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High-Rise Timber Offices: Main Architectural and Structural Design Parameters

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Abstract: High-rise office structures constructed using timber material (with a minimum of eight stories) signify a burgeoning and favorable sector, mainly owing to their ability to offer substantial environmental and economic advantages across their lifespan. However, it is crucial to recognize that the current corpus of scholarly literature lacks a thorough investigation into vital aspects concerning the architectural and structural planning of these sustainable structures. In an effort to fill this gap and augment the understanding of advancing international tendencies, this paper delved into data originating from 27 high-rise offices on a worldwide scale. The primary findings were: (i) Central core arrangements were the most popular, accounting for 67%, followed by peripheral types at 22%. (ii) Prismatic designs were the most frequently used at 85%, with free forms making up 11%. (iii) Material combinations involving timber and concrete were widely prevalent, making up 70% of composite constructions, which were 74% of the sample group, with pure timber constructions at 26%. (iv) Structural systems predominantly utilized shear walled frame systems, comprising 85% of the total. This article serves as a valuable resource for architectural designers, offering guidance on planning and executing future sustainable developments in the domain of high-rise timber office.

Keywords: timber/wood; high-rise; office; architectural and structural design parameters

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1. Introduction

Architectural evolution of contemporary urban spaces reflects a compelling narrative characterized by a profound shift towards sustainability and innovation, notably embodied in the soaring structures of high-rise timber buildings [1]. These edifices, standing as symbols of departure from conventional construction norms, emerge as pioneers in a movement that not only redefines urban skylines but also challenges preconceived notions regarding environmental impact and architectural possibilities [2].

The rise of high-rise timber structures goes beyond vertical dominance, symbolizing a fusion of eco-conscious design and technological advancement [3]. The integration of sustainable materials and construction practices not only lessens the urban carbon footprint but also showcases the synergy of modern architecture with ecological responsibility. In this shift, these buildings emerge as more than structures, becoming beacons of a future where cities harmonize aesthetic grandeur with environmental stewardship, laying the foundation for a sustainable and forward-thinking urban environment [4].

The transformation of high-rise wooden office towers hinges on a meticulous exploration where technological developments, environmental stewardship, and visionary design converge [5]. Engineered wood products (EWPs), specifically cross-laminated timber (CLT), laminated veneer lumber (LVL), and glued laminated timber (GLT), lead this shift [6]. For instance, CLT benefits from streamlined manufacturing processes enabled by advanced digital technologies [7], marking a notable transformation in urban architecture [8].

EWPs have evolved significantly over centuries, starting with ancient practices of laminating thin wood veneers and advancing through modern innovations in adhesives and manufacturing processes [9]. Plywood, made by gluing together thin layers of wood veneer (plies) with the grain of adjacent layers perpendicular to each other, dating back to ancient Egypt and China, developed into a versatile material widely used in construction and furniture by the early 20th century. Particleboard, composed of wood particles (chips, shavings, sawdust) bonded together with synthetic resin or other suitable binder under heat and pressure, and MDF—made from fine wood fibers combined with wax and resin binder under high pressure and temperature—emerged in the mid-20th century, offering economical alternatives with improved dimensional stability and surface quality. OSB—consisting of layers of wood strands (chips) oriented in specific directions and bonded with adhesives—gained prominence in the 1970s for its strength and affordability in sheathing applications. As contemporary EWPs, CLT (a prefabricated multi-layer engineered wood product, manufactured from at least three layers of boards by gluing their surfaces together with an adhesive under pressure [10]), LVL (made by bonding together thin vertical softwood veneers with their grain parallel to the longitudinal axis of the section, under heat and pressure [11]), and GLT (made by gluing together several graded timber laminations with their grain parallel to the longitudinal axis of the section [12]), have been used extensively in the wood construction industry. Throughout their history, EWPs have been driven by advancements in adhesive technology and sustainability, becoming essential components in contemporary building.

Integration of modern EWPs highlights timber's versatility, strength, and sustainable construction practices, reducing carbon footprint [13]. Beyond structural benefits, EWPs enable aesthetically striking designs, fostering a connection with nature in high-rise timber office buildings, symbolizing innovation and sustainability [14]. This evolution signifies a transformative shift toward eco-friendly technologies for an esthetically stunning urban future.

Exploring high-rise timber office buildings entails a detailed analysis of structural and design intricacies, focusing on EWPs. This analysis demonstrates how EWPs are transforming vertical architecture, offering architects flexibility in designing offices and ushering in a new era of design possibilities. Case study towers like Wellington in Australia exemplify timber's transformative potential in urban office environments [15].

It is worth noting that the fire-resistance of timber buildings hinges on several key factors, including the inherent properties of timber, effective design strategies, and strict adherence to current building standards [16]. Timber has a predictable charring rate, which helps form a protective layer that insulates its core, allowing it to maintain structural integrity during a fire [17]. Additionally, fire-retardant treatments and the use of CLT, which exhibits excellent fire resistance due to its mass and charring behavior, further enhance safety [18]. Design strategies play a crucial role in fire resistance, with compartmentation creating fire-resistant barriers within the building, protected escape routes ensuring safe egress, and the integration of sprinkler systems significantly improving overall fire safety [19]. Various standards, such as the Eurocodes (EN 1995-1-2:2004) in Europe [20], the International Building Code (IBC) in the USA [21], and the National Building Code of Canada (NBC) in Canada [22], provide comprehensive guidelines for fire resistance in timber structures. These standards typically require structural elements like load-bearing walls, floors, and roofs to meet specific fire resistance ratings, quantified in minutes (e.g., 30, 60, 90, 120 min), indicating the duration these elements can withstand fire exposure while retaining their structural roles. The standards also emphasize the importance of fire compartments to prevent fire spread and mandate the use of active fire protection systems like sprinklers, especially in larger or higher-occupancy buildings. By adhering to these rigorous regulations, timber buildings are designed to effectively withstand fire hazards, ensuring both the structural integrity of the building and the safety of its occupants are preserved.

As mentioned above, pure timber buildings, particularly those utilizing advanced EWPs like CLT and GLT, have demonstrated significant fire resistance due to their predictable charring behavior [17]. When exposed to fire, these materials develop a char layer on their surface that acts as an insulating barrier, protecting the inner core from high temperatures and maintaining structural integrity. This charring occurs at a known rate, which allows for precise engineering calculations to ensure safety and compliance with fire safety standards. For instance, a properly designed CLT panel can withstand fire exposure for up to two hours or more without losing its load-bearing capacity [19]. Furthermore, the mass and density of large timber elements contribute to their slow and predictable burning behavior, unlike thinner, more combustible materials that can exacerbate fire spread. This characteristic makes pure timber buildings not only feasible but also robust in terms of fire safety, addressing concerns that traditionally might have been associated with wood as a construction material.

In this sense, hybrid timber buildings, which integrate timber with other materials such as steel and concrete, offer enhanced fire resistance by combining the advantageous properties of each material [23]. In these structures, timber elements are often encapsulated with non-combustible materials like gypsum board or concrete, providing an additional layer of protection against fire. This encapsulation can significantly delay the onset of charring, thereby extending the time the structure can withstand fire without compromising its integrity [24]. For example, timber beams encased in concrete or protected with fire-rated gypsum board can prevent the rapid progression of fire and heat, allowing more time for evacuation and firefighting efforts [25]. The use of hybrid designs also enables the construction of larger and taller buildings [26], leveraging the aesthetic and environmental benefits of timber with the proven fire-resistant properties of materials like steel and concrete. This synergy not only enhances the overall safety of the building but also meets rigorous building codes and fire safety regulations [27]. Consequently, hybrid timber buildings represent a forward-thinking approach to construction, offering both sustainability and resilience in fire-prone scenarios.

As another critical issue in the domain of high-rise timber buildings, creep deformation refers to the gradual, time-dependent deformation of wood when it is subjected to a sustained load over an extended period [28]. This process is particularly pronounced in timber due to its viscoelastic nature, where both elastic and plastic deformation components play a role. As wood creeps, stress within the structural elements is redistributed [29]. Initially loaded areas may deform and relax, causing stress to shift to other regions that were originally less loaded. Over time, this can lead to differential deformation, altering the intended load paths and potentially causing uneven settling, increased deflections, and structural integrity concerns. In high-rise timber structures, the vertical load accumulation over multiple stories exacerbates these effects, making accurate prediction and mitigation of creep-induced stress redistribution critical for ensuring long-term stability and performance of the building [30].

In addition to creep deformation, the intrinsic low density and stiffness of wood pose significant challenges related to human-induced vibrations in high-rise timber buildings [31]. The low density of wood results in a lower overall mass compared to traditional construction materials like concrete and steel, which can amplify the building's responsiveness to dynamic loads, such as those generated by foot traffic, machinery, or environmental factors like wind [32]. Furthermore, wood's lower stiffness contributes to a lower natural frequency for the structure, making it more susceptible to resonance with the frequencies generated by human activities. This can result in noticeable vibrations, which may lead to discomfort for occupants and could potentially affect the building's serviceability and perceived safety. To mitigate these issues, engineers must incorporate strategies such as increasing the mass and stiffness of the structure through hybrid construction methods, adding tuned mass dampers, and enhancing structural damping [33]. These measures help to control and reduce the amplitude of vibrations, ensuring a more stable and comfortable environment for the occupants of high-rise timber buildings.

Mitigating these above-mentioned encounters necessitates cooperative efforts among architectural and engineering disciplines, constructors, and governing entities [34]. Advances in technology, research, and ongoing experience with high-rise timber construction will contribute to overcoming these challenges and further establishing wood as a viable material for tall buildings [35].

It is worth mentioning that one of the most compelling reasons for opting for wooden construction systems is their exceptional energy efficiency across both the production and operational phases of buildings [36]. Wood, as a raw material, has a notably low embodied energy compared to traditional materials like steel and concrete [37]. This lower energy requirement during processing results in reduced carbon emissions and environmental impact during manufacturing, aligning with global sustainability goals. Furthermore, wooden structures offer significant advantages during building operation due to their natural thermal insulation properties. Wood has a high thermal resistance, which means it effectively reduces heat transfer between indoor and outdoor environments [38]. This inherent insulation capability reduces reliance on mechanical heating and cooling systems, thereby lowering energy consumption throughout the building's lifetime. By choosing wood, builders not only contribute to immediate energy savings and reduced carbon footprint but also support sustainable forestry practices that promote biodiversity and carbon sequestration [39–41]. This holistic approach underscores wood as a versatile, environmentally responsible choice for contemporary construction, addressing both current energy efficiency needs and long-term environmental stewardship.

The scientific exploration of these considerations advances knowledge, informs best practices, and contributes to the sustainable evolution of the construction industry, providing solutions that balance environmental, economic, and societal needs. Addressing a gap in scholarly literature, this article conducts a thorough investigation into the design considerations specific to high-rise office buildings made of timber. Analyzing data from 27 projects globally, the aim is to enhance the understanding of the evolving architectural landscape. This effort seeks to contribute valuable insights into the complexities associated with planning and implementing environmentally-friendly structures, enriching the existing knowledge base.

In conclusion, this paper deeply explores the complexity of high-rise timber office buildings, highlighting their transformative role in urban settings. By delving into technological intricacies, real-world applications, and environmental advantages, it was aimed to contribute significantly to the discourse on integrating high-rise timber structures. Envisioning a future where these buildings symbolize harmonious coexistence between human innovation and the natural world, the aspiration is for architecture to serve as a testament to sustainability, resilience, and a balanced relationship between urban development and the environment.

The classification of high-rise structures lacks a universally accepted standard concerning height and the number of floors, leading to ongoing debate, especially within the realm of wooden buildings. The precise definition of a 'high-rise' is particularly contentious in this context. In this paper, a 'high-rise timber building' is defined as a structure consisting of eight or more stories, aiming to contribute to the discourse with a clear and specific criterion [42].

2. Literature Review

The literature review underscores an increasing interest in wooden structural systems, particularly focusing on EWPs for various practical, ecological, societal, and economic aspects [43–45]. A notable gap exists in the architectural and structural design considerations for high-rise wooden office projects. Some studies [46,47] emphasized interdisciplinary collaboration and spatial efficiency in mid-rise timber dwellings, respectively, while others [48,49] focused on contemporary trends and global preferences, highlighting central core layouts, prismatic shapes, and sustainability. The authors of [50–52] analyzed engineering aspects, industry perspectives, and design principles of multi-story timber towers.

Design issues in high-rise European timber constructions were explored by the authors of [53–55], with a focus on geographical variations and structural classifications. The authors of [56,57] noted the financial and ecological efficiency of taller timber constructions and preferences for rigid frame structures and rectilinear floor plans. The authors of [58,59] discussed public acceptance challenges and the benefits and drawbacks of off-site mass timber manufacturing, respectively. The literature review above identifies a gap in investigating architectural and structural planning for high-rise wooden office towers, prompting this article to address and enhance understanding in the global architectural landscape.

3. Research Methods

Integration of case studies was utilized to collect, structure, and combine information pertaining to contemporary high-rise timber office towers, enabling a thorough examination and scrutiny of both their design considerations. The acceptance of the case study methodology is a customary practice in reviews associated with the built environment [60–63]. Figure 1 demonstrates the methodical attempt applied in identifying and selecting the towers under examination.

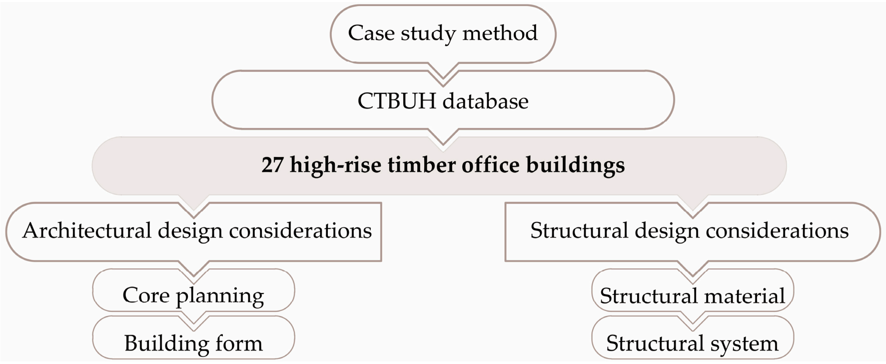

Figure 1. Flowchart of the methodology and process (image by authors).

This study encompassed an array of 27 high-rise timber office structures, either built or in the construction stage. The chosen structures were distributed across diverse locations in the world (Figure 2), with six in Australia, five in Canada, four in France, three in Germany and USA, two in Switzerland, and one each in Norway, Denmark, Japan, and UK, as detailed in Appendices A and B. The criterion for selection encompassed towers with eight floors or greater, and the data were extracted from the documents supplied by the Council on Tall Buildings and Urban Habitat (CTBUH) [42].

It is noteworthy that the CTBUH enjoys widespread recognition among the general populace due to its authoritative position in determining tall building heights and conferring the esteemed designation of 'the World's Tallest Building'. In addition to this, the CTBUH oversees the implementation of the 'Buildings of Distinction' initiative, which recognizes remarkable projects through the installation of public signboards. Operating on an international level, the CTBUH stands as an outstanding forum for the dissemination of state-of-the-art information and the facilitation of business networking.

The design characteristics of high-rise wooden structures are delineated as follows [47].

Concerning architectural features, the ensuing elements exert a significant influence:

- planning the core layout;
- building form.

Concerning structural features:

- structural/construction materials;
- load-bearing system.

The core organization suggested by [15] is utilized for its complete structure, covering the subsequent categorizations (Figure 3): (i) central core, (ii) atrium core, (iii) external core, and (iv) peripheral core.

Figure 2. Selected towers situated in various geographical regions around the world (image by authors).

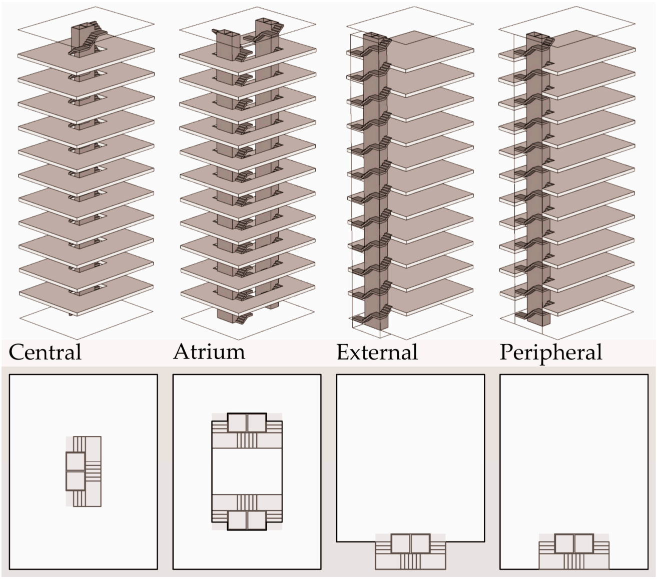

Figure 3. Core types (image by authors).

This manuscript uses the categorization of architectural forms according to the subsequent compositions, as depicted in Figure 4 [15]:

(1) Prismatic forms relate to structures described by consistency, and parallel geometric patterns at both extremities, displaying equivalent facets and vertical axes, particularly orthogonal to the ground.
(2) Setback arrangements are discerned in constructions that exhibit horizontally recessed divisions along their vertical elevation.
(3) Tapered structures are accomplished by reducing floor plans as they rise.
(4) Tilted forms relate to edifices distinguished by an architectural composition that integrates a tilted structure.

(5) Twisted configurations indicate continuous rotation as they ascend along a central axis, involving a twisting angle.
(6) Free forms are linked with constructions that diverge from the formerly specified configurations.

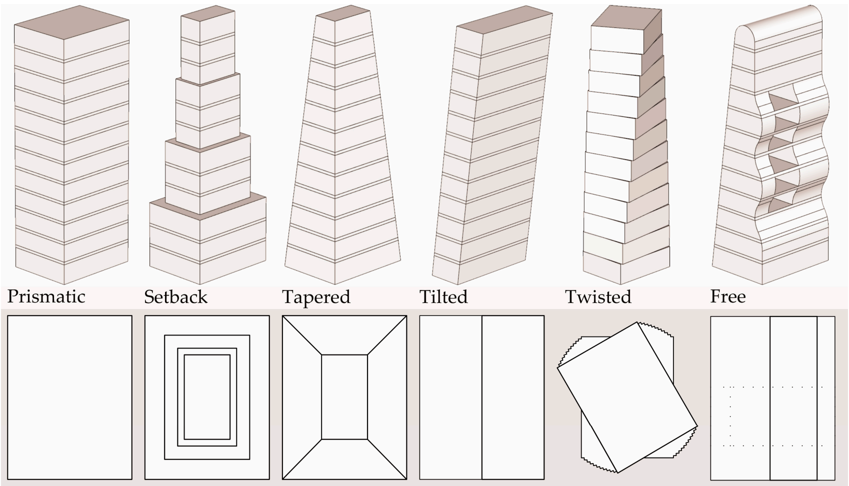

Figure 4. Building forms (image by authors).

Materials for structural use can be grouped into two groups: (a) 'timber' or 'pure timber' and (b) 'composite' or 'hybrid' materials, encompassing configurations like timber combined with concrete or steel, or amalgamations of timber, concrete, and steel (Figure 5). This article specifically focuses on main structural components, such as columns and beams, excluding consideration of horizontal building components. In alignment with this classification of construction materials for structures, to provide further clarification, a building is classified as 'timber' exclusively when both its primary vertical and horizontal load-bearing elements are entirely made of timber [47]. It is crucial to note that a construction identified as 'timber' might incorporate non-timber fasteners in particular regions connecting timber elements.

Concerning the implementation of lateral load-bearing mechanisms for tall structures, especially in addressing lateral forces, diverse load-bearing systems and categorizations are utilized. This aspect is a central topic of discussion in recent scholarly literature, such as [64]. In this article, the author opted to embrace the load-bearing system categorization delineated in [64] because of its comprehensive nature (Figure 6). It is important to highlight that supertall structures exceeding 300 m in height typically employ an outriggered frame and various tube systems. These are preferred for their efficacy and cost competitiveness. The case of Mjøstarnet in Norway serves as a rare example of a high-rise timber building that integrate features resembling tube systems.

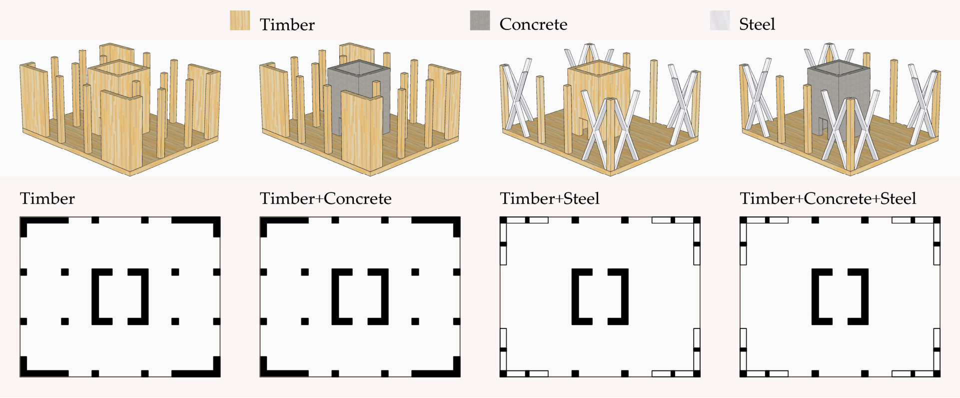

Figure 5. Structural materials (image by authors).

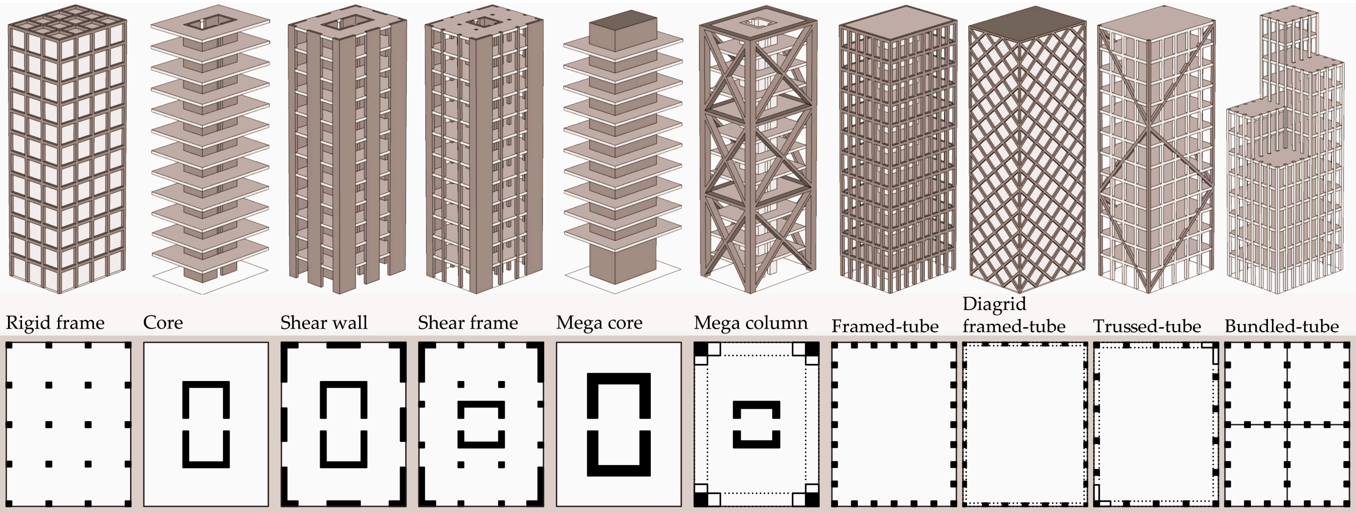

Figure 6. Structural systems (image by authors).

4. Results

4.1. Examination of Architectural Design Parameters

This part conducts a complete analysis of architectural design elements for 27 high-rise wooden office towers. These parameters include core planning and form.

4.1.1. Core Planning

Figure 7 illustrates that dominance of central core configurations, accounting for 67% of instances in high-rise timber offices, reflects a deliberate strategy to maximize both structural robustness and spatial efficiency. By centralizing the core, these designs effectively consolidate load-bearing elements and streamline vertical circulation, crucial for supporting the height and complexity typical of high-rise timber buildings. This approach not only ensures optimal use of materials but also enhances the overall stability and safety of the structure. In contrast, peripheral core layout, observed in 22% of cases, offers an alternative that may cater to specific architectural or functional needs. This configuration could provide greater flexibility in internal space utilization or accommodate unique design requirements while maintaining structural integrity. Together, these insights illustrate the evolving capabilities and adaptive potentials of timber construction in high-rise applications, where core arrangement plays a pivotal role in achieving both engineering excellence and architectural innovation.

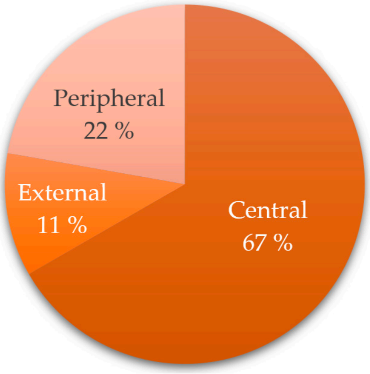

Figure 7. Examined cases by core type.

Moreover, the multifaceted benefits inherent in the adoption of a central core arrangement are intricately supported by empirical evidence derived from scholarly sources, particularly elucidated by [65]. One primary advantage of this configuration lies in its inherent capacity to efficiently distribute loads, thereby significantly enhancing structural strength. This efficiency is a result of the core's strategic placement, allowing for a more balanced and uniform transfer of forces throughout the architectural framework. The consequential elevation in overall stability is not only critical for the longevity of the structure but also bears implications for its resilience against external forces, such as seismic events or dynamic loads.

The optimization of design for space efficiency within the central core arrangement is a pivotal aspect of its widespread adoption. By consolidating key structural elements centrally, the architectural layout achieves an intelligent utilization of space, maximizing functionality within the confines of the given spatial parameters. This optimization extends beyond mere spatial efficiency; it also translates into a more adaptable and versatile environment, accommodating a spectrum of potential uses.

The creation of open spaces is a logical corollary of the central core arrangement's design philosophy. By concentrating essential structural components centrally, peripheral spaces are liberated, affording architects and occupants the flexibility to tailor these areas to specific needs. This adaptability is not only aesthetically pleasing but also serves functional purposes, allowing for the integration of communal spaces, recreational zones, or customized configurations in response to evolving needs.

The positive impact on fire safety measures constitutes another significant advantage of the central core arrangement. The centralized core facilitates a more effective compartmentalization strategy, limiting the potential spread of fire and confining its impact to specific zones. This strategic containment not only enhances the safety profile of the structure but also provides crucial time for intervention and evacuation measures during emergencies.

4.1.2. Form

The predominant use of prismatic structures in high-rise timber office designs, accounting for 85% of occurrences (Figure 8), suggests a strong architectural preference likely driven by structural and practical considerations. Prismatic forms, characterized by their simple geometry and uniform verticality, are inherently well-suited for maximizing space efficiency and structural stability in tall buildings. In contrast, the infrequent utilization of free and setback forms, totaling only three occurrences, indicates a less common but potentially innovative approach to design within this context. Free forms can offer greater design flexibility and aesthetic variation, while setback forms can provide opportunities for outdoor spaces and visual interest. The rarity of these forms suggests that while there is some interest in exploring unconventional design approaches, the industry may still be navigating technical challenges or regulatory constraints associated with these alternatives.

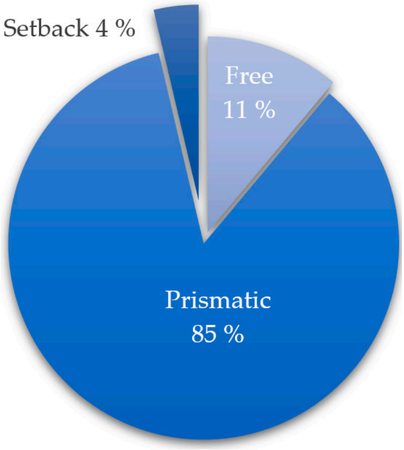

Figure 8. Examined cases by building form.

Prevalence of prismatic configurations in high-rise timber structures is explained by their advantageous characteristics [47].

1. Simplified Construction Procedure:
    - Geometric simplicity mitigates complexities in the construction process.
2. Practicality:
    - Conforms seamlessly to conventional construction methods, reducing labor and material expenses.
3. Effective Spatial Utilization:
    - Combined with rectangular floor layouts, enhances internal space efficiency.
    - Straightforward, orthogonal arrangements optimize space utilization, reducing unnecessary areas.
4. Economic Efficiency:
    - Compatibility with standardized construction methods makes prismatic configurations an economical choice.
    - Straightforward design minimizes complexities, lowering the likelihood of errors or delays, enhancing overall efficiency and cost-effectiveness.

Architects' growing endorsement of non-prismatic forms in high-rise timber office buildings stems from a fervent pursuit of unique and striking architectural designs. Motivated by a quest for unique expression and the desire to craft iconic structures, architects are increasingly inclined to delve into free forms [66]. Departing from conventional rectangular shapes, these architectural articulations offer an expansive canvas for architects to explore and materialize imaginative and groundbreaking concepts.

This trend allows architects to break from traditional design constraints, pushing creative limits and redefining aesthetics in high-rise timber constructions. Embracing free forms showcases a dynamic evolution in architectural expression, opening possibilities for inventive solutions in tall wooden edifices. Architects utilizing non-traditional geometries create structures that are functional and fascinating works of art.

4.2. Anlaysis of Architectural Design Parameters

This part engages in an extensive evaluation of structural design considerations for the ensemble of 27 high-rise wooden office towers. The analysis encompasses two pivotal factors essential to the overall structural integrity and performance: (i) structural material, and (ii) structural system.

4.2.1. Structural Material

Figure 9 indicates a predominant preference for hybrid structural systems in high-rise timber offices, comprising 74% of the instances analyzed. This suggests a strategic approach where timber is integrated with other materials to optimize structural performance and overcome inherent limitations of timber alone at greater heights. The remaining 33% of instances are solely timber structures, highlighting a growing but still limited adoption of pure timber systems in high-rise office construction. This trend underscores a cautious yet progressive shift towards utilizing timber as a viable material in tall buildings, supported by advancements in engineering techniques and materials science aimed at enhancing its load-bearing capacity and fire resistance.

The advantages of hybrid materials actively contribute to the preference for high-rise timber office buildings:

(i) Structural Robustness and Load-Carrying Capability [67]: Timber's commendable strength-to-weight ratio is enhanced by incorporating steel or concrete for augmented load-carrying capacity.

(ii) Structural Stability and Rigidity [68]: Integration with steel or concrete provides supplementary stiffness and stability, mitigating sway during wind or seismic events.

(iii) Fire Resilience [69]: Incorporating non-combustible materials like steel or concrete enhances overall fire resilience, meeting building code requirements for occupant safety.
(iv) Environmental Sustainability [70]: Wood's reduced carbon footprint contributes to overall ecological impact reduction. Integrating timber in hybrid structures aligns with the increasing emphasis on sustainable construction practices.
(v) Energy Efficiency [71]: Wood's inherent insulating properties, combined with other materials, optimize insulation and thermal performance, reducing the need for additional energy consumption.
(vi) Construction Speed and Economic Efficiency [72]: Premanufacturing components accelerates construction, enhancing economic efficiency. Hybrid structures allow the use of materials with varied manufacturing procedures, facilitating a faster and cost-effective construction schedule.

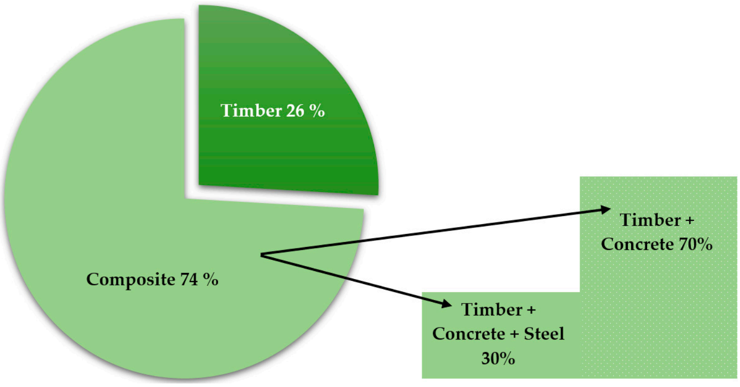

Figure 9. Examined cases by structural material.

In Figure 9, composite buildings are depicted, categorized based on the clustering of structural materials. Noteworthy is the prevalence of timber combined with concrete, accounting for 70% of the instances.

It is worth noting that composite timber/wood structures combine timber and concrete to leverage the strengths of both materials. There are several specific forms of these composites, each with unique advantages and disadvantages:

1. Wood–Concrete Composite (WCC) [73–75]: In WCC, a concrete slab is bonded to a timber beam or deck using connectors like steel dowels or adhesive. Its advantages are as follows: (i) Structural Efficiency: Combines the high compressive strength of concrete with the tensile strength of timber. (ii) Lightweight: Generally lighter than traditional reinforced concrete structures. (iii) Improved Fire Resistance: Timber is protected by the concrete, enhancing fire performance. (iv) Sustainability: Uses timber, a renewable resource, and reduces concrete usage. On the other hand, WCC's disadvantages are as follows: (i) Complexity: Requires careful design and detailing to ensure effective composite action. (ii) Cost: Initial costs may be higher due to specialized connectors and construction techniques. (iii) Durability: Timber may require maintenance to prevent decay.
2. Timber–Concrete Composite (TCC) [76–78]: TCC involves embedding a concrete slab within a timber structure, typically using connectors or shear studs. Its advantages are as follows: (i) Strength and Stiffness: Enhances bending stiffness and load-carrying capacity. (ii) Reduced Weight: Compared to solid concrete structures. (iii) Aesthetics: Utilizes natural timber finishes. (iv) Fire Resistance: Concrete provides fire protection to timber elements. On the other hand, TCC's disadvantages are as follows: (i) Construction Complexity: Requires careful detailing and construction techniques. (ii) Moisture Sensitivity: Timber may be sensitive to moisture, requiring protection. (iii) Long-Term Behavior: Requires monitoring and maintenance to ensure durability.
3. Glulam–Concrete Composite [79–81]: Glued laminated timber beams are combined with a concrete slab, often with mechanical connectors or shear studs. Its advantages

are as follows: (i) Strength and Stiffness: Efficient load transfer between materials. (ii) Fire Resistance: Concrete protects the timber. (iii) Architectural Versatility: Can be used in various structural forms. On the other hand, its disadvantages are as follows: (i) Complex Design: Requires expertise in both timber and concrete design. (ii) Maintenance: Requires periodic inspection and maintenance due to exposure. (iii) Cost: Can be higher due to specialized construction methods.

Each form of composite wood and concrete structure offers distinct benefits, primarily centered around structural performance, sustainability, and aesthetic appeal. However, they also require careful consideration of design, construction, and maintenance to realize their full potential and longevity.

The inclusion of a concrete core in composite structures is guided by multiple considerations. Firstly, it significantly enhances horizontal stiffness, improving structural integrity, especially against lateral forces like seismic activities or strong winds. Secondly, concrete in the core provides inherent fire resistance, crucial for safety and meeting stringent standards. Thirdly, the decision is driven by concrete's ability to dampen building sway, addressing the challenge of lateral movement induced by wind forces, contributing to overall stability and occupant comfort in high-rise structures.

Effectively managing building sway is crucial, especially in tall structures, posing a significant challenge to structural safety and overall serviceability [82]. This extends beyond material variations, demanding a universal focus on sway control approaches. Engineers play a key role in mastering sway control, particularly during turbulent weather like windstorms, ensuring structural integrity and user comfort. Ensuring building sway remains within standard limits is crucial for those on the upper floors., enhancing the overall safety and well-being of occupants and contributing to a safer built environment.

The establishment of a concrete podium at ground level, as highlighted in examined instances, offers diverse benefits supported by research [83]. This intentional choice enables the seamless integration of facilities, enhancing accessibility for occupants. It also results in well-lit communal areas with expansive openings, improving the aesthetic appeal and functionality of the ground floor. Additionally, the concrete podium serves as fire-resistant space for crucial mechanical and electrical facilities [84], enhancing safety protocols and optimizing spatial utilization. This emphasizes the deliberate integration of structural elements with practical and safety-oriented considerations in the architectural framework.

4.2.2. Structural System

In the context of high-rise timber office construction, the predominance of shear–frame systems, specifically the subtypes 'shear walled frame' and 'shear trussed frame' detailed in Figure 6, can be attributed to several structural advantages. Shear-walled frame systems, in particular, emerge as the overwhelming preference, comprising 85% of selected systems in scrutinized towers as shown in Figure 10. This preference underscores their effectiveness in distributing lateral forces throughout the building, ensuring stability and resilience against seismic activity or wind loads. The lower adoption rate of tube systems, observed in only one instance, suggests less favorability, likely due to challenges in adapting traditional steel or concrete tube designs to timber's properties, such as its lower stiffness-to-weight ratio and different structural behavior under stress. Therefore, the dominance of shear-walled frame systems highlights their optimized performance in high-rise timber structures, balancing structural integrity with the inherent characteristics of timber as a building material.

In the domain of shear–frame systems, encompassing both shear-trussed frame and shear-walled frame systems, a thorough comprehension arises when assessing the respective disadvantages and limitations of each component system. Research, as delineated in reference [85], proposes that the inherent limitations of a rigid frame, when compared to the benefits of shear truss or wall systems and vice versa, can be effectively mitigated by strategically combining these members.

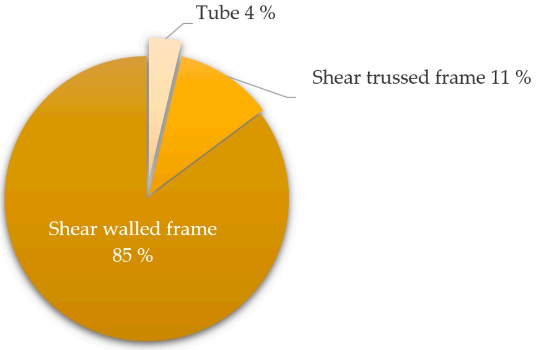

Figure 10. Examined cases by structural system.

Shear-trussed and shear-walled frame systems collaborate synergistically, balancing each other's limitations and enhancing structural integrity. This symbiotic association is evident in applications where frames fortify upper levels, reinforcing shear trusses or walls and vice versa. The resulting shear–frame systems exhibit exceptional resilience against horizontal loads, surpassing the stiffness achieved by depending on a shear wall or a rigid frame system.

5. Discussion

The results demonstrate both parallels and distinctions when juxtaposed with previous investigations, encompassing those previously carried out by researchers such as [86]. The main findings are as follows:

(i) Regarding core configuration, the dominant choice is the central core design.
(ii) Prismatic form assumes prominence as the prevailing design preference.
(iii) One prominent tendency is the extensive adoption of hybrid materials, with the melding of timber and concrete emerging as the prevalent selection in hybrid usage.
(iv) Employed structural systems demonstrate a distinct inclination towards shear–frame configurations, particularly emphasizing shear-walled frames.

It is worth mentioning that when considering high-rise timber office buildings specifically, the challenges often become more pronounced due to the unique requirements of office spaces and the height of the buildings. Here are some specific problems [87]:

1. Fire Safety Concerns [88]: (i) Code Compliance: Meeting stringent fire safety codes can be particularly challenging for high-rise wooden buildings housing offices. Ensuring adequate fire resistance in materials and design is crucial. (ii) Evacuation and Safety: Managing evacuation routes, fire suppression systems, and safe egress becomes more complex as the building height increases.
2. Structural Integrity and Stability [89]: (i) Load-Bearing Capacity: Wood's load-bearing capacity must be carefully engineered to support the weight of multiple floors, office equipment, and occupants without compromising structural integrity. (ii) Dynamic Loads: Offices often have dynamic loads from equipment, furniture, and foot traffic, which require careful consideration in the design and construction phases.
3. Acoustic Performance [90]: (i) Noise Control: Offices require effective sound insulation to maintain a productive environment. Achieving adequate acoustic performance in a wooden high-rise can be challenging due to wood's natural properties.
4. Moisture and Environmental Conditions [91]: (i) Weather Resistance: Protecting the wooden structure from moisture, rain, and humidity is critical to prevent decay, mold growth, and structural damage over time. (ii) HVAC Requirements: Managing heating, ventilation, and air conditioning (HVAC) systems to maintain comfort and indoor air quality in high-rise wooden buildings can be complex.
5. Perception and Market Acceptance [92]: (i) Tenant and Investor Confidence: Potential tenants and investors may have reservations about the safety, durability, and long-term performance of wooden high-rises compared to traditional materials like steel

and concrete. (ii) Resale Value: Concerns about resale value and market demand for wooden office spaces could impact financing and development decisions.

6. Regulatory and Insurance Considerations [93]: (i) Building Codes: Ensuring compliance with building codes and regulations that may not have specific provisions for high-rise wooden office buildings can pose hurdles during planning and construction. (ii) Insurance Costs: Higher insurance premiums due to perceived risks associated with fire and structural integrity could affect overall project costs and feasibility.
7. Construction and Maintenance Challenges [94]: (i) Material Sourcing: Securing high-quality, sustainable wood sources suitable for high-rise office buildings may be challenging and affect project timelines and costs. (ii) Skill Requirements: Specialized construction techniques and expertise are needed for erecting and maintaining high-rise wooden structures, which may not be widely available.
8. Environmental Impact [95]: (i) Sustainability: While wood is renewable, ensuring sustainable forestry practices and minimizing environmental impact in the construction and lifecycle of high-rise wooden office buildings is essential for maintaining green credentials.

Addressing these specific challenges requires a multidisciplinary approach involving architects, engineers, developers, regulators, and stakeholders to innovate and implement solutions that ensure the safety, functionality, and sustainability of high-rise wooden office buildings.

In tall timber offices, there has been a clear preference for central cores as the dominant tendency. This inclination towards central cores is not limited to timber structures but is also prevalent in buildings made with other materials. Similarly, research on spatial efficiency in mid-rise wooden apartments in Finland has observed a consistent trend: floor layouts with square shapes tend to favor the use of a central core space [47]. Additionally, examinations of supertall towers constructed from non-timber materials underscored a current tendency of central service core domination, such as [86]. This implies that incorporating central cores strategically is a repeated and efficient method in achieving height and structural efficacy across different materials and building designs.

The research conducted by [65], investigating a cohort of 500 tall structures built from non-wood materials, provides support for this tendency. Their results disclosed that an outstanding 85% of the analyzed tall structures showcased central core configurations. This additional emphasizes the importance and extensive adoption of central core layouts in high-rise building projects, regardless of the foundational materials.

High-rise timber structures consistently adopted prismatic forms, distinguished by their rectangular outlines and extrusions. This inclination was supported by the study performed by [47], where an analysis of 55 mid-rise wooden dwellings indicated a prevalent preference for these prismatic shapes. This architectural pattern was further confirmed by the results of [59], confirming the prevalence of prismatic forms of multi-story buildings. In a comparable context, the investigation carried out by [86] offered further backing to the predominance of prismatic forms, noting that these configurations comprised the majority, surpassing 44%, among the 18 non-timber residential skyscrapers in their study of 93 cases.

Composite materials were prominently used, and among the various alternatives, the amalgamation of timber and concrete occurred as the most common choice in hybrid construction. This strategic fusion of materials appears to be preferred due to the complementary attributes and synergies that timber and concrete offer. Integrating these materials not only enhances structural rigidity but also refers to robustness and resilience considerations. This tendency was not confined to particular scales of building construction but also extended to skyscraper projects. The widespread use of composite in skyscrapers indicates that its benefits, including improved structural performance and versatility, are especially advantageous for the ambitious and complex designs commonly seen in these buildings [96]. This underscores the recognition of composite construction as a practical and operational solution for enhancing the structural and functional features of high-rise buildings.

In load-bearing systems for timber office structures, a distinct order is observed based on structure height. Shear-walled frame systems are favored for high-rise timber towers, emphasizing vertical stability and load distribution. Mid-rise timber structures lean towards shear wall systems, reflecting a nuanced approach to harmonize structural integrity and design efficiency, considering scale and load distribution differences from taller structures [47]. In contrast, the construction of supertall structures often involves the routine use of outriggered frame systems. This choice strategically addresses the exceptional tasks posed by extraordinary heights, stressing the need for horizontal stability and innovative structural arrangements for load distribution. The organization of structural systems in timber buildings seems complexly connected to their height classifications, demonstrating a detailed comprehension of structural requirements at various construction scales.

The applicability and implications of the findings can be summarized as follows:

1. Central Core vs. Peripheral Arrangements: According to this study, central core arrangements are the most popular, accounting for 67% of the high-rise timber office structures analyzed. Peripheral types follow at 22%. From an applicability point of view, this finding suggests that central core arrangements are favored, possibly due to structural efficiency and spatial organization benefits. Architects and engineers can consider this data when designing similar structures, understanding that central cores might offer advantages in terms of structural integrity and functional layout.
2. Prismatic vs. Free Form Designs: This study notes that prismatic designs are predominant, constituting 85% of the designs studied, with free forms making up 11%. From an applicability point of view, prismatic designs, which are more geometrically regular, might offer advantages in construction ease and structural stability. Free forms, while less common, could inspire more innovative and unique architectural expressions. Designers can weigh these options based on their project goals, aesthetic preferences, and structural feasibility.
3. Material Combinations: This study highlights that 70% of the composite constructions involve timber and concrete, with the remaining 26% being pure timber constructions. From an applicability point of view, composite constructions offer a balance between the strength and versatility of concrete with the sustainability and aesthetic appeal of timber. This combination is likely favored for its structural robustness while maintaining environmental benefits. Pure timber constructions, while less common, indicate a potential for projects emphasizing sustainability and timber's intrinsic properties.
4. Structural Systems: Shear-walled frame systems are reported to be the predominant structural system, comprising 85% of the total systems analyzed. From an applicability point of view, shear-walled frame systems are known for their seismic resistance and structural efficiency. This finding underscores their suitability for tall timber structures where stability and safety are paramount. Designers and engineers can leverage this data to inform their choice of structural systems, ensuring both safety and sustainability.

As implications for future design and research: (a) Design Flexibility: The findings from this study highlight a spectrum of design choices from central core arrangements to varying geometric forms and material combinations. This flexibility allows architects to tailor designs based on site-specific conditions, aesthetic preferences, and functional requirements. (b) Research Gaps and Future Directions: This study acknowledges a lack of comprehensive research in certain aspects of architectural and structural planning for high-rise timber buildings. This gap suggests opportunities for future research to delve deeper into areas such as life cycle assessments, fire safety, and innovative structural solutions. In conclusion, the findings from this study provide valuable insights into the design strategies and methods employed in high-rise timber office structures globally. Architects and engineers can leverage this knowledge to advance sustainable architectural practices, enhance structural efficiency, and innovate in the field of tall timber construction.

The observational information accessible for this investigation is explicitly restricted to buildings that have been completed or are presently in the construction phase, underscoring buildings with a height surpassing seven floors. The justification for this constraint is rooted in the worldwide dearth of high-rise wooden structures, making it impractical to further subdivide and conduct an in-depth analysis of 27 specific high-rise timber office structures due to the potential introduction of bias into the results. Nevertheless, it is essential to confirm that the total number of buildings that meet the research's predefined constraints has significantly increased in the past decades. With the rising number of high-rise wooden edifices, there is the potential for a larger pool of structures that could be considered for sub-categorization in future analyses. This potential dataset increases promises to provide deeper understandings into particular subgroups of high-rise timber constructions, promoting a more nuanced understanding of the varied attributes within this classification.

In the future, forthcoming studies could expand their scope by encompassing timber buildings below eight stories. This strategic adjustment aims to capture a more comprehensive range of structures, incorporating lower-height buildings into the sample set. By doing so, subsequent research endeavors would contribute to a more holistic understanding of wooden construction across various height categories, allowing for a more robust and representative analysis of the growing trends and dynamics in this domain.

6. Conclusions

High-rise timber office towers are gradually finding their place in the current architectural landscape. These structures feature central core arrangements and shear-walled frame systems that incorporate hybrid materials in prismatic forms. Designers face a multifaceted challenge as they endeavor to integrate aesthetics, functionality, and ecological sustainability into these extraordinary towers. Achieving a harmonious balance among these elements is paramount for the successful realization of high-rise timber office structures. Architects navigate this intricate process by harmonizing visual appeal with design finesse, thereby meeting contemporary aesthetic standards. Simultaneously, they optimize spatial efficiency and incorporate diverse functionalities to meet practical needs.

Furthermore, architects are committed to upholding environmental sustainability throughout the design and construction phases. They achieve this by utilizing renewable materials and embracing eco-conscious construction practices. This holistic approach not only aligns with modern architectural norms but also signifies a profound commitment to environmental responsibility. It marks a transformative era in the implementation of high-rise timber office buildings, demonstrating a shift towards sustainable architecture in urban landscapes.

Ultimately, the integration of these principles not only enhances the structural integrity and functionality of these green towers but also underscores their potential as iconic landmarks. By striking a delicate balance between aesthetics, functionality, and sustainability, architects pave the way for the future of high-rise timber architecture. This approach not only elevates the urban skyline but also sets a precedent for innovative design and environmental stewardship in the construction industry. Thus, these towers stand not just as structures of height and form but as testaments to a progressive vision for architecture in the 21st century.

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Appendix A. High-Rise Timber Office Buildings

#	Building Name	Country	City	Height (meters)	# of stories	Completion date
1	Metropolitan Park Building 7/8	United States	Arlington	99	23	2023
2	TRAE	Denmark	Aarhus	82	20	UC
3	Wellington	Australia	Melbourne	65	15	UC
4	Abro (Baufeld 1 Suurstoffi Campus)	Switzerland	Risch-Rotkreuz	60	15	2019
5	Sub Station No. 164	Australia	Sydney	57	14	2021
6	Geelong Civic Precinct	Australia	Greater Geelong	52	12	UC
7	Ngytan Koriayo (Geelong Civic Precinct)	Australia	Greater Geelong	52	12	UC
8	503 on Tenth	United States	Portland	50	10	2023
9	25 King	Australia	Brisbane	47	10	2018
10	2150 Keith Drive	Canada	Vancouver	45	10	UC
11	Obayashi Training Facility	Japan	Yokohama	44	11	2022
12	Palazzo Nice Meridia	France	Nice	44	10	2019
13	T3 Bayside	Canada	Toronto	42	10	2023
14	Spor X	Norway	Drammen	41	10	2021
15	T3 Sterling Road Building 5A	Canada	Toronto	40	8	UC
16	77 Wade	Canada	Toronto	38	8	2020
17	Suurstoffi 22	Switzerland	Risch-Rotkreuz	36	10	2018
18	Apex Plaza	United States	Charlottesville	35	8	2022
19	Green Office ENJOY	France	Paris	35	8	2018
20	Opalia	France	Saint-Ouen-sur-Seine	35	8	2017
21	Pont de Flandres Batiment 007	France	Paris	35	8	2019
22	Wood and Innovation Design Centre	Canada	Prince George	35	8	2014
23	38 Berkeley Square	UK	London	32	9	2024
24	Timber Pioneer	Germany	Frankfurt am Main	30	8	UC
25	EDGE Suedkreuz	Germany	Berlin	29	8	2022
26	Timber Pioneer	Germany	Frankfurt am Main	28	8	2023
27	LCT One	Australia	Dunrobin	27	8	2012
	Note on abbreviations: 'UC' indicates under construction.					

Appendix B. High-Rise Timber Office Buildings by Building Form, Core Type, Structural System, and Structural Material

#	Building Name	Building form	Core Type	Structural System	Structural material
1	Metropolitan Park Building 7/8	Prismatic	Central	Shear walled frame	Composite(T+C+S)
2	TRAE	Prismatic	Central	Shear walled frame	Composite(T+C)
3	Wellington	Setback	Central	Shear walled frame	Composite(T+C)
4	Abro (Baufeld 1 Suurstoffi Campus)	Prismatic	Central	Shear walled frame	Composite(T+C)
5	Sub Station No. 164	Free	Peripheral	Shear walled frame	Composite(T+C+S)
6	Geelong Civic Precinct	Prismatic	External	Shear walled frame	Composite(T+C)
7	Ngytan Koriayo (Geelong Civic Precinct)	Prismatic	External	Shear walled frame	Composite(T+C)
8	503 on Tenth	Prismatic	Central	Shear walled frame	Timber
9	25 King	Prismatic	External	Shear trussed frame	Timber
10	2150 Keith Drive	Free	Peripheral	Framed-tube	Composite(T+C)
11	Obayashi Training Facility	Prismatic	Peripheral	Shear walled frame	Timber
12	Palazzo Nice Meridia	Prismatic	Peripheral	Shear walled frame	Composite(T+C)
13	T3 Bayside	Prismatic	Central	Shear walled frame	Timber
14	Spor X	Prismatic	Central	Shear walled frame	Timber
15	T3 Sterling Road Building 5A	Prismatic	Central	Shear walled frame	Timber
16	77 Wade	Prismatic	Central	Shear walled frame	Composite(T+C+S)
17	Suurstoffi 22	Prismatic	Central	Shear walled frame	Composite(T+C)
18	Apex Plaza	Prismatic	Central	Shear trussed frame	Composite(T+C)
19	Green Office ENJOY	Prismatic	Central	Shear walled frame	Composite(T+C)
20	Opalia	Prismatic	Peripheral	Shear walled frame	Composite(T+C+S)
21	Pont de Flandres Batiment 007	Free	Central	Shear walled frame	Composite(T+C+S)
22	Wood and Innovation Design Centre	Prismatic	Central	Shear walled frame	Timber
23	38 Berkeley Square	Prismatic	Central	Shear frame	Composite(T+C+S)
24	Timber Pioneer	Prismatic	Peripheral	Shear walled frame	Composite(T+C)
25	EDGE Suedkreuz	Prismatic	Central	Shear walled frame	Composite(T+C)
26	Timber Pioneer	Prismatic	Central	Shear walled frame	Composite(T+C)
27	LCT One	Prismatic	Central	Shear walled frame	Composite(T+C)
	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				

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