25% addressing sustainability concerns and 5% concentrating on collaborative design aspects.

Santana-Sosa and Kovacic [58] evaluated the current procedures and practices for designing and carrying out timber constructions in Austria through a series of 15 detailed interviews with industry experts. These interviews provided insights into the obstacles and prospects, presenting suggestions designed to encourage the use of wood in multi-story buildings. The results were organized into planning, manufacturing, and construction and were further broken down into challenges and promising avenues. This structure was established as a reference for future research and initiatives intended to advance the incorporation of timber in construction projects.

Svatoš-Ražnjević et al. [59] conducted an examination of the diverse architectural designs and spatial possibilities in multi-story timber buildings, drawing from a dataset consisting of 350 contemporary case studies. The main result of their study involved categorizing design ideas into four groups based on load-bearing systems and four classifications based on materials used.

Žegarac Leskovar and Miroslav [60] examined the architectural and structural design approaches used in 32 multi-story timber buildings constructed between 2007 and 2021 across Europe. The results highlighted distinct changes in architectural design, particularly in the appearance of the buildings, along with a shift from solid panel systems to composite load-bearing systems. The research also identified substantial variations in structural and energy efficiency designs, which were influenced by factors including location and considerations related to seismic and climatic conditions.

Salvadori [61,62] conducted a comparative analysis involving over 190 multi-story timber buildings with the goal of identifying regional differences in the features of such structures. The study [61] was a part of the larger thesis [62], with a primary focus on structural categorization. In contrast, Salvadori [62] presented a more extensive investigation of multi-story timber constructions, which included an assessment of various building materials for components, such as exterior cladding, and other aspects of design.

Tupėnaitė et al. [63] carried out a comparative examination of the tallest contemporary timber buildings, assessing their economic and environmental performance. Their analysis demonstrated that taller timber structures display increased efficiency in both economic and environmental aspects, primarily due to the utilization of advanced lightweight EWPs. Additionally, the integration of prefabricated elements resulted in reduced project durations and costs.

Kuzmanovska et al. [64] conducted an extensive investigation into the emerging trends in tall timber applications, specifically focusing on structural, envelope, and architectural aspects. Their research covered 46 multi-story structures, encompassing both residential and non-residential categories, with a particular emphasis on their spatial and aesthetic attributes. These attributes primarily centered around structural systems, envelope designs, and construction methods. Notable findings from this study included (1) a growing preference for post and beam structures with CLT slab floors, (2) a decreasing use of load-bearing external walls, and (3) a prevalent presence of rectangular floor plans and regularly extruded building forms.

Ramage et al. [65] focused on design research for the forthcoming evolution of supertall timber buildings, rooted in natural structural principles. The findings indicated that it is indeed possible to construct tall timber towers, although there remain significant, albeit conquerable, challenges to address. Through the proposal of innovative and well-grounded solutions for tall timber building designs that push boundaries beyond the existing constraints, this project has the potential to stimulate the design community to break free from conventional thinking and enthusiastically embrace the opportunities presented by timber construction.

In Salvadori's study [66], an investigation was conducted involving 40 case studies, which included both completed and proposed projects that exceeded seven stories in height. The analysis considered various aspects, such as the structural system, structural materials, facade systems, and specific fire safety strategies implemented. The main goal of the research was to provide a comparative analysis between an alternative mass timber structure and a similar concrete structure. Interestingly, instead of highlighting technological obstacles as the primary hindrance to taller timber buildings, the study emphasized that the main challenge was the public's acceptance of wood as a construction material.

In study of Smith et al. [67], the main advantages of off-site solid timber production were determined to be speed, adaptability to different weather conditions, efficient use of raw materials, and a reduction in carbon emissions. Conversely, the primary disadvantages included issues related to knowledge and labor, logistical challenges, planning, acoustic properties, and vibration control.

Perkins and Will [68] conducted a survey involving 10 case studies of timber buildings that were taller than five stories. Simultaneously, Holt and Wardle's research [69] focused on the market context and rationale for using timber in high-rise construction. The findings highlighted that utilizing timber in taller structures is a feasible construction method with the potential to significantly reduce the negative environmental effects of buildings.

Smith and Frangi [70] conducted an examination of design challenges for tall timber buildings. The consensus reached was that designing timber structures of moderate height, using simplified structural engineering methods, has been widely accepted. However, in order to create high-performance buildings ranging from 10 to 20 stories in height, it will be imperative to employ the most cutting-edge analysis and design techniques. Pursuing this goal will undoubtedly necessitate raising the overall technical proficiency of the timber engineering discipline, with potential benefits extending to other structure types in which timber serves as the primary construction material.

3. Materials and Methods

Case studies were utilized to acquire, organize, and amalgamate information concerning modern high-rise residential timber buildings, facilitating a thorough investigation and assessment of their architectural and structural characteristics. The utilization of case studies is a prevalent method in assessments associated with the constructed environment [71,72]. In this study, a comprehensive examination was conducted, encompassing a total of 55 case study towers. These towers were either already completed or in the process of construction, with a specific emphasis on timber buildings (55 out of 56). The selection criteria included buildings with eight stories or more, and the information was derived from the documentation provided by the Council on Tall Buildings and Urban Habitat (CTBUH) [73].

It is worth nothing that CTBUH is widely recognized by the public for its role as the authority on tall building height and the prestigious title of "The World's Tallest Building". Beyond this, the CTBUH administers the "Buildings of Distinction" program, which acknowledges noteworthy projects by installing public signboards and plaques. Functioning on a global scale, the CTBUH serves as a prominent platform for the exchange of cutting-edge information and facilitates business networking.

The case study buildings in this research were situated in diverse locations, including 36 in Europe (comprising 10 in Norway, 9 in Sweden, 6 in France, 5 in Finland, 2 in the Netherlands, 2 in Germany, 1 in Italy, and 1 in Spain), 8 in North America (including 4 in Canada and 4 in the United States), and 7 in the United Kingdom (UK), along with 4 in Australia, as detailed in Appendix A. Figure 3 depicts the systematic approach utilized in the identification and selection of the case studies.

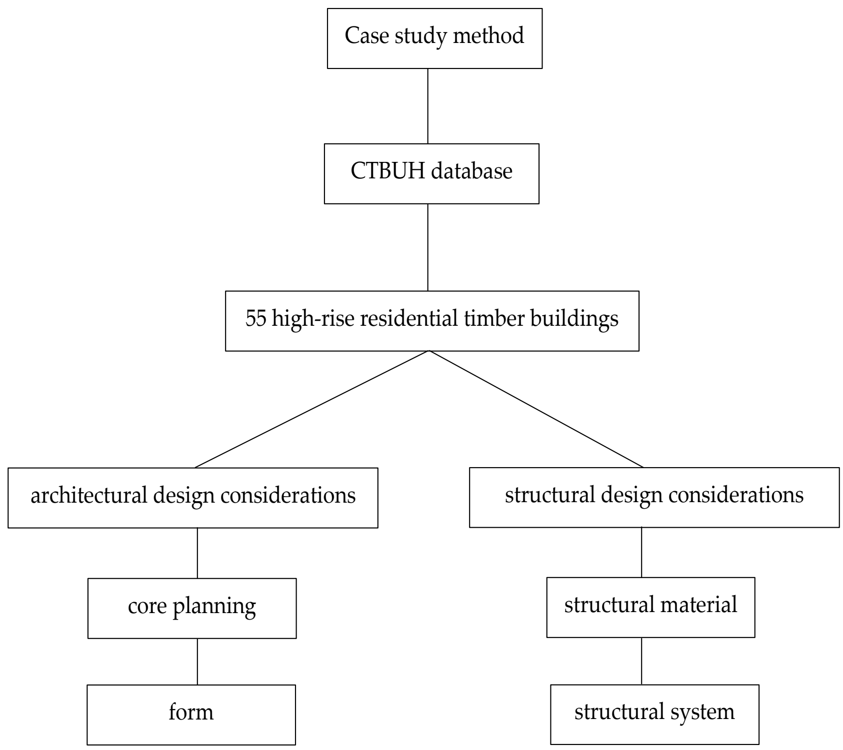

Figure 3. Flowchart of the methodology and process.

In the context of high-rise timber towers, decision making is primarily guided by architectural and structural requirements, in addition to the fundamental purpose of the building. These identical features also impact decision making in various other building types. The essential attributes are delineated as follows [74]:

When considering architectural features, the following factors play a significant role:

- Designated purpose of the structure.
- Design of the service core, which may impact the organization of vertical movement and, in certain situations, the placement of elevator shafts.
- Form of the building, which can affect the size and shape of floor structures.

Regarding structural attributes:

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

The core classification system proposed by [74] is chosen for adoption due to its broader framework, encompassing the following categories: (1) central core, (2) atrium core, (3) external core, and (4) peripheral core.

In this study, the categorization of building forms is established based on the following configurations (as depicted in Figure 4) [75]:

(1) Prismatic forms refer to buildings in which both ends display similarities, equality, and parallel geometrical figures, featuring identical sides and vertical axes that are perpendicular to the ground. This concept is exemplified in buildings such as the Lighthouse Joensuu (as shown in Figure 2).
(2) Leaning forms refer to buildings with an inclined architectural form.
(3) Tapered forms are a defining feature of buildings that display a narrowing effect as they rise, achieved by diminishing floor plans and surface areas, leading to either linear or non-linear profiles.
(4) Setback forms are evident in buildings that incorporate horizontally indented segments along their height. This characteristic is visible in structures.
(5) Twisted forms are a hallmark of buildings in which the floors or facade gradually rotate as they ascend along a central axis, incorporating a twisting angle.
(6) Free forms refer to buildings that do not conform to the previously mentioned configurations. This concept is exemplified in buildings such as HAUT (Figure 5) and Sensations (Figure 6).

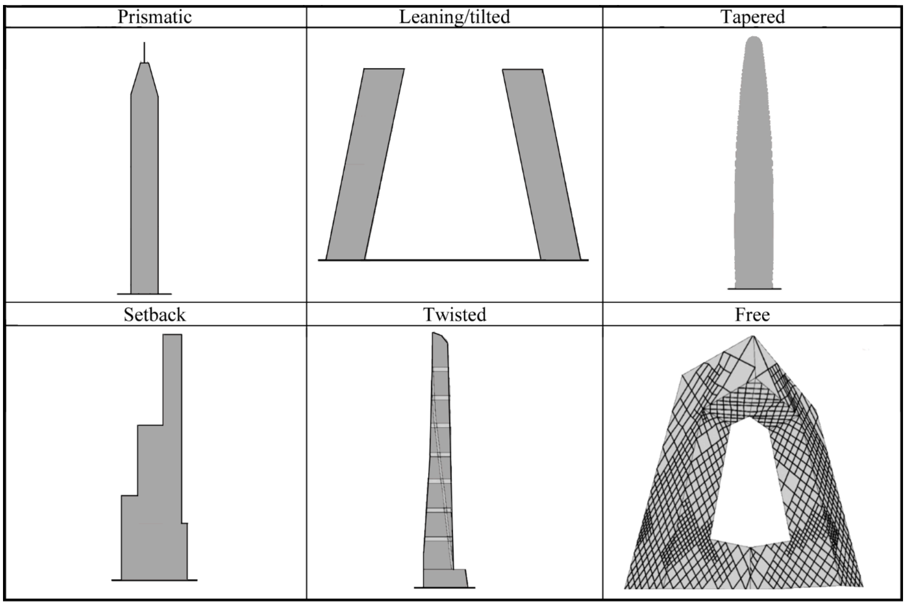

Figure 4. High-rise timber building forms (figure by author).

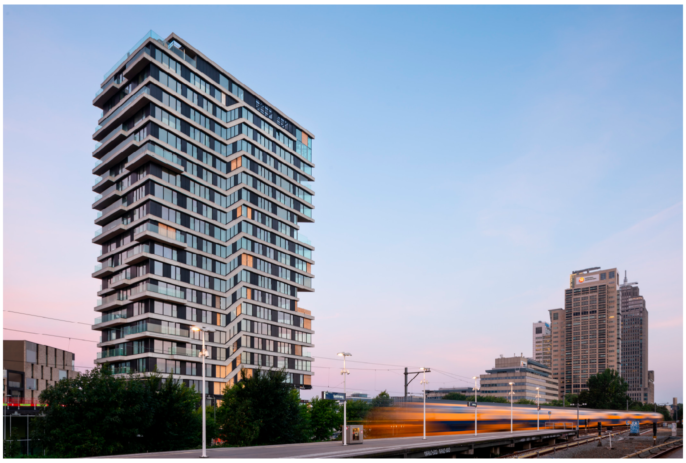

Figure 5. HAUT (photo courtesy of Jannes Linders).

Figure 6. Sensations (photo courtesy of Cécile Septet).

Structural materials can be divided into two primary categories: (i) 'timber' or 'all-timber', and (ii) composite or hybrid materials, which involve combinations such as timber with concrete, timber with steel, or timber with both concrete and steel. This paper specifically concentrates on essential load-bearing components, comprising columns, beams, shear trusses, and shear walls, excluding the consideration of floor slabs. It is essential to emphasize that the material composition of the load-bearing elements on the first floor does not alter the categorization of the entire structural system.

In accordance with the detailed classification of structural materials, it is a fundamental requirement for a structure to be categorized as 'timber' that both its primary vertical and lateral structural elements are exclusively fashioned from timber [73]. It is noteworthy that a 'timber' structure can integrate non-timber connections in specific regions among the timber components. Even if a building is primarily constructed using timber but features a floor system consisting of concrete planks or a concrete slab supported by timber beams, it maintains its classification as a 'timber' structure, as the concrete elements do not serve as the principal load-bearing framework. A notable and widely acknowledged example of this can be observed in Lighthouse Joensuu, as illustrated in Figure 2.

Conversely, within the composite or hybrid category that includes timber, a substantial proportion of the vertical or lateral load-bearing system comprises materials other than timber, specifically steel, concrete, or a combination of both. For example, in structures that blend timber and concrete, it is customary to encounter a concrete core providing support to a timber framework, as exemplified by HAUT (Figure 5). Conversely, when considering structures that combine timber and steel, a significant part of the vertical or lateral load-bearing system relies on steel. This often encompasses elements such as steel-framed cores, buckling-restrained braces, perimeter frames, or exoskeletons, as demonstrated by Tallwood 1 at District 56 in Canada. Similarly, hybrid structures that incorporate timber, concrete, and steel employ a combination of all three materials to carry primary loads. A typical arrangement involves a concrete core working in conjunction with steel beams and columns, while timber is utilized for flooring and partition walls. The tallest known building that employs concrete, steel, and timber in a hybrid manner is De Karel Doorman in Rotterdam, Netherlands, which reaches a height of 71 m with 22 stories.

Within the context of establishing lateral stiffness to high-rise structures, particularly in addressing forces like wind and seismic loads, numerous structural systems and categorizations have been implemented in practical scenarios and have been a topic of scrutiny in the existing body of literature (as seen in [74]). In this paper, the author chose to adopt the structural system classification put forth by [76] because of its all-encompassing scope (as illustrated in Figure 7).

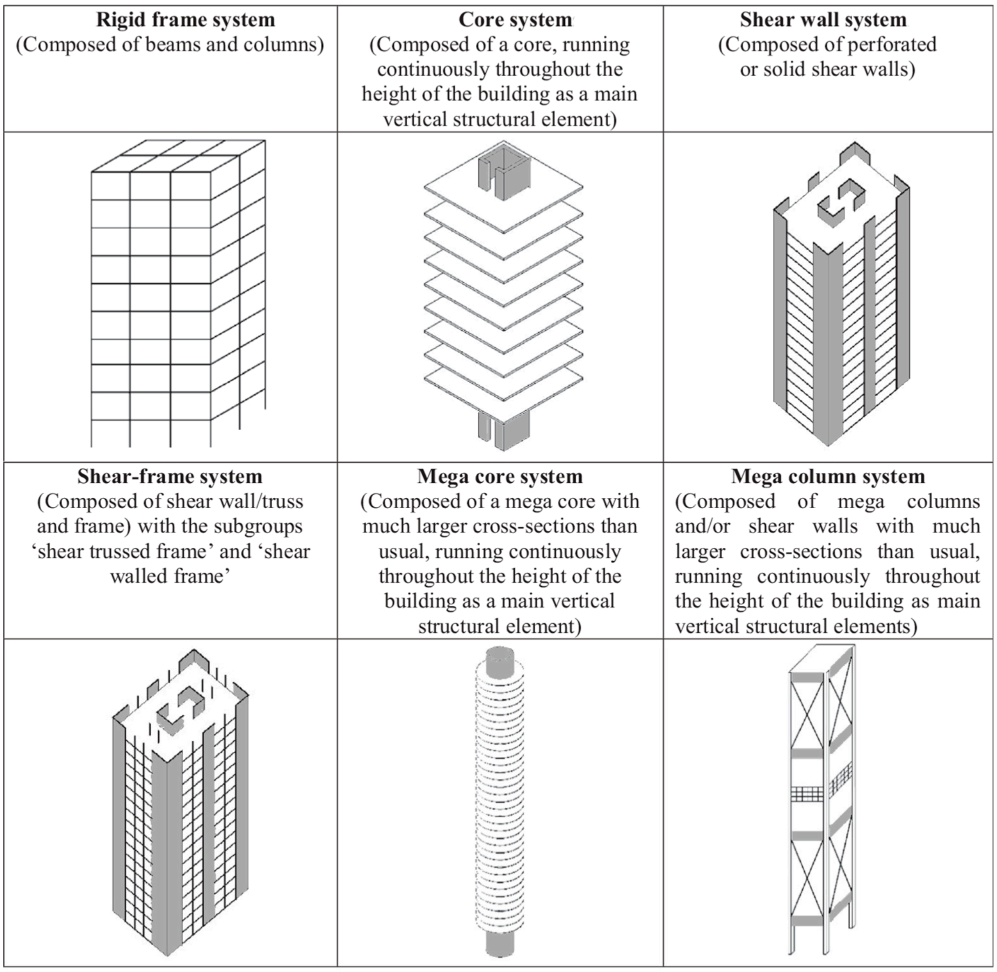

Figure 7. High-rise timber building structural systems (figure by author).

Furthermore, it is worth emphasizing that structural configurations such as outrigged frame systems, various tubular systems (including framed-tube, diagrid-framed-tube, trussed-tube, and bundled-tube), and buttressed core systems are primarily applied in supertall buildings surpassing a height of 300 m. These systems are chosen for their efficiency and cost-effectiveness. Consequently, these specific structural systems were not considered for inclusion in this research, as it focuses on high-rise buildings rather than supertall ones. However, as exemplified by Treet in Norway (Figure 8), there is only one instance of a high-rise residential timber structure that incorporates a tubular system.

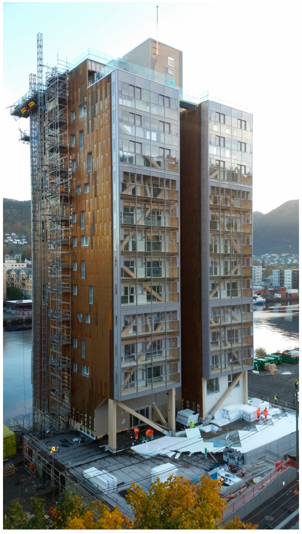

Figure 8. Treet (photo courtesy of ARTEC).

Regarding the definition of tall or high-rise buildings, there is still a lack of a universally agreed-upon standard pertaining to their height and the number of stories, and even the classification of 'tall' or 'high-rise' within the context of timber structures remains a topic of ongoing debate. Within the scope of this research, a 'high-rise timber building' is specifically defined as a structure that consists of 8 stories or more [73].

4. Results

Europe, assuming the role of an early pioneer in the domain of mass timber technology, possesses numerous advantages that establish it as the leading global center for the construction of high-rise residential timber buildings. This dominance can be ascribed to a convergence of factors. Initially, Europe benefits from well-maintained forests that are subject to rigorous management, guaranteeing a consistent and sustainable supply of timber, which is a foundational element in mass timber construction [77]. Furthermore, the continent features an extensive framework of strict environmental regulations, underscoring a dedication to environmentally responsible construction methods and the prudent use of resources [78]. Given these favorable conditions, it comes as no surprise that Europe holds an impressive 65 percent share of the total within the realm of high-rise residential timber buildings, as depicted in Figure 9. This predominant position emphasizes the region's role as a leader in the worldwide shift toward high-rise construction using timber as a primary material.

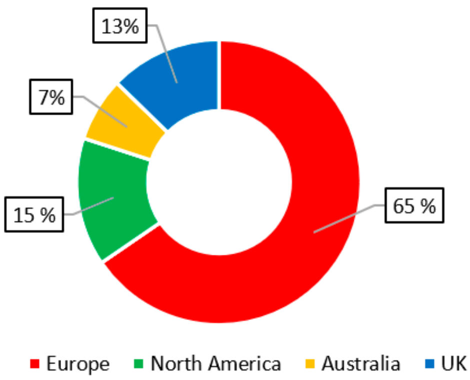

Figure 9. High-rise residential timber buildings by location.

The Nordic region, encompassing Norway, Sweden, and Finland, stands out as a focal point for the convergence of tradition, innovation, and sustainable architecture in the realm of high-rise timber residential buildings (Figure 10). This prominence can be attributed to a rich historical legacy of wood-centered construction [79]. Throughout the centuries, these countries have harnessed the versatility and durability of timber in their architectural traditions. From the iconic stave churches of Norway to the intricate log cabins of Finland [80] and the intricate wooden detailing of Swedish architecture, the Nordic countries have cultivated a profound relationship with wood as a building material [81,82]. What distinguishes the high-rise timber structures in the Nordic region is their ability to reflect a distinctive regional character. This character draws inspiration from cultural heritage, design aesthetics, and a deep-rooted connection with the natural landscape that surrounds them. In these buildings, one can observe a seamless integration of architectural elements that pay homage to the local culture, while also embracing modern design principles.

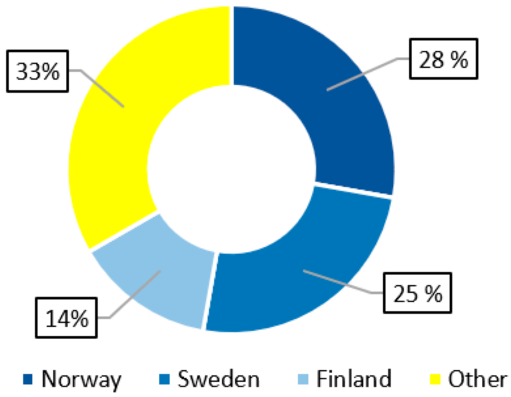

Figure 10. High-rise residential timber buildings by European location.

The use of timber not only provides a sustainable and eco-friendly construction solution but also results in structures that harmonize with the natural environment, creating a sense of belonging and oneness with nature. This harmonious coexistence between architectural innovation and environmental sensitivity has led to the construction of 24 high-rise residential timber buildings within the Nordic region, a noteworthy achievement that accounts for two-thirds of the total European inventory (Figure 10). These structures serve as exemplars of the region's commitment to sustainable urban development and its dedication to preserving the cultural heritage that has been interwoven with wood as a building material for centuries. The Nordic countries have, therefore, emerged as pioneers in the renaissance of timber-based high-rise construction, setting a compelling precedent for the global architectural community as they chart a path towards more sustainable and culturally resonant urban landscapes.

Subsequent to Europe's prominent role in high-rise timber residential construction, North America assumes a significant position in this evolving architectural landscape. One of North America's distinguishing features is its possession of the world's most extensive managed forests [83]. The continent's vast forested areas not only provide an abundant source of timber but also represent an asset in terms of sustainable resource management. This advantageous situation aligns with the global push for eco-conscious construction solutions, making North America a key player in the adoption of timber in high-rise buildings. Moreover, North America can look back on a long-established tradition of wooden construction [84]. However, it is essential to distinguish that this tradition has primarily revolved around conventional wood construction techniques, rather than the specialized category of mass timber. The region's architectural history features a rich tapestry of wooden structures, from log cabins in remote wilderness areas to the charming timber-framed houses that grace many urban neighborhoods. While traditional wood construction methods have their roots in North America, the contemporary emergence of mass timber represents a notable departure from the conventional practices, harnessing timber in more technologically advanced ways [85]. Despite the predominantly traditional nature of wooden construction in North America, these factors contribute to the continent's presence in the high-rise timber residential sector, accounting for a respectable 16 percent representation within this context. As the global construction industry continues to evolve, North America's abundant forest resources, along with its adaptability to embrace innovative mass timber technologies, positions it as a region with significant potential to further shape the future of sustainable urban development through timber-based high-rise construction.

Australia's contribution to the realm of high-rise mass timber buildings is quite remarkable. Despite its relatively modest timber industry [86], which is just a fraction of the global total, Australia has made a significant impact in this field [87]. A notable example of their achievement is exemplified by early projects such as Forte in Melbourne [88]. What makes Australia's accomplishments in high-rise mass timber construction even more noteworthy is the fact that they heavily rely on importing most of their timber materials from Europe, which is located thousands of kilometers away. This highlights the country's ability to overcome the logistical challenges and establish itself as a prominent player in the world of high-rise timber structures. It showcases their innovation, engineering prowess, and commitment to sustainable and eco-friendly construction practices. This unique blend of factors underlines Australia's notable presence in the global landscape of high-rise mass timber buildings.

In the sample group under consideration, there are seven high-rise residential timber towers located in the UK. These towers represent a significant proportion, accounting for 13 percent of the total number of buildings in the sample. This statistic underscores the growing prevalence and acceptance of high-rise timber constructions in the UK. Historically, the UK has a rich tradition of employing timber-based construction techniques [89]. However, with the advent of mass timber technology, a new chapter has opened for the construction of high-rise timber structures. Mass timber technology offers advanced and innovative solutions that facilitate the creation of tall buildings using sustainable and environmentally friendly materials. The UK's enthusiastic embrace of high-rise timber structures is indicative of a global shift in construction preferences. This shift is characterized by an increasing recognition of timber as a viable and environmentally responsible alternative to traditional construction materials, such as concrete and steel.

The benefits of timber construction, including its renewable nature and lower carbon footprint, are aligning with the growing awareness of the need to combat climate change and promote sustainable urban development. This trend in the UK mirrors broader efforts seen throughout Europe and in many parts of the world. As nations aim to reduce their environmental impact, address climate change, and create more sustainable urban environments, the adoption of high-rise timber structures serves as a tangible and environmentally conscious step in the right direction. It not only showcases architectural innovation but also contributes to the broader global commitment to building a more sustainable future.

As previously demonstrated, the construction of high-rise residential timber buildings is currently undergoing extensive development across multiple global regions, particularly in Europe, where there is a growing demand and increasing appreciation for such structures. The subsequent discourse delves deeply into the crucial architectural and structural design elements that play a substantial role in shaping the evolution of these buildings.

4.1. Analysis of Architectural Design Considerations

In this section, the author present a comprehensive examination of the architectural design considerations for a total of 55 high-rise residential timber buildings. These buildings are either already completed or currently in the construction phase. The factors to be delved into include core planning and building form. Each of these parameters will be thoroughly explained and explored in the following discussions.

4.1.1. Core Planning

By examining Figure 11, it is clear that the central core configuration is the most commonly utilized core arrangement, constituting 56% of the instances. Following closely is the peripheral core arrangement, which accounts for over 40% of the cases, while external cores are never encountered.

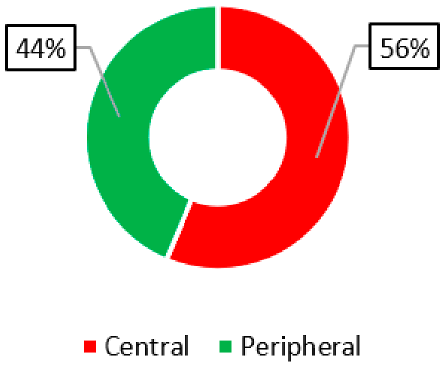

Figure 11. High-rise residential timber buildings by core planning.

The advantages linked with a central core configuration are manifold and exert a significant influence on its widespread adoption [90]:

1. Structural robustness: A central core delivers robust structural support to high-rise timber buildings, bolstering their stability and load-bearing capacity. The core's central placement ensures efficient distribution of loads and resistance to structural deformations, thus contributing to the overall structural strength and safety of the building.
2. Compact and space-efficient design: Central cores are typically designed to occupy a minimal footprint within the building, allowing for a more efficient utilization of available space. This compact design maximizes the usable floor area, making it an appealing choice for space optimization within the structure.
3. Creation of open spaces: Central cores play a pivotal role in establishing open and unobstructed spaces along the building's outer facade. This arrangement enables an abundance of natural light to permeate the interior and provides panoramic views, enhancing the overall quality of the living or working environment.
4. Improved fire safety: Central cores often serve as a crucial component of a building's fire safety strategy. Their positioning provides a centralized and controlled pathway for fire evacuation, facilitating safe escape in the event of an emergency. This enhanced fire safety feature is of paramount importance for the well-being of occupants and compliance with safety regulations.

Many structures in the sample group featured rectangular floor layouts. In cases where a building's size is restricted, especially when it takes on a narrow and rectangular form, an architectural approach that positions the core near the outer perimeter of the structure becomes a prominent design practice. This deliberate core placement primarily aims to enhance the overall efficiency of the floor plan, explaining why peripheral core arrangements are the second most favored option in this particular situation. This design strategy guarantees the optimal utilization of interior space, enabling greater flexibility in space allocation and usage, which can be particularly advantageous in buildings with limited dimensions.

4.1.2. Form

According to the morphological classification system for high-rise residential timber buildings, the prismatic form, which accounts for 80% of the cases, stands out as the dominant design preference, while free forms make up 20% of the total, as illustrated in Figure 12.

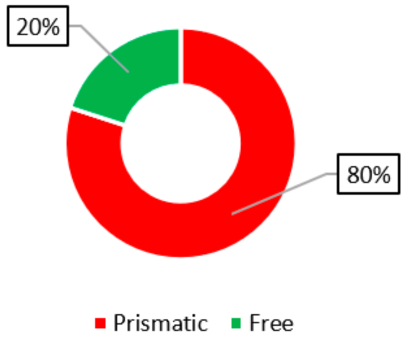

Figure 12. High-rise residential timber buildings by building form.

The widespread use of prismatic shapes in architecture can be explained by the numerous advantageous characteristics linked to this design method. These qualities play a crucial role in influencing the appeal of prismatic shapes, especially in the context of constructing high-rise residential timber buildings using timber [54]:

1. Easier to build: Prismatic shapes are recognized for their simple and uncomplicated construction. Their straightforward geometry reduces the intricacy of building processes, from designing the structure to handling materials and assembling components. This streamlined construction method improves efficiency and cost-effectiveness, making it an attractive option for numerous projects.
2. Practicality: The practicality of prismatic shapes is another important reason for their widespread use. These designs fit nicely with traditional construction methods, often leading to reduced labor and material expenses. Furthermore, the practical nature of prismatic shapes makes them suitable for a range of building purposes, increasing their adaptability.
3. Optimal use of space: Prismatic shapes, especially when combined with rectangular floor plans, are highly effective at making the most of interior space. The uncomplicated, right-angled layouts of these designs maximize the usable area, reducing wasted spaces and encouraging a more efficient arrangement of rooms, corridors, and amenities. This efficiency is particularly valuable in residential and office settings where making the most of available space is essential.
4. Cost efficiency: Prismatic shapes, because of their simplicity and alignment with established construction methods, frequently result in cost savings for developers and builders. The reduced intricacy of the design lowers the risk of construction errors or delays, adding to overall cost efficiency.

The rising prevalence of free forms in the realm of high-rise timber building design can be linked to architects' unwavering pursuit of creative and distinctive architectural arrangements. These architects are fueled by a deep passion for pushing the boundaries of traditional design and a keen aspiration to establish buildings that are not only functional but also stand out as iconic and visually captivating structures. This motivation has led them to explore the exciting world of free forms [91].

Free forms, in this context, are marked by their departure from the conventional rectilinear or prismatic geometries that have dominated architectural design for so long. They represent a break from the rigid constraints of straight lines and right angles, allowing architects to unleash their creativity and embark on innovative architectural journeys. Free forms serve as a canvas on which imaginative and pioneering architectural concepts can be brought to life. These fluid, organic shapes open up a realm of endless possibilities, inviting architects to shape and mold timber structures in ways that were previously unexplored, resulting in buildings that not only serve their practical functions but also serve as works of art that inspire and capture the imagination.

4.2. Analysis of Structural Design Considerations

This section provides an analysis of the structural design elements for the group of 55 high-rise residential timber buildings. These factors include:

- structural material, and
- structural system.

4.2.1. Structural Material

Figure 13 underscores a noteworthy occurrence of entirely timber-based construction, constituting around 55% of the dataset, while composite materials come next, accounting for 45% within a set comprising 55 high-rise residential timber buildings. The deliberate integration of timber in combination with these materials plays a pivotal role in the pursuit of a diverse range of significant objectives. These goals encompass not only reducing carbon emissions but also enhancing the efficiency of construction and rapidly providing essential housing solutions for the increasingly urbanized global population. This harmonious utilization of materials serves as a fundamental element in addressing the urgent challenges related to sustainability, efficient resource use, and meeting the growing housing needs of our expanding urban communities.

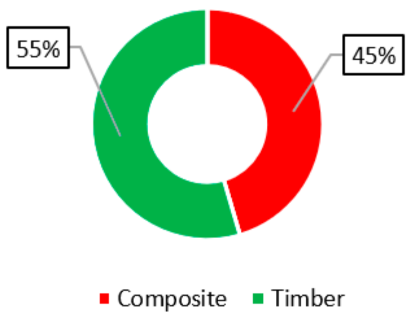

Figure 13. High-rise residential timber buildings by structural material.

In the context of high-rise residential timber structures in Europe, there is a distinct inclination towards the utilization of timber as the primary construction material, as indicated in Appendix B. Several key factors contribute to the prevalence of timber-based constructions across Europe. These factors include the strategic location of timber forests in close proximity to construction sites [92], a resolute dedication to environmental objectives focused on minimizing carbon footprints and promoting sustainability [93], and a notable concentration of construction projects falling within the lower height range considered within the scope of this study. The proximity of timber forests to construction sites plays a significant role in the preference for timber-based structures. This proximity simplifies the logistics of timber procurement, reducing transportation costs and environmental impacts. Additionally, the availability of local timber resources encourages the use of this renewable material in construction, fostering a more sustainable approach to building. The commitment to environmental goals further underscores the choice of timber as the preferred material.

Timber construction aligns with the broader objective of reducing carbon emissions and minimizing the environmental impact of high-rise structures. Timber, as a renewable and low-carbon material, aligns well with the sustainability goals and regulations in place across Europe [94]. Furthermore, the concentration of projects within the lower height range considered in this study has a notable influence. Timber is particularly well suited for buildings within this height range due to its structural properties, ease of construction, and environmental benefits. As a result, it is a natural choice for many European construction projects in this category.

Figure 14 illustrates composite structures classified based on the combination of structural materials. Timber combined with concrete emerged as the predominant preference, constituting 68% of the instances. Following, timber combined with both concrete and steel was observed in 20% of the cases. In contrast, timber combined with steel was the least frequent, occurring in only three instances.

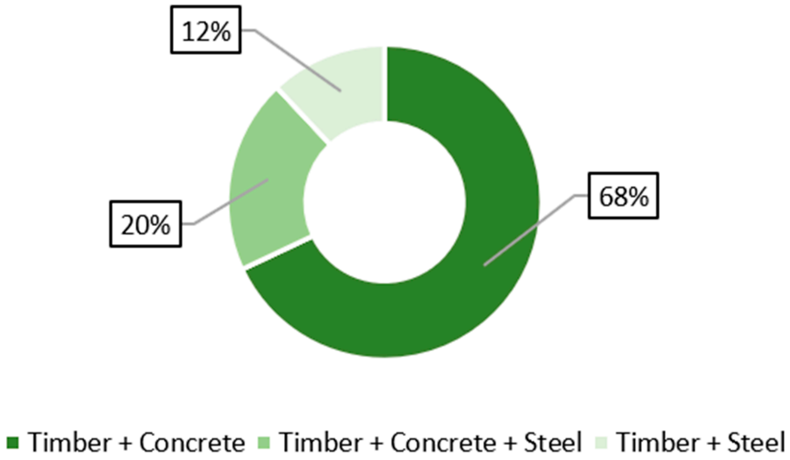

Figure 14. Composite high-rise residential timber buildings by structural material combinations.

In the context of composite structures, the utilization of concrete within the central component can be ascribed to a multitude of considerations. Firstly, it augments the global lateral rigidity and robustness of the structure. Secondly, it capitalizes on the inherent fire resistance of concrete. Thirdly, it exploits concrete's superior capacity to mitigate wind-induced oscillations, a prevalent issue faced in the construction of high-rise buildings [95].

It is worth highlighting that timber and concrete composite construction features reinforced concrete cores that play a pivotal role in significantly improving their lateral stiffness [96]. Additionally, it was noted that incorporating concrete cores into the design, as demonstrated in the instance of Brock Commons Tallwood House, facilitated the project approval process [97]. This expedited regulatory clearance can be ascribed to the widespread presence of concrete cores in traditional high-rise buildings, irrespective of the materials employed. Significantly, in this particular case study, the fire escape stairs were housed within the concrete cores, ensuring their non-combustible construction.

It is crucial to underscore that in taller buildings, the mitigation of building sway represents a substantial challenge that has implications for both structural safety and the functionality of the building [98]. This challenge is relevant regardless of the materials used in construction. Effectively managing building sway is a vital responsibility for designers to guarantee the comfort of occupants, especially in adverse weather conditions such as strong winds. Keeping building sway within acceptable parameters is essential, particularly in minimizing the discomfort experienced by individuals occupying the uppermost floors. Moreover, contemporary high-rise buildings, including timber towers, typically have a lower overall weight compared to their earlier counterparts [99]. As a result, they are more prone to lateral drift, primarily due to their reduced damping capacity, making wind-induced building sway a prominent consideration in their design. In this context, the inclusion of concrete can offer advantages, as it furnishes the required mass to counterbalance wind forces in high-rise timber towers.

The adoption of timber and steel hybrid structures can, to some extent, be attributed to the flexibility and efficiency of steel, especially in addressing seismic risks [100], particularly in areas with thriving timber industries, such as the Pacific Northwest in the United States and British Columbia in Canada [101]. Hybrid timber and steel structures capitalize on the advantages of both timber, characterized by its low density and ease of construction, and steel, renowned for its high ductility and energy dissipation capabilities [102]. Timber, typically exhibiting brittle failure characteristics [103], has limitations in absorbing seismic energy, whereas steel possesses a high ductility capacity. The combination of these two materials synergizes to provide an efficient response to seismic forces, ultimately achieving the desired structural performance during seismic activities.

It is of significance to underscore that within the analyzed cases, the ground level was assembled using reinforced concrete, commonly denoted as a concrete podium. The application of a concrete podium framework presents numerous benefits [104], such as the incorporation of facilities and services at ground level, the generation of expansive and well-illuminated public spaces with sizable apertures, and the creation of fire-resistant zones to accommodate extensive mechanical and electrical services and equipment [105].

4.2.2. Structural Systems

As depicted in Figure 15, shear-frame systems exhibited a prevalent preference, being employed at a rate of 53%, followed closely by the shear wall systems, which account for 45%. In the case of shear-frame systems, shear walled frames, with 26 instances, were predominantly employed with a substantial margin.

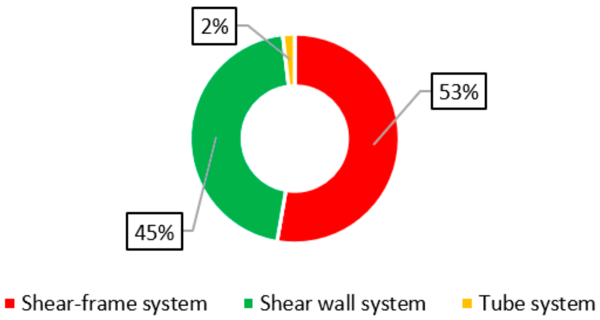

Figure 15. High-rise residential timber buildings by structural system.

The widespread adoption of shear wall systems, with 25 cases, can be explained by several compelling reasons. These include the following advantages:

1. Speed of construction: Shear wall systems offer a swifter construction process compared to alternative methods. Their simplicity and efficiency contribute to reduced construction time, which is particularly attractive in projects with tight schedules or where timely completion is essential.
2. Compatibility for prefabrication techniques [106]: Shear walls are well suited for prefabrication techniques. Prefabricating wall elements in a controlled environment and then assembling them on-site can enhance the overall construction efficiency, reduce labor costs, and ensure higher precision in the assembly process.
3. Efficiency: Shear wall systems are recognized for their structural efficiency. They efficiently distribute and dissipate lateral forces, making them a cost-effective choice for resisting wind and seismic loads. This efficiency translates to material savings and a more sustainable construction approach.
4. Adequate stiffness: Shear walls provide the necessary stiffness to resist lateral loads, making them a suitable choice for buildings with heights of up to approximately 35 stories [107]. Their inherent ability to withstand lateral forces, such as those induced by wind or earthquakes, ensures the structural integrity and safety of the building.

On the other hand, in shear-frame systems, which encompass shear trussed frame and shear walled frame systems, the disadvantages of a rigid frame when compared to shear truss or wall systems, as well as the limitations of shear truss or wall systems when contrasted with rigid frames, are mutually mitigated when these components are used together [108]. In these situations, the frame enhances the performance of the shear truss or wall in the upper levels, while the shear truss or wall improves the performance of the frame in the lower levels. As a result, shear-frame systems exhibit highly effective resilience against lateral forces, providing the structure with greater stiffness than if it consisted solely of a 'shear wall' or a 'rigid frame' system, as seen in examples like Ascent, the world's tallest timber building [109]. This attribute may explain the prevalence of shear-frame systems.

The inherent cantilever behavior seen in shear wall systems results in a significant rise in the inter-storey drift, which is the horizontal displacement between consecutive floors, especially in the upper levels when compared to the lower levels [110]. This pattern remains consistent regardless of the particular construction materials used. This observed phenomenon can be seen as a significant contributing factor to the limited use of shear wall systems in the construction of high-rise residential timber towers.

Apart from its structural efficiency, the use of tube systems provides various benefits [111], such as increasing the available interior space in the building while simultaneously reducing the size of the structural elements in the central core. This is achieved through the presence of an external tubular framework that carries the entire lateral load. This explanation may clarify the choice to use tube systems in the construction of high-rise timber residential towers. Moreover, incorporating braces on the exterior of a framed-tube system brings it closer to achieving nearly pure tubular cantilever behavior, leading to increased structural stiffness and efficiency. It also reduces the negative effects of 'shear lag' caused by the flexibility of the spandrel beams [112]. In contrast, the trussed-tube system allows for greater column spacing, enabling an increase in the structure's height, as demonstrated by the example of Treet.

In the context of taller timber residential structures, specifically those towering at or exceeding 300 m, namely supertall buildings, there is a foreseeable emergence of a notable inclination towards the adoption of tube systems [113]. This inclination can be attributed to the remarkable structural efficiency exhibited by such systems, particularly in comparison to shear-frame and shear wall systems.

5. Discussion

The primary aim of this study is to systematically gather and integrate comprehensive data related to 55 contemporary high-rise residential timber buildings. This research predominantly focuses on the architectural and structural elements of these towers with the objective of deepening our understanding of the intricacies involved in designing and constructing high-rise buildings. Ultimately, this research aims to make a significant addition to the existing knowledge base in the field of high-rise structure design and construction.

The results outlined in this paper demonstrate similarities and differences when compared to previous research efforts, such as those conducted by (e.g., [54,114]). The main findings from this study can be summarized concisely as follows:

(1) Europe, especially Nordic nations, emerged as the region with the largest quantity of high-rise residential timber buildings, with North America and the UK also displaying a similar trend.
(2) Central cores were the most frequently chosen core configuration, with peripheral configurations being the second most adopted option.
(3) Prismatic shapes were the most preferred design choices.
(4) The extensive use of (pure) timber as a construction material was prevalent, with timber and concrete composite combinations being the next most employed.
(5) Structural systems were largely characterized by the utilization of shear walled frames and shear wall systems.

In the context of high-rise residential timber buildings, there was a strong inclination towards using central cores. Likewise, when investigating the efficient use of space in mid-rise timber apartment complexes in Finland, the results showed that floor layouts with a square shape were predominantly conducive to maximizing the utilization of central core space [54]. Moreover, in studies related to tall and supertall structures constructed using non-timber materials, a consistent pattern of central core predominance was noted [115–117]. Similarly, Oldfield and Doherty [90] determined that 85% of the sampled 500 tall buildings built from non-timber materials featured central core configurations as the prevailing design.

High-rise residential timber towers often showcased the use of prismatic forms characterized by linear designs and uniform extensions. This discovery was supported by the outcomes of Tuure and Ilgın's paper [54], which observed 55 wooden residential buildings of medium height displaying these uncomplicated arrangements. The results reported by Kuzmanovska and her colleagues [64] provided additional validation for the prevalence of prismatic geometries in multi-story buildings. Likewise, in line with the conclusions drawn in reference [114], prismatic configurations constituted the majority (>44%) among the 18 non-timber supertall residential buildings (out of a total of 93) investigated. It is also worth noting that modern supertall residential buildings, primarily constructed with reinforced concrete, predominantly employ prismatic forms, as emphasized in reference [116].

In the realm of high-rise residential construction, there was a widespread adoption of pure timber as a building material, followed closely by the utilization of composite materials combining timber and concrete. A significant evolution within the realm of construction has centered on the widespread adoption of composite materials, marking a pivotal shift in the industry's landscape. Among the diverse array of composite materials at the forefront, the fusion of timber and concrete has risen to prominence as the preeminent and most highly sought after choice for composite construction. This predilection for timber and concrete composites can be attributed to their exceptional versatility and the array of distinct advantages they afford, which have positioned them as the frontrunners in the field of modern construction [114]. Timber and concrete composites represent a harmonious marriage of two contrasting but complementary materials, each bringing its own unique characteristics to the construction process. Timber, a classic and time-tested building material, offers natural warmth and aesthetic appeal [118,119], while concrete contributes unparalleled strength, durability, and versatility. This fusion of materials harnesses the strengths of both wood and concrete, resulting in a construction approach that capitalizes on the best of both worlds.

In terms of structural systems for timber buildings, a discernible hierarchy has evolved that is closely tied to the height of the structure. This hierarchy is critical in determining the optimal structural approach for different types of timber buildings. For high-rise timber buildings, those that reach considerable heights, the primary and favored choice revolves around shear walled frame and shear wall systems. These systems are designed to efficiently distribute lateral loads and provide the necessary stability, making them the top selections for high-rise timber structures. The preference for these systems stems from their proven track record in handling the unique challenges posed by high-rise timber buildings, such as wind and seismic forces. As a result, they have become the go-to choices for ensuring the structural integrity of these structures. In the case of mid-rise timber structures, those that are not as tall as their high-rise counterparts, a prevailing trend emerges, emphasizing the use of shear wall systems.

This distinction in structural preference sets mid-rise buildings apart from their taller counterparts. Shear wall systems offer an effective balance between structural stability and construction efficiency, making them well suited for buildings of mid-rise height [54]. This preference is driven by the need to maintain cost-effectiveness while ensuring structural robustness in mid-rise timber constructions.

Conversely, when dealing with the construction of supertall timber buildings, which represent an elite category of exceptionally tall structures, a unique and distinctive trend emerges. These extraordinary structures often employ outriggered frame systems, which offer a compelling solution for addressing the distinct challenges associated with their extreme height [120,121]. Outriggered frames distribute lateral forces throughout the building, enhancing its overall stability [122,123].

The available empirical data in this study are constrained to buildings that have been both completed and are currently under construction. These buildings must also meet the criteria of being at least eight stories tall or taller. Due to the limited global presence of high-rise timber structures, it is not feasible to further subdivide the data with a specific focus on the 55 high-rise residential timber buildings, as doing so may introduce bias into the results. Nevertheless, it is worth noting that the number of buildings falling within the scope of this study has increased significantly in recent decades, potentially paving the way for more diverse subcategories in the future. Additionally, future research endeavors could extend their scope to include timber buildings that are less than eight stories in height, thereby incorporating a wider variety of lower-rise timber structures in the sample set.

Potential future studies that could further advance the research on high-rise residential timber buildings: (1) Economic analysis and cost-effectiveness: Conduct a comprehensive economic analysis to assess the long-term cost-effectiveness of high-rise timber buildings. This study could compare initial construction costs, maintenance expenses, and the return on investment over time. (2) Architectural design and aesthetics: Explore the architectural design possibilities and aesthetics of high-rise timber buildings. Investigate how innovative designs can be integrated into these structures, enhancing their visual appeal and functionality. (3) Regulatory and policy analysis: Investigate the regulatory and policy frameworks in various regions that support or hinder the development of high-rise timber buildings. Analyze the impact of building codes, zoning regulations, and incentives on the adoption of timber construction. (4) Occupant satisfaction and well-being: Study the experiences of occupants living in high-rise timber buildings, focusing on aspects like thermal comfort, indoor air quality, noise levels, and overall well-being. Assess how timber construction affects the quality of life for residents. (5) Material sourcing and supply chain analysis: Examine the availability and sustainability of timber resources for high-rise construction. Investigate the supply chain and explore strategies for responsible sourcing and procurement. (6) Public perception and acceptance: Study public perception and acceptance of high-rise timber buildings. Conduct surveys and interviews to understand how communities view these structures and whether there are any barriers to acceptance.

These future studies could contribute to a more comprehensive understanding of high-rise residential timber buildings and help architects, engineers, and policymakers make informed decisions when planning and implementing sustainable projects in this domain.

6. Conclusions

In the contemporary era, there is a growing trend in Europe of constructing high-rise residential buildings using timber as the primary building material. These structures are notable for their central core designs and the utilization of shear walled frame and shear wall systems, which are primarily composed of (pure) timber material. Architects undertaking the design of these tall residential skyscrapers face a complex challenge in balancing three key factors: aesthetics, functionality, and environmental sustainability. Achieving this delicate equilibrium is crucial, as it facilitates the creation of remarkable tall timber buildings that not only align with modern architectural principles but also emphasize a strong dedication to ecological responsibility.

The finite nature of timber as a resource poses a critical challenge for the sustainable development of the timber construction sector, particularly in light of the increasing prevalence of taller timber buildings. As the demand for timber rises, scientific approaches must be employed to address resource limitations. This involves conducting comprehensive life cycle assessments to quantify and minimize environmental impacts, optimizing forest management practices to ensure sustainable harvesting and reforestation, exploring innovative engineered wood products that enhance resource efficiency, and promoting circular economy principles to extend the lifespan of timber materials through recycling and repurposing. Additionally, strategic urban and agroforestry initiatives, coupled with responsible sourcing certifications, can contribute to a more sustainable timber supply chain. Educating stakeholders about the finite nature of timber resources and advocating for balanced practices that integrate alternative materials and construction techniques are essential steps in directing the timber construction sector towards a more environmentally resilient and sustainable future.

The regulations and expectations surrounding high-rise residential timber buildings, which represent a relatively new architectural category, are still in a state of flux. Designing these structures is a multifaceted undertaking, and the design process is in a constant state of evolution, driven by technological advancements and new methods of wood construction. The diversity in design and construction approaches for such buildings is continually changing to accommodate various factors such as building codes, market demands, regulatory restrictions, contextual influences, and climate conditions. This paper presents the most up-to-date evaluation of this new building typology.

Funding: This research received no external funding.

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

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

Appendix A. High-Rise Residential Timber Buildings

#	Building Name	Country	City	Height (Meters)	# of Stories	Completion Date
1	Ascent	United States	Milwaukee	87	25	2022
2	HAUT	Netherlands	Amsterdam	73	22	2022
3	De Karel Doorman	Netherlands	Rotterdam	71	22	2012
4	Roots Tower	Germany	Hamburg	65	19	UC
5	Brock Commons Tallwood House	Canada	Vancouver	58	18	2017
6	Hyperion	France	Bordeaux	55	16	2021
7	Rundeskogen Hus B	Norway	Sandnes	55	16	2013
8	Treet	Norway	Bergen	49	14	2015
9	Lighthouse Joensuu	Finland	Joensuu	48	14	2019
10	Cederhusen	Sweden	Stockholm	44	13	UC
11	Hoas Tuuliniitty	Finland	Espoo	44	13	2021
12	Tallwood 1 at District 56	Canada	Victoria	42	12	UC
13	Origine	Canada	Quebec	41	13	2017
14	INTRO Residential Tower	United States	Cleveland	40	9	2022
15	Sensations	France	Strasbourg	38	11	2019
16	Rundeskogen Hus C	Norway	Sandnes	38	11	2013
17	Monterey	Australia	Brisbane	37	12	2021
18	Trafalgar Place	UK	London	36	10	2015
19	Aveo Bella Vista	Australia	Sydney	36	11	2018
20	Kringsja Studentby	Norway	Oslo	34	10	2018
21	Rundeskogen Hus A	Norway	Sandnes	34	10	2012
22	SKAIO	Germany	Heilbronn	34	10	2019
23	Dalston Works	UK	London	34	10	2017
24	The Cube Building	UK	London	33	10	2015
25	Forte	Australia	Melbourne	32	10	2012
26	Botanikern	Sweden	Uppsala	31	9	2019
27	Cenni di Cambiamento	Italy	Milan	31	9	2013

#	Building Name	Country	City	Height (Meters)	# of Stories	Completion Date
28	Kajstaden	Sweden	Vasteras	31	9	2019
29	Press House	UK	London	31	9	2017
30	Vallen	Sweden	Vaxjo	31	9	2015
31	Stadthaus	UK	London	29	9	2009
32	Carbon12	United States	Portland	29	8	2018
33	Moholt 50/50	Norway	Trondheim	28	9	2016
34	Arbora Condominium	Canada	Montreal	27	8	2019
35	Contralaminada	Spain	Lleida	27	8	2014
36	DAS Kelo	Finland	Rovaniemi	27	8	2019
37	Docenten	Sweden	Vaxjo	27	8	2018
38	Dramsvegen	Norway	Tromso	27	8	2017
39	Frostaliden	Sweden	Skövde	27	8	2018
40	Highpoint Terrace	UK	London	27	8	2017
41	Jo & Joe	France	Gentilly	27	8	2019
42	Limnologen	Sweden	Vaxjo	27	8	2014
43	Maskinparken TRE	Norway	Trondheim	27	8	2018
44	Puukuokka Housing Block	Finland	Jyvaskyla	27	8	2018
45	Residences J.Ferry	France	Saint-Dié-des-Vosges	27	8	2014
46	St. Dié-des-Vosges	France	Saint-Dié-des-Vosges	27	8	2014
47	Strandparken	Sweden	Stockholm	27	8	2014
48	The Gardens Macarthur	Australia	Sydney	27	8	2018
49	Trummens Strand	Sweden	Vaxjo	27	8	2019
50	Wood City Residential Buildings	Finland	Helsinki	27	8	2018
51	Lucien Cornil Student Residence	France	Marseille	27	8	2017
52	Pentagon I	Norway	As	27	8	2013
53	Emmons on 3rd	United States	Seattle	26	8	2014
54	Bridport House	UK	London	27	8	2010
55	Pentagon II	Norway	As	24	8	2013

Appendix B. High-Rise Residential Timber Buildings by Building form, Core Type, 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	HAUT	Free	Peripheral	Shear walled frame	Composite (T + C)
3	De Karel Doorman	Prismatic	Peripheral	Shear walled frame	Composite (T + C + S)

	Building Name	Building Form	Core Type	Structural System	Structural Material
4	Roots Tower	Prismatic	Central	Shear walled frame	Composite (T + C)
5	Brock Commons Tallwood House	Prismatic	Peripheral	Shear walled frame	Composite (T + C)
6	Hyperion	Free	Central	Shear walled frame	Composite (T + C + S)
7	Rundeskogen Hus B	Free	Central	Shear walled frame	Composite (T + C)
8	Treet	Prismatic	Peripheral	Trussed-tube	Timber
9	Lighthouse Joensuu	Prismatic	Central	Shear wall	Timber
10	Cederhusen	Prismatic	Central	Shear wall	Timber
11	Hoas Tuuliniitty	Prismatic	Peripheral	Shear wall	Timber
12	Tallwood 1 at District 56	Prismatic	Central	Shear trussed frame	Composite (T + S)
13	Origine	Free	Central	Shear wall	Timber
14	INTRO Residential Tower	Prismatic	Peripheral	Shear walled frame	Composite (T + C)
15	Sensations	Free	Central	Shear walled frame	Timber
16	Rundeskogen Hus C	Free	Central	Shear walled frame	Composite (T + C)
17	Monterey	Free	Peripheral	Shear walled frame	Composite (T + C + S)
18	Trafalgar Place	Prismatic	Peripheral	Shear wall	Timber
19	Aveo Bella Vista	Free	Central	Shear walled frame	Composite (T + C)
20	Kringsja Studentby	Prismatic	Central	Shear walled frame	Timber
21	Rundeskogen Hus A	Free	Central	Shear walled frame	Composite (T + C)
22	SKAIO	Prismatic	Central	Shear walled frame	Composite (T + C)
23	Dalston Works	Prismatic	Central	Shear wall	Timber
24	The Cube Building	Free	Central	Shear walled frame	Composite (T + C + S)
25	Forte	Prismatic	Central	Shear wall	Timber
26	Botanikern	Prismatic	Peripheral	Shear trussed frame	Timber
27	Cenni di Cambiamento	Free	Central	Shear wall	Timber
28	Kajstaden	Prismatic	Peripheral	Shear wall	Timber
29	Press House	Prismatic	Central	Shear walled frame	Timber
30	Vallen	Prismatic	Central	Shear walled frame	Composite (T + C)
31	Stadthaus	Prismatic	Central	Shear wall	Timber
32	Carbon12	Prismatic	Central	Shear trussed frame	Composite (T + S)
33	Moholt 50/50	Prismatic	Central	Shear wall	Timber
34	Arbora Condominium	Prismatic	Peripheral	Shear walled frame	Timber
35	Contralaminada	Prismatic	Central	Shear wall	Timber
36	DAS Kelo	Prismatic	Peripheral	Shear walled frame	Timber
37	Docenten	Prismatic	Peripheral	Shear wall	Composite (T + C)
38	Dramsvegen	Prismatic	Peripheral	Shear wall	Composite (T + C)
39	Frostaliden	Prismatic	Central	Shear walled frame	Composite (T + C)

	Building Name	Building Form	Core Type	Structural System	Structural Material
40	Highpoint Terrace	Prismatic	Peripheral	Shear wall	Timber
41	Jo & Joe	Prismatic	Peripheral	Shear walled frame	Composite (T + C)
42	Limnologen	Prismatic	Central	Shear wall	Composite (T + C + S)
43	Maskinparken TRE	Prismatic	Central	Shear wall	Timber
44	Puukuokka Housing Block	Prismatic	Central	Shear wall	Timber
45	Residences J.Ferry	Prismatic	Peripheral	Shear walled frame	Timber
46	St. Dié-des-Vosges	Prismatic	Peripheral	Shear walled frame	Timber
47	Strandparken	Prismatic	Peripheral	Shear wall	Composite (T + S)
48	The Gardens Macarthur	Prismatic	Peripheral	Shear wall	Timber
49	Trummens Strand	Prismatic	Peripheral	Shear wall	Timber
50	Wood City Residential Buildings	Prismatic	Peripheral	Shear walled frame	Timber
51	Lucien Cornil Student Residence	Prismatic	Peripheral	Shear walled frame	Composite (T + C)
52	Pentagon I	Prismatic	Central	Shear wall	Timber
53	Emmons on 3rd	Prismatic	Central	Shear wall	Composite (T + C)
54	Bridport House	Prismatic	Peripheral	Shear wall	Timber
55	Pentagon II	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; '(T + S)' indicates composite/hybrid structures combining timber and steel.

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