The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2398-4708.htm

Contemporary tall residential timber buildings: what are the main architectural and structural design considerations?

Hüseyin Emre Ilgın, Markku Karjalainen and Sofie Pelsmakers
Faculty of Built Environment, School of Architecture, Tampere University, Tampere, Finland

Received 29 October 2021
Revised 30 January 2022
18 March 2022
Accepted 24 March 2022

Abstract

Purpose – This study examined data from 13 international tall residential timber building case studies to increase our understanding of the emerging global trends.

Design/methodology/approach – Data were collected through literature surveys and case studies to examine the architectural, structural and constructional points of view to contribute to knowledge about the increasing high-rise timber constructions globally.

Findings – The main findings of this study indicated that: (1) central cores were the most preferred type 10 of core arrangements; (2) frequent use of prismatic forms with rectilinear plans and regular extrusions were identified; (3) the floor-to-floor heights range between 2.81 and 3.30 m with an average of 3 m; (4) the dominance of massive timber use over hybrid construction was observed; (5) the most used structural system was the shear wall system; (6) generally, fire resistance in primary and secondary structural elements exceeded the minimum values specified in the building codes; (7) the reference sound insulation values used for airborne and impact sounds had an average of 50 and 56 dB, respectively.

Originality/value – There is no study in the literature that comprehensively examines the main architectural and structural design considerations of contemporary tall residential timber buildings.

Keywords Tall building, Residential building, Timber construction, Sustainable design considerations, Structural and architectural design considerations, Constructional aspects

Paper type Research paper

Introduction

Due to their compact land use and density, tall buildings could be one of the most sustainable solutions to grapple with rapid population growth and expansive urban sprawl (e.g. Gerges *et al.*, 2017; Opoku, 2019). Timber is considered to be one of our best allies in solving the climate crisis, owing to its potential environmental-friendly features, e.g. low carbon emissions in processing and carbon sequestration, and is at the forefront of addressing European climate policy.

Engineered wood products (EWPs) specifically are increasingly being used as structural materials toward sustainable construction (Karjalainen and Ilgın, 2021). Mass timber products are also EWPs, usually laminated from smaller boards or lamella into larger structural components, with excellent load-bearing properties and hence make it possible to build more complex timber structures (Harte, 2017). Global production of mass timber panels is estimated to more than double by 2025 compared to 2019 (when production was 1.44 million m^3) (UNECE, 2019–2020). Cross-laminated timber (CLT) dominates this production volume; it

---

© Hüseyin Emre Ilgın, Markku Karjalainen and Sofie Pelsmakers. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at http://creativecommons.org/licences/by/4.0/legalcode

International Journal of Building Pathology and Adaptation
Emerald Publishing Limited
2398-4708
DOI 10.1108/IJBPA-10-2021-0142

is a prefabricated multi-layer EWP, manufactured from at least three layers of boards by gluing their surfaces together with an adhesive under pressure. In addition to CLT, other EWPs used in building construction are laminated veneer lumber (LVL), which is made by bonding together thin vertical softwood veneers with their grain parallel to the longitudinal axis of the section, under heat and pressure; glue-laminated timber/glulam (GL) is made by gluing together several graded timber laminations with their grain parallel to the longitudinal axis of the section, and parallel strand lumber (PSL), which is made by cutting long thin strands from timber veneers.

EWPs such as CLT, for example, are being utilized in progressively demanding applications to meet the challenge of sustainable construction, and this is made possible by worldwide intensive research and development since its launch in the 1990s (e.g. Karjalainen *et al.*, 2021). The many advantages of CLT include its low carbon and high thermal insulation, its excellent in-plane and out-of-plane strength, high strength-to-weight ratio and its stability, which has allowed large-scale and taller buildings to be erected (e.g. Tulonen *et al.*, 2021). Thus, improvements in the manufacturing of EWPs as well as advances in connection systems have significantly contributed to the advanced structural performance and allowed timber to achieve great heights to rival steel and concrete.

Multistorey and tall timber buildings are a new promising industry with a high capacity for supporting the bioeconomy (Ilgın *et al.*, 2021a). Besides its potential in accomplishing significant ecological and economic life cycle benefits, it can contribute to social sustainability both within primary production and processing of materials, such as in wood-based value-chains.

The aim of this paper is to identify, collate and consolidate the information about contemporary tall residential timber buildings from the main architectural, structural and constructional points of view to increase understanding about the design and construction of tall buildings, with a specific focus on residential buildings.

To achieve this goal, information was gathered from 13 tall residential timber buildings with completed status. At the time of writing, these 13 case studies were the complete number of existing residential timber buildings over 8 storeys in the world.

The scope of the study was limited by the obtainable data and uses four main points to identify emerging trends in tall residential timber construction: General information (building name, location – country and city, height, number of storeys, number of residential units and construction period), architectural design considerations (building form, core type and floor-to-floor-height), structural design considerations (structural system and structural material) and constructional aspects (gross floor area, total construction cost, construction cost per m^2 and the amount of timber). Additionally, information about the fire resistance of the main and secondary structural elements, and sound insulation values (airborne and impact sounds) for multistorey housing by country is provided in this study. Despite an in-depth literature survey and correspondence with companies involved in the projects, some important information (e.g. owner and/or user evaluations) was not available, which could otherwise have further contributed to the value of the study. It is also recognized that social issues play a role in the long-term feasibility and sustainability of tall residential buildings (Gifford, 2007); however, this was not the focus of this paper.

By revealing these up-to-date characteristics of contemporary tall residential timber buildings, it is believed that this research will contribute to assisting and guiding architects in the design and implementation of future tall residential timber building projects. This study offers an introductory overview of considerations that are important to the design of tall residential timber buildings, most of which were built with CLT (see Table 5).

Potential benefits of timber compared to other building materials

Globally, for more than a century steel and concrete have been the default structural material for the design and construction of tall buildings. Nevertheless, timber has typically been utilized in single and multi-residential construction projects for many centuries all over the world. There is much research from different perspectives about the benefits of wood over non-wood substitutes such as steel and concrete, a summary is provided below.

While concrete production accounts for about 8% of world CO_2 emissions, timber construction represents a lower embodied energy consumption compared to the production of steel and concrete (Andrew, 2018). The buildings using steel and concrete embody and consume 12 and 20% more energy than timber buildings, respectively (CWC, 2007). For example, the global warming potential of the 10-storey Forté building (Case 10 – see Table 1) constructed with CLT panel is 22% lower than a similar reference building with reinforced concrete due to the latter having a higher embodied energy impact and also higher operational energy use (Durlinger *et al.*, 2013). The Forté CLT building has lower embodied carbon and uses less energy during the in-use phase, due to decreased electricity use in heating and cooling, and decreased natural gas use for the hot water supply (see Figure 1). Other studies found that embodied carbon can contribute up to 80% of a residential building's total life cycle emissions (Chastas *et al.*, 2018), and the selection of the structural material has a considerable effect on the embodied carbon.

By using bio-based materials with high carbon storage capacities, such as wood technologies and construction assemblies, a man-made global carbon sink can be created, while also reducing CO_2 emissions associated with construction industry activities.

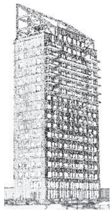
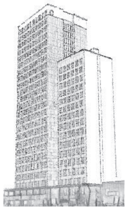
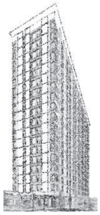
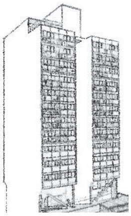
Additionally, in both manufacturing and on-site construction, steel and concrete buildings use 7 and 50% more resources while generating 6 and 16% more solid waste than wood (CWC, 2007). Furthermore, steel and concrete buildings release 10 and 12% more air pollution and discharge 3 and 2.25 times more water pollution, respectively (CWC, 2007). In concrete and steel construction, the associated embodied carbon emissions are largest at the design and construction stages (i.e. "upfront carbon"); some of this impact can be reduced if the components can be reclaimed and reused at the end of life. The significantly reduced embodied carbon for timber at the design and construction stages, especially when taking carbon sequestration into account, can be jeopardized if all of the sequestered carbon is released at the end of life if the building is demolished and if no opportunities exist for reuse or reclamation. For example, Hart *et al.* (2021) compared timber frames with steel and concrete frames for whole-life embodied carbon in multistorey buildings and found that the use of timber could provide a reduction of 48 and 19%, respectively, compared to steel and concrete.

The Timber Tower Research Project by Skidmore, Owings and Merrill LLP (Johnson and Horos, 2014), included an alternative structural system with timber (referred to as "concrete jointed timber frame") for a 42-storey high "The Plaza on Dewitt" in Chicago to enable a carbon footprint comparison. As expected, the research highlighted that the embodied carbon footprint of the timber structure was substantially lower (60–75%) than that of the concrete benchmark building.

Similarly, a feasibility study by Cary Kopczynski and Company (2018) compared CLT and *in situ* cast concrete structural systems for buildings with 10-storey in the United States and highlighted that the carbon footprint of CLT is noticeably lower than that of the concrete frame. However, the cost of a CLT structural frame is slightly higher than that of a competing *in situ* cast concrete structure. Nevertheless, with time, CLT is expected to become more cost-effective if availability, competition and contractors' familiarity rise – also confirmed by Mallo *et al.* (2015). For example, Thomas and Ding (2018) compared timber building envelopes with conventional brick and concrete when construction is designed with equivalent thermal performance. The study by Mallo *et al.* (2015) revealed that both life cycle energy and the time of construction can create considerable differences in cost but only marginal differences between the cost of wood and heavy material construction.

Greater cost implications were noted by Dunn (2015) who compared wood, concrete and steel construction, including material and construction costs for four different types of building: a 7-storey building, an 8-storey apartment complex, a 2-storey aged care facility and a single industrial structure. Each of the building types was independently evaluated for all material costs, installation, construction costs and delivery to the project location in Sydney, Australia. For all four cases, timber construction was found to be less expensive

Table 1.
International tall residential timber buildings

Building name & image		Country	City	Height	# of stories	# of residential units	Construction period
1		Norway	Brumunddal	85m	18	39	Apr. 2017 - Mar. 2019
2 **HoHo**		Austria	Vienna	84m	24	24	Oct. 2016 - Feb. 2019
3 **Brock Commons Tallwood House**		Canada	Vancouver	58m	18	404-bed student residence	Oct. 2015 - May 2017
4 **Treet**		Norway	Bergen	49m	14	62	Apr. 2014 - Dec. 2015

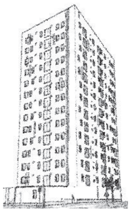
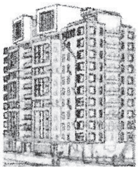
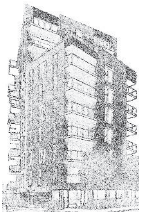
5 **Lighthouse Joensuu**		Finland	Joensuu	48m	14	117 student apartments	June 2018 - Aug. 2019
6 **Origine**		Canada	Quebec	41m	13	92	June 2016 - Oct. 2017
7 **Trafalgar Place**		UK	London	36m	10	235	Oct. 2013 - Jan. 2015
8 **The Cube (Wenlock Cross)**		UK	London	34m	10	49	Mar. 2013 - May 2015
9 **Dalston Lane**		UK	London	34m	10	121	Jan. 2015 - June 2017

Table 1.

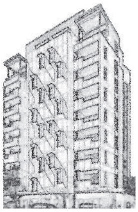
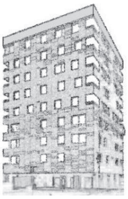
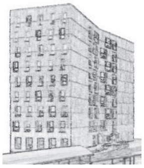
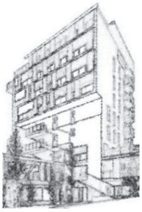
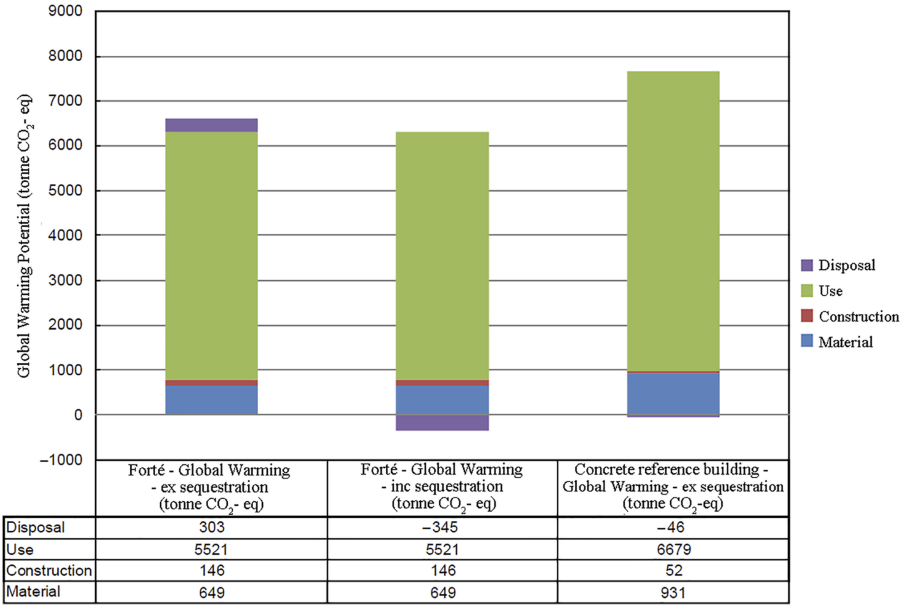
10 **Forte**		Australia	Melbourne	32m	10	23	Feb. 2012 - Dec.2012
11 **Stadthaus (Murray Grove)**		UK	London	29m	9	29	Mar. 2008 - Feb. 2009
12 **Moholt 50150**		Norway	Trondheim	28m	9	632 dormitory units	July 2015 - Dec. 2016
13 **Via Cenni (Cenni di Cambiamento)**		Italy	Milan	27m	9	124	Jan. 2012 - Nov. 2013

Table 1.

within a range of about 2–14% compared to non-timber constructions. Moreover, Smyth (2018) underlined the fact that timber is more cost-effective for taller buildings than low-rise buildings. Furthermore, Mallo and Espinoza (2016) studied the market obstacles of extensive CLT adoption in the United States related to the economic performance of CLT compared to concrete and steel. They found that CLT would signify a cost reduction of up to 22% in the cost of the structure, depending on the extent to which CLT is used in the building and the manufacturer selected. Additionally, construction time is reduced by almost 60%.

Hence, due to its considerably lower environmental and carbon footprint as well as its potential cost-effectiveness compared to non-wood traditional materials, timber construction with technological advances has started to be considered for tall building utilization.



	Forté - Global Warming - ex sequestration (tonne CO_2- eq)	Forté - Global Warming - inc sequestration (tonne CO_2- eq)	Concrete reference building - Global Warming - ex sequestration (tonne CO_2-eq)
Disposal	303	–345	–46
Use	5521	5521	6679
Construction	146	146	52
Material	649	649	931

Source(s): Durlinger *et al*. (2013)

Figure 1. Global warming potential for the reinforce concrete building and Forté

Particularly, the emergence of CLT over the last 2 decades has provided a feasible alternative to non-timber construction.

Tall timber building literature survey

Due to the ever-growing interest in timber structural systems combined with the substantial progress in the construction market, much research has been conducted about the technological, ecological, social and economic aspects of EWPs in the various types of building solutions (e.g. Ilgın *et al.*, 2022; Rinne *et al.*, 2022). However, there is an extremely limited number of studies focused on global trends and typologies regarding the architectural and structural design considerations of tall timber buildings, with exception of Kuzmanovska *et al.* (2018). The following literature review examines case study-based research involving architectural and structural design aspects of tall timber buildings.

Kuzmanovska *et al.* (2018) surveyed emerging trends for tall timber practices in terms of structure, envelope and architectural massing. They examined 46 residential and non-residential multistorey buildings particularly concerned with their spatial and aesthetic features. These mainly include structural systems, envelope systems and fabrication methods. Some of the important key findings were (1) increased use of post and beam structures with CLT slab floors, (2) decreased use of load-bearing external walls and (3) dominance of rectilinear plans and regular extrusions.

Tupėnaitė *et al.* (2020) reviewed and compared the tallest contemporary timber buildings in terms of economic and environmental efficiency. This indicated that higher timber buildings are more efficient both economically and environmentally due to the utilization of lightweight modern EWPs. Additionally, the prefabrication of elements decreases the duration and cost of the project.

Salvadori (2017) covered 40 completed and proposed case studies (7-storey and over) with their structural system and structural material, façade system and some fire safety strategies. In the study, the main goal was to compare an alternative mass timber structure with a similar concrete one. Rather than the technological obstacles for realizing taller timber buildings, public acceptance of wood was highlighted as an obstacle.

Smith *et al.* (2015) found that speed, weather versatility, raw material and carbon reduction were the main advantages of off-site solid timber production with knowledge and labor, logistics, planning, acoustics and vibration as the main disadvantages. Perkins+Will (2014) conducted a survey with 10 timber case studies of 5 or more storeys. In conjunction with the above-mentioned survey, Holt and Wardle's (2014) research summarizes the market context and rationale for the use of timber in high-rise applications. Findings highlight that timber for taller buildings is a viable construction method with the potential to significantly contribute to reducing the negative effects of buildings on the environment. However, design and construction techniques are still being developed to meet the different building code requirements, market demands and expectations, and different climatic conditions. Additionally, survey respondents highlighted a gap in the market perception of solid wood construction, particularly regarding fire safety and durability. Emphasis was placed on the importance of market research and education to increase familiarity with the qualities of massive wood and the quality of space achievable with wood to advance timber construction practices.

The environmental benefits of using timber in tall building construction include CO_2 reductions by approximately 50,000 tons for a 43-storey tall CLT-walled building with a concrete core and outriggers that comply with Chinese wind loading regulations (Kuilen *et al.*, 2011).To compare the impact of climate change, Skullestad *et al.* (2016) analyzed the potential to reduce greenhouse gas emissions from the construction industry by replacing multistorey concrete building structures with timber structures and compared the life cycle assessment for four buildings with 3- to 21-storeys. Findings indicate that timber structures had a 34–84% reduced climate change impact compared to concrete structures. Moreover, Li *et al.* (2019) explored the potential benefits and limitations of using timber to construct a tall building in Australia, using a hypothetical 43-storey building as the base model. The study highlighted the environmental benefits such as embodied carbon when using timber in tall buildings.

Research methods

The study was conducted through a literature survey including the Council of Tall Building and Urban Habitat (CTBUH) database (CTBUH, 2022), peer-reviewed-research, MSc theses and PhD dissertations, official/governmental documents and reports, conference proceedings, fact sheets, architectural and structural magazines, related standards and building codes, Internet sources as well as photographs and videos.

Furthermore, case studies were used to identify, collate and consolidate the information about contemporary tall residential timber buildings to understand and analyze the architectural, structural and constructional points of view. The cases were 13 tall residential timber buildings from the last decade to present, in a variety of countries (10 from Europe – 4 from the UK, 3 from Norway, 3 from Finland, Austria and Italy; 2 from Canada and 1 from Australia). In addition to their residential use, some were multi-functional developments: *Mjøstårnet* (Case 1 – see Table 1) and *HoHo* (Case 2 – see Table 1) also had hotel and office use, and *The Cube* (Case 8 – see Table 1) included office use. At the time of writing, these 13 cases were the only existing residential timber buildings with over 8 storeys all over the world, with sufficient detailed information available for this study (see Table 1). Note that the 10-storey and 31 m high *Lagerhuset* was excluded from this study since it is a retrofitted residential building, originally built as a grain silo, and there was a lack of data to assess all its architectural, structural and constructional features to include in the study. Another limitation was the lack of access to detailed information, including in-use data, hence not enabling a more in-depth study of the cases. For this study, architectural and structural design offices, contractors, developers and estate owners were contacted by email to obtain case study data.

Regarding the definition of tall buildings, there is still no global consensus on the height or number of storeys for tall buildings and the definition of “tall” for timber buildings is still debatable. According to Smith and Frangi (2008), tall timber buildings can be defined as timber buildings of nearly 10-storey with an upper limit of 20-storey; while the Wood Solutions Technical Design Guide (2017) defines mass timber high-rise as the buildings with an effective height of 25 m or more above the ground line, or, where this information is not available, buildings of over 8 storeys. As such, in this research, “tall timber building” is defined as a structure with more than 8 storeys. Moreover, this height limitation is the current maximum allowable height for the “P2 class” solution for wood construction in some European countries such as Finland (The National Building Code of Finland, 2017). Historically, “fire” has played an important role in the technical definition of “building tallness” as a basic height limit such as in North America and elsewhere (Calder *et al.*, 2014). Additionally, according to the CTBUH, buildings of 300 m’ height and above are classified as “supertall buildings” (CTBUH, 2022).

While lightweight timber-frame multistorey housing up to 4- or 5-storey is more common in many areas of the world; this research covers only tall residential timber buildings (over 8 storeys), where the load-bearing structure is for the most part made of wood or wood-based products. This includes both post-beam construction (rigid frame or shear walled frame systems – see Figure 4d), and panelized or honeycomb construction (shear wall systems – see Figure 4c).

Findings

Main architectural design considerations

This section presents an analysis of architectural design considerations for the 13 tall residential timber case study buildings. These considerations include:

(1) Core planning (i.e. stair configuration)

(2) Building form

(3) Floor-to-floor height

These three parameters are focused on because they are essential architectural parameters in tall building design; their analyses are discussed in detail below.

Core planning. Core planning, i.e. the vertical lift and staircase location and organization, is an essential architectural parameter of tall buildings. The authors employed the core classification of Ilgın (2021) as depicted in Figure 2.

As highlighted in Table 2, the central core arrangement was the most common circulation arrangement with nine cases, while peripheral cores occurred in the remaining four cases. The advantages of a central core are considerations such as structural contribution, compactness, enabling of openness of the spaces on the exterior façade for light and views, and better safety performance for fire escape, which may have helped this typology’s dominant occurrence. On the other hand, low efficiency in space use due to longer circulation paths and challenging fire escape distances are drawbacks of peripheral core configurations. This is a similar weakness in external core configurations that were never used for tall residential timber (Ilgın, 2018). The requirement of additional fire safety cautions (owing to its potential for allowance of fire spread by the chimney effect), as well as poor space efficiency,

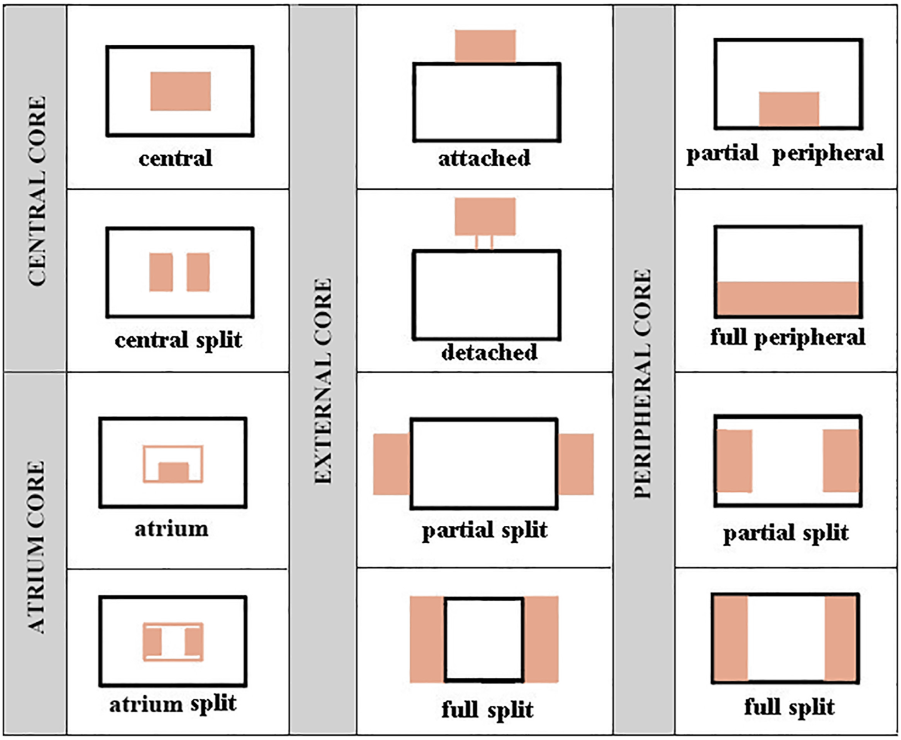


Figure 2.
Core arrangement classification for tall buildings

Table 2.
Tall timber residential buildings by core planning

Building name	Core type
Mjøstårnet	Peripheral
HoHo	Central
Brock Commons Tallwood House	Peripheral
Treet	Peripheral
Lighthouse Joensuu	Central
Origine	Central
Trafalgar Place	Peripheral
The Cube	Central
Dalston Lane	Central
Forte	Central
Stadthaus	Central
Moholt 50I50	Central
Via Cenni	Central

are major disadvantages of the atrium core, which may have contributed to its absence in the case studies.

Building form. Among the architectural design considerations of tall buildings, building form is also a significant parameter. The following classification by Ilgın and Gunel (2021) was utilized for the classification of the 13 cases (Figure 3):

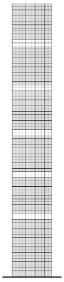
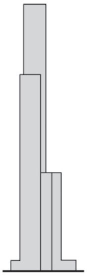
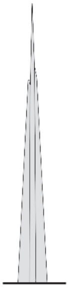
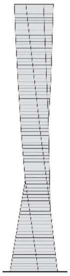
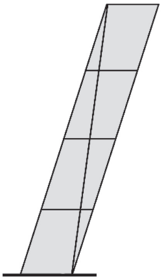
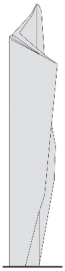
Prismatic forms (square, rectangular, or more complex plan shapes that continue unchanged throughout the building height)	**Setback forms** (buildings with recessed horizontal sections through the height of the building)	**Tapered forms** (buildings with tapering effect by reduced floor plans and surface areas through the height into either linear or non-linear profiles)
		
Twisted forms (buildings with progressively rotating floors or façade as they multiply upward along an axis by inputting a twist angle)	**Leaning/tilted forms** (buildings with inclined form)	**Free forms** (buildings which are not in the before mentioned forms)
		

Figure 3.
Tall building forms

Building name	Building form
Mjøstårnet	Prismatic
HoHo	Prismatic
Brock Commons Tallwood House	Prismatic
Treet	Prismatic
Lighthouse Joensuu	Prismatic
Origine	Free
Trafalgar Place	Prismatic
The Cube	Free
Dalston Lane	Prismatic
Forte	Prismatic
Stadthaus	Prismatic
Moholt 50I50	Prismatic
Via Cenni	Free

Table 3.
Tall timber residential buildings by building form

Using the above-mentioned morphological classification, prismatic forms were most prevalent, occurring in 10 cases (Table 3), and the remaining three cases were free forms. Although when designed and constructed properly, timber has very few structural

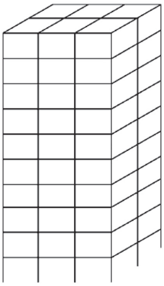
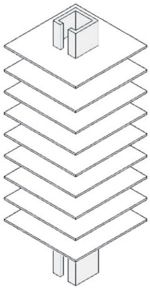
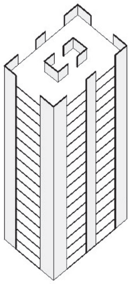
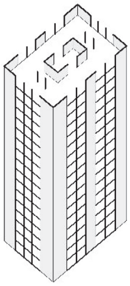
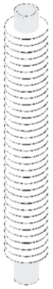
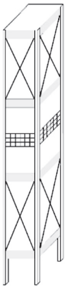
Rigid frame systems (Composed of beams and columns)	**Core systems** (Composed of a core, running continuously throughout the height of the building as a main vertical structural element)	**Shear wall systems** (Composed of perforated or solid shear walls)
		
(a)	**(b)**	**(c)**
Shear-frame system (Composed of shear wall/truss and frame) with the subgroups ‘shear trussed frame’ and ‘shear walled frame’	**Mega core system** (Composed of a mega core with much larger cross-sections than usual, running continuously throughout the height of the building as a main vertical structural element)	**Mega column system** (Composed of mega columns and/or shear walls with much larger cross-sections than usual, running continuously throughout the height of the building as main vertical structural elements)
		
(d)	**(e)**	**(f)**

Figure 4.
Tall building structural systems

limitations and its properties make more complicated structures possible today. The reason behind the prevalence of prismatic forms could be the ease of workmanship compared to the complex forms, practicality, and allowing effective use of interior space (particularly, for rectangular plans).

Floor-to-floor height. Floor-to-floor height is also an important architectural design consideration in tall timber buildings. It is defined as the sum of the required ceiling height, the depth of the structural floor system and the depth of the space required for accommodating the horizontal mechanical and electrical services. Floor-to-ceiling height is the distance between the room’s finished floor and finished ceiling. Ali and Armstrong (1995) suggested floor-to-ceiling heights of 2.4–2.7 m for residential functions, regardless of country or region, and in “Tall Buildings Statement of London” (2018) the floor-to-floor height of residential functions is defined as 3.2 m, reflecting the need for services and structural systems.

Floor-to-floor height has an influence on the overall building economics because of extra cost for many items such as the external glazed curtain walls, interior partition

Building name	Floor-to-floor height
Mjøstårnet	3.8 m
HoHo	3.3 m
Brock Commons Tallwood House	2.81 m
Treet	3 m
Lighthouse Joensuu	3.15 m
Origine	3 m
Trafalgar Place	3 m
The Cube	2.94 m
Dalston Lane	3 m
Forte	3 m
Stadthaus	Not available
Moholt 50I50	2.96 m
Via Cenni	3.15 m

Table 4.
Tall timber residential buildings by floor-to-floor height

Building name	# of stories	Structural material	Structural system (lateral load resistance)	Structural description
Mjøstårnet	18	Timber	Trussed-tube	Nonstructural core: CLT Column: GL Exterior braces: GL
HoHo	24	Composite	Shear walled frame	Core: Reinforced concrete Column: GL
Brock Commons Tallwood House	18	Composite	Shear walled frame	Core: Reinforced concrete Column: GL and PSL
Treet	14	Timber	Trussed-tube	Nonstructural core: CLT Exterior braces, belt, outrigger: GL
Lighthouse Joensuu	14	Timber	Shear wall	(Core) shear wall: LVL
Origine	13	Timber	Shear wall	Core and shear walls: CLT
Trafalgar Place	10	Timber	Shear wall	Core and shear walls: CLT
The Cube (Wenlock Cross)	10	Composite	Shear walled frame	Core: Reinforced concrete Column: Steel and CLT
Dalston Lane	10	Timber	Shear wall	Core and shear walls: CLT
Forte	10	Timber	Shear wall	Core and shear walls: CLT
Stadthaus (Murray Grove)	9	Timber	Shear wall	Core and shear walls: CLT
Moholt 50I50	9	Timber	Shear wall	Core and shear walls: CLT
Via Cenni	9	Timber	Shear wall	Core and shear walls: CLT

Note(s): "CLT" indicates cross-laminated timber; "GL" indicates glue-laminated timber; "PSL" indicates parallel strand lumber

Table 5.
Tall timber residential buildings by structural material and structural system

height, insulation quantity, vertical pipes and conduits. It also affects foundations due to the extra load of added height, since a small difference in this height, when multiplied by the number of floors, can have a major effect on the building's exterior as well as its structure and thus, its total cost. According to the analyzed tall residential timber building case studies, the floor-to-floor heights range between 2.81 and 3.30 m with an average of 3 m, where the 3.8 m high Mjøstårnet was excluded because it was an outlier (see Table 4). Only two cases met or exceeded the 3.2 m suggested by the Tall Buildings Statement of London (2018).

Main structural design considerations

This section presents an analysis of structural design considerations for the 13 tall timber case studies. These considerations include:

1. Structural materials
2. Structural systems

These two parameters are focused on as they are essential structural parameters in tall building design (Ilgın *et al.*, 2021b).

Structural materials. Structural materials can be divided into four main categories for tall building construction:

1. Steel
2. Reinforced concrete
3. Timber
4. Composite/hybrid (either structural member or cross-section based)

This study takes into account the main structural elements: columns, beams, shear trusses, shear walls and outriggers, which are lateral extensions of the core shear truss/shear wall to the perimeter columns in the form of a knee; floor slabs are excluded. This study uses the term "composite" or "hybrid" construction for buildings in which some structural elements are made of reinforced concrete and other structural elements are made of timber (structural member-based); or those in which some structural elements are made of both structural steel and concrete together (cross-section based), or both.

In terms of structural material, for residential timber buildings, CLT is the most commonly used structural material in the 13 case studies (Table 5). This might be explained by composite/hybrid solutions that necessitate additional contractors and staff on-site and increased coordination for the interfaces between materials (WTA, 2018), though they benefit from the combination of the advantages of different materials. Hence, the selection of these material combinations can be a critical issue because of the risk of adverse effects on the timeline, which is an advantage related to timber-frame structures such as CLT.

Where composite/hybrid structures were used, reinforced concrete was most common in all three cases. Additionally, in all case studies, the ground floor was made of reinforced concrete (also called concrete podium), and three of them used a reinforced concrete core. The concrete podium structure has many benefits, such as housing amenities and services at ground level, providing high clearances in public spaces and large openings, and generating fireproof areas for large mechanical and electrical services and equipment (Harte, 2017). On the other hand, the reason behind the use of the concrete in the core could be: (1) to provide most of the lateral stiffness and strength of the structure, (2) to benefit from concrete's natural resistance to fire, (3) to take advantage of its superiority in dampening wind-induced building sway as one of the problems frequently encountered in tall buildings (Gunel and Ilgın, 2014a). It was also found to simplify the project approval in the case of *Brock Commons Tallwood House* (Case 3 – see Table 1) (Naturallywood, 2020): due to the use of concrete cores, regulatory approval was swift because concrete cores are among the typical features in standard high-rise buildings, for all materials. Moreover, in this case study, the fire escape stairs are located within the concrete cores and are therefore of non-combustible construction.

Tall building structural systems. For lateral bracing of tall buildings, i.e. wind and earthquake loads, many structural systems and classifications are used in practice, and discussed in the literature (e.g. Kuzmanovska *et al.*, 2018). The authors utilized the structural system classification of Ilgın *et al.* (2021b) due to its comprehensive nature (see Figure 4).

On the other hand, considering outrigger frame, tube (framed-tube, diagrid-framed-tube, trussed-tube and bundled-tube) and buttressed core systems are efficiently and economically used in supertall buildings (≥300 m) rather than tall buildings; hence, these structural systems were not included in Figure 4.

As highlighted in Figure 4c, the shear wall system was predominantly utilized, occurring in eight cases. The reasons behind this prevalence might be the advantages of shear wall systems such as the speed of construction, compatibility for prefabrication techniques, efficiency and sufficient stiffness to resist lateral loads in buildings of up to about 35-storey (Gunel and Ilgın, 2014b). Moreover, in these systems, all walls, floor slabs and elevator hubs are made of solid timber, so they act together like a honeycomb, creating cellular spaces by providing a very stable and efficient structure as in the case of Stadthaus (Case 11 – see Table 1). Due to the nature of the cantilever behavior of shear wall systems, the inter-storey drift between adjacent floors is greater on the upper storeys than on the storeys below, regardless of building material. On the other hand, in rigid frame systems, the inter-storey drift between adjacent storeys is higher in the lower storeys. However, in shear frame systems (i.e. shear trussed frame and shear walled frame systems), the disadvantages of rigid frame compared with shear truss or wall, and of shear truss or wall compared with rigid frame, are compensated for by one another in a system where they are used together. In these cases, the frame contributes to the shear truss or wall in the upper storeys, while the shear truss or wall contributes to the frame in the lower storeys. In this way, shear-frame systems exhibit a very effective behavior against lateral loads by giving the structure a greater stiffness than a system of "shear wall" or "rigid frame" acting alone as in the cases of HoHo (Case 2) and Brock Commons Tallwood House (Case 3) – see Table 1. In addition, mega core and mega column systems efficiently and economically provide sufficient stiffness to resist wind and earthquake-induced lateral loads in buildings of more than 40 storeys (Gunel and Ilgın, 2014b).

In taller buildings, it is difficult to control the building sway that affects both the structural safety and the serviceability of a building. Regardless of material type, building sway could become a serious challenge for designers to enable comfortable use by building occupants, and particularly during windstorms, it is necessary to keep it within acceptable limits, especially to reduce the discomfort felt by occupants on the top floors. Furthermore, all contemporary tall buildings including tall timber towers are lighter than their predecessors. Hence, they are more prone to lateral drift with low damping, and wind-induced building sway has become one of the most important problems in their design. In tall buildings, which can be described as vertical cantilever beams, the maximum lateral top drift caused by lateral loads is expected to be approximately 1/500 of the building height (Gunel and Ilgın, 2014b).

Main constructional aspects

This section covers the case study data related to constructional aspects including the amount and type of timber, total construction cost, construction cost per m^2, fire resistance of main and secondary structural elements, and sound insulation values (airborne and impact sounds) as the minimum requirements for multistorey housing by country as summarized in Table 6.

The average gross floor area of all 13 cases was 11,780 m^2, with 2,750 m^2 as the lowest and 25,000 m^2 as the highest (see Table 6). The average construction cost per m^2 of the 13 cases was 2,430€. Because information about "total construction cost" and correspondingly "construction cost per m^2" is defined taking different boundaries into account, it seems exceedingly difficult to provide a comparable value among tall residential timber buildings. While the limited available case study data did not enable a case-by-case investigation to understand the reasons for the different CLT costs, several parameters such as material

Table 6. Tall timber residential buildings by gross floor area, total construction cost, construction cost per m^2, the amount of timber, fire resistance and sound insulation values

Building name	Gross floor area	Total construction cost[a] and cost per m^2	Amount of timber[b]	Fire resistance (in minute)	Airborne and impact sounds (dB)
Mjøstårnet (Norway)	11,300 m^2	€44.4 M 3,930 €/m^2*	2,600 m^3/ GL(Structural timber)	MLB:120 min SLB:90 min	≥55 ≤53
HoHo (Austria)	25,000 m^2	€65 M 2,600 €/m^2*	4,350 m^3 (entire construction)	MLB:90 min SLB:90 min	≥55 ≤48
Brock Commons Tallwood House (Canada)	15,115 m^2	€44 M 2,905 €/m^2	1,973 m^3/CLT 260 m^3/GL-PSL	MLB:60–120 min SLB:120 min	≥50 ≤47
Treet (Norway)	7,140 m^2	€22 M 3,080 €/m^2*	550 m^3/GL 385 m^3/CLT	MLB:90 min SLB:60 min	≥55 ≤53
Lighthouse Joensuu (Finland)	5,935 m^2	€10.9 M 1,836 €/m^2*	2,000 m^3 (entire construction)	MLB:90 min SLB:90 min	≥55 ≤53
Origine (Canada)	13,124 m^2	€21.4 M 1,630 €/m^2*	3,111 m^3 (mass timber)	MLB:120 min SLB:120 min	≥50 ≤47
Trafalgar Place (UK)	16,661 m^2	€60.5 M 3,630 €/m^2*	750 m^3 (timber volume)	MLB:60 min SLB:60 min	≥45 ≤62
The Cube (UK)	6,750 m^2	€115.5 M 1,705 €/m^2*	1,313 m^3 (timber volume)	MLB:90 min SLB:90 min	≥45 ≤62
Dalston Lane (UK)	12,000 m^2	€33 M 2,750 €/m^2*	4,649 m^3 (timber volume)	MLB:120 min SLB:90 min	≥45 ≤62
Forte (Australia)	2,890 m^2	€9.4 M 3,250 €/m^2*	966 m^3/CLT	MLB:90–120 min SLB:90 min	≥50 ≤62
Stadthaus (UK)	2,750 m^2	€4.2 M 1,540 €/m^2	901 m^3 (timber volume)	MLB:60–120 m SLB:60 min	≥45 ≤62
Moholt 50I50 (Norway)	17,500 m^2	€40.4 M (NOK 450 M) 1,740 €/m^2	6,300 m^3 (mass timber)	MLB:90 min SLB:60 min	≥55 ≤53
Via Cenni (Italy)	17,000 m^2	€21.7 M 1,000 €/m^2	6,100 m^3/CLT	MLB:60–120 min SLB:60 min	≥50 ≤63

Note(s): "MLB" indicates the main load-bearing elements (e.g. structural core, column, beam, external truss, outrigger, belt), "SLB" indicates the secondary load-bearing elements (e.g. floor)

*Calculated by the authors (total construction cost/gross floor area)

[a] Since different terms e.g. project cost, investment are used in different sources without any explanatory breakdown for the value stated as "construction cost" here, this value should be taken for indicative purposes only

[b] Different levels and types of information for "the amount of timber" e.g. structural timber, entire construction, or only CLT are provided by different sources

Euro/US Dollar, -/Australian Dollar and -/British Pound exchange rates were taken as 1.17, 1.64 and 0.91€, respectively

transportation, domestic production, insurance and the overall cost of the finished product (of which CLT is one component) is likely to have contributed to price fluctuations (Smyth, 2018).

By taking into consideration the fire regulations of different countries, the main load-bearing elements were generally designed to withstand up to 120 min of fire, while 90 min could be taken as the median for secondary load-bearing elements (see Table 6), though some structures are less than that. From the sample, it seems that additional measures were often included especially in primary and secondary structural elements to exceed the minimum building code values, as was the case for the Forte and Lighthouse Joensuu case study buildings.

According to the different building codes of the countries where the cases were constructed, sound insulation values for airborne and impact sounds ranged between 45–55 dB and 47–63 dB with an average of 50 and 56 dB, respectively. Notably, there were significant differences between some countries. For example, in terms of impact sound range, Canada has a much lower limit (≤47 dB) compared to Italy (≤63 dB).

Discussion and conclusion

Tall residential timber buildings (over 8 storeys) have been at the foreground of innovative building practice in urban contexts for over a decade to address the major challenges of urbanization, climate change and sustainable development and to meet housing needs. The height of tall residential timber buildings has been increasing over time, and this trend can be anticipated to continue into the future. The research is based on 13 tall residential timber building case studies and provides insights into the making of more technically and economically sound design decisions in the planning and development of these projects in the future.

Regarding the main design considerations of these pioneering projects, the study scrutinized core planning, building form, floor-to-floor height, structural system, structural material, and constructional considerations including the amount and type of timber, total construction cost, construction cost per m^2, and finally considerations regarding fire safety and sound insulation.

Central cores were the most preferred type by a wide margin and indicate empirical evidence of the advantages of this core arrangement, also in non-timber buildings (e.g. Ilgın, 2021). Ilgın *et al.* (2021b) found that central core arrangements occurred for about 89% of the time among 18 supertall residential buildings (out of 93) with non-timber structures. Similarly, Oldfield and Doherty's (2019) reported 85% of central core typologies among 500 tall non-timber buildings.

Frequent use of prismatic forms with rectilinear plans and regular extrusions may show the designers' choice of the building that can be constructed easily and quickly rather than with concerns about being "iconic". Namely, it is an indication that these buildings tend to use simple geometry in plan and elevation because of the regularity as their common feature and the difficulty of giving timber construction complex forms, e.g. twisted. Similarly, according to the findings by Ilgın *et al.* (2021b), the most used forms (>44%) in 18 supertall non-timber residential buildings (out of 93) were prismatic forms. In addition, residential buildings examined in the study by Ilgın *et al.* (2021b) study had mostly (~89%) reinforced concrete construction. This might indicate that the tendency of building form in multistorey residential buildings is mostly prismatic, so there may not be a typological change in the building form depending on the structural material.

On the subject of fire resistance, particularly in primary and secondary structural elements of these buildings, it was observed that minimum values specified in the building codes were typically exceeded by taking extra precautions. For example, in Forte building (Case 10 – see Table 1), gypsum elements were used for the encapsulation of many walls and ceilings to provide additional protection to structural panels. Likewise, functional fire design in Lighthouse Joensuu (Case 5 – see Table 1) showed that the building can withstand a fire even if the sprinklers do not work.

The 13 case study buildings are also characterized by the shear wall system as the structural system (Figure 4c), mostly because of its ease of construction accompanied by lateral stiffness at heights reached so far with timber. On the other hand, shear walled frame systems (Figure 4d) were widely utilized in tall concrete residential buildings, while outrigger frame systems were mainly used in supertall residential construction.

In terms of structural material, the dominance of pure/solid timber use over composite/hybrid is worth mentioning. This might be due to the composite structures' need for additional coordination and experienced staff on the construction site, requiring more time to integrate the whole timber construction process. On the other hand, some studies (e.g. Demirci *et al.*, 2019) highlighted the need to take additional structural measures against seismic loads after exceeding a certain height limit for timber-only multistorey structures. In this sense, hybrid solutions using reinforced concrete cores in Brock Commons Tallwood House

(Case 3 – see Table 1) and HoHo (Case 2 – see Table 1) were particularly effective structural approaches against earthquake-induced loads (Gallo *et al.*, 2020).

Besides providing information on general facts, by using the study lenses of architectural, structural and constructional features, 13 tall residential timber buildings with completed status were scrutinized to provide a step toward analyzing emerging international trends in this area.

The rules and expectations for tall timber buildings which is a relatively new building typology are not yet clear. Their design is a complicated task where the design is subject to dynamic changes as a result of the technological advances and new construction techniques of wood products. The variety in design and construction techniques of these buildings are still advancing to meet the different building codes, market demands and expectations, regulatory conditions, context and climate. This paper has provided the most up-to-date status of this pioneering building type.

The aim of this study was to present in detail contemporary cases that will assist and guide architects and other construction professionals in the planning and development of tall timber buildings. However, the empirical data provided in this study were limited to 13 tall residential timber buildings, making generalizations about future tall timber buildings difficult. Considering the increasing number of tall timber buildings being constructed, future studies can build on this research, increasing the sample size and the level of detail and in-use data, from which broader generalizations and new knowledge could be drawn.

References

Ali, M.M. and Armstrong, P. (1995), *Architecture of Tall Buildings*, Council on Tall Buildings and Urban Habitat Committee (CTBUH), McGraw-Hill Book Company, New York.

Andrew, R.M. (2018), “Global CO2 emissions from cement production”, *Earth System Science Data*, Copernicus GmbH, Vol. 10 No. 1, pp. 195-217, doi: 10.5194/essd-10-195-2018.

Calder, K., Senez, P. and Mcphee, R. (2014), “The risk basis for height and area limits in North American building codes”, *Proceedings of World Conference on Timber Engineering (WTCE) 2014*, Quebec City, Ottawa, 10-14 August, Canadian Wood Council.

Cary Kopczynski and Company (2018), “Cross laminated timber feasibility study, a comparison between cross laminated timber and cast-in-place concrete framing for mid-rise urban buildings”, available at: http://www.buildingstudies.org/pdf/related_studies/Cross_Laminated_Timber_Feasibility_Study_Feb-2018.pdf (accessed 18 March 2022).

Chastas, P., Theodosiou, T., Kontoleon, K.J. and Bikas, D. (2018), “Normalising and assessing carbon emissions in the building sector: a review on the embodied CO2 emissions of residential buildings”, *Building and Environment*, Vol. 130, pp. 212-226, doi: 10.1016/j.buildenv.2017.12.032.

CTBUH (2022), Council on Tall Buildings and Urban Habitat, Illinois Institute of Technology, Illinois, Chicago, available at: www.ctbuh.org (accessed 18 March 2022).

CWC (2007), “Energy and the environment in residential construction”, *Sustainable Building Series*, No. 1, available at: https://cwc.ca/wp-content/uploads/publications-Energy-and-the-Environment.pdf (accessed 18 March 2022).

Demirci, C., Málaga-Chuquitaype, C. and Macorini, L. (2019), “Seismic shear and acceleration demands in multi-storey cross-laminated timber buildings”, *Engineering Structures*, Vol. 198, 109467, doi: 10.1016/j.engstruct.2019.109467.

Dunn, A. (2015), *Final Report for Commercial Building Costing Cases Studies: Traditional Design versus Timber Project*, Forest and Wood Products Australia, Melbourne, Report No. PNA308-1213], available at: https://www.fwpa.com.au/images/marketaccess/2017/PNA308c-1314_Timber_Frame_v_Precast_Concrete_Cost_Comparison.pdf (accessed 18 March 2022).

Durlinger, B., Crossin, E. and Wong, J. (2013), “Life cycle assessment of a cross laminated timber building”, *Prepared for Forest and Wood Products Australia*, Project No: PRA282-1112.

available at: https://www.fwpa.com.au/images/marketaccess/PRA282-1112_Life-Cycle_Assessment_of_a_cross_laminated_timber_building_0.pdf (accessed 18 March 2022).

Gallo, P.Q., Carradine, D.M. and Bazaez, R. (2020), "State of the art and practice of seismic-resistant hybrid timber structures", *European Journal of Wood and Wood Products*, Vol. 79 No. 1, pp. 5-28, doi: 10.1007/s00107-020-01556-3.

Gerges, M., Mayouf, M., Rumley, P. and Moore, D. (2017), "Human behaviour under fire situations in high-rise residential building", *International Journal of Building Pathology and Adaptation*, Vol. 35 No. 1, pp. 90-106, doi: 10.1108/IJBPA-09-2016-0022.

Gifford, G. (2007), "The consequences of living in high-rise buildings", *Architectural Science Review*, Vol. 50 No. 1, pp. 2-17, doi: 10.3763/asre.2007.5002.

Gunel, M.H. and Ilgın, H.E. (2014a), *Yüksek Bina: Taşıyıcı Sistem ve Aerodinamik Form, Turkey (in Turkish)*, METU Faculty of Architecture Press, Ankara, ISBN: 978-975-429-278-7.

Gunel, M.H. and Ilgın, H.E. (2014b), *Tall Buildings: Structural Systems and Aerodynamic Form*, Routledge, London and New York.

Hart, J., D'Amico, B. and Pomponi, F. (2021), "Whole-life embodied carbon in multistory buildings: steel, concrete and timber structures", *Journal of Industrial Ecology*, Vol. 25 No. 2, pp. 403-418, doi: 10.1111/jiec.13139.

Harte, A.M. (2017), "Mass timber – the emergence of a modern construction material", *Journal of Structural Integrity and Maintenance*, Vol. 2 No. 3, pp. 121-132, doi: 10.1080/24705314.2017.1354156.

Holt, R. and Wardle, K. (2014), "Lessons from tall wood buildings: what we learned from ten international example", *Perkins+Will Research Journal*, Vol. 6 No. 2, pp. 7-19, available at: https://www.brikbase.org/sites/default/files/PWRJ_Vol0602_01_Lessons_from_Tall_Wood_Buildings.pdf (accessed 18 March 2022).

Ilgın, H.E. (2018), "Potentials and limitations of supertall building structural systems: guiding for architects", PhD dissertation, Department of Architecture, Middle East Technical University, Ankara.

Ilgın, H.E. (2021), "Space efficiency in contemporary supertall office buildings", *Journal of Architectural Engineering*, Vol. 27 No. 3, 4021024, doi: 10.1061/(ASCE)AE.1943-5568.0000486.

Ilgın, H.E. and Gunel, M.H. (2021), "Contemporary trends in supertall building form: aerodynamic design considerations", *LIVENARCH VII Livable Environments and Architecture 7th International Congress Other Architect/ure(s)*, Trabzon, 28–30 September 2021, Vol. 1, pp. 61-81.

Ilgın, H.E., Karjalainen, M. and Koponen, O. (2022), *Various Geometric Configuration Proposals for Dovetail Wooden Horizontal Structural Members in Multistory Building Construction*, IntechOpen, London. doi: 10.5772/intechopen.101725.

Ilgın, H.E., Karjalainen, M. and Pelsmakers, S. (2021a), "Finnish architects' attitudes towards multi-storey timber-residential buildings", *International Journal of Building Pathology and Adaptation*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/IJBPA-04-2021-0059.

Ilgın, H.E., Ay, B.Ö. and Gunel, M.H. (2021b), "A study on main architectural and structural design considerations of contemporary supertall buildings", *Architectural Science Review*, Vol. 64 No. 3, pp. 212-224, doi: 10.1080/00038628.2020.1753010.

Johnson, B. and Horos, P. (2014), "Timber tower research project", *Structure Magazine*, No. 3, pp. 22-23.

Karjalainen, M. and Ilgın, H.E. (2021), "A statistical study on multi-story timber residential buildings (1995–2020) in Finland", *Proceedings of the LIVENARCH VII Livable Environments and Architecture 7th International Congress Other Architecture(s)*, Trabzon, 28–30 September 2021, Vol. 1, pp. 82-94.

Karjalainen, M., Ilgın, H.E. and Somelar, D. (2021), "Wooden extra stories in concrete block of flats in Finland as an ecologically sensitive engineering solution", in *Ecological Engineering – Addressing Climate Challenges and Risks*, IntechOpen, London. doi: 10.5772/intechopen.101171.

Kuilen, J.W.G.V.D., Ceccotti, A., Xia, Z. and He, M. (2011), "Very tall wooden buildings with cross laminated timber", *Procedia Engineering*, Vol. 14, pp. 1621-1628, doi: 10.1016/j.proeng.2011.07.204.

Kuzmanovska, I., Gasparri, E., Monne, D.T. and Aitchison, M. (2018), "Tall timber buildings: emerging trends and typologies", *Proceedings of the 2018 World Conference on Timber Engineering (WCTE 2018)*, Seoul, August 2018, pp. 20-23.

Li, J., Rismanchi, B. and Ngo, T. (2019), "Feasibility study to estimate the environmental benefits of utilising timber to construct high-rise buildings in Australia", *Building and Environment*, Vol. 147, pp. 108-120, doi: 10.1016/j.buildenv.2018.09.052.

Mallo, M.F.L. and Espinoza, E. (2016), "Cross-laminated timber vs. concrete/steel: cost comparison using a case study", *WTCE 2016, World Conference on Timber Engineering*, Vienna, 22-25 August.

Mallo, M.F.L., Fernanda, M. and Espinoza, O. (2015), "Awareness, perceptions and willingness to adopt cross-laminated timber by the architecture community in the United States", *Journal of Cleaner Production*, Vol. 94, pp. 198-210, doi: 10.1016/j.jclepro.2015.01.090.

Naturallywood (2020), "Brock commons Tallwood House: design and preconstruction overview", available at: https://www.naturallywood.com/wp-content/uploads/2020/08/brock-commons-design-preconstruction-overview_case-study_naturallywood.pdf (accessed 18 March 2022).

Oldfield, P. and Doherty, B. (2019), "Offset cores: trends, drivers and frequency in tall buildings", *CTBUH Journal*, No. 2, pp. 40-45.

Opoku, A. (2019), "Sustainable development, adaptation and maintenance of infrastructure", *International Journal of Building Pathology and Adaptation*, Vol. 37 No. 1, pp. 2-5, doi: 10.1108/IJBPA-02-2019-074.

Perkins+Will (2014), *Survey of International Tall Buildings*, Summary Report, Forestry Innovations Investment and Binational Softwood Lumber Council, available at: https://www.woodworks.org/wp-content/uploads/Survey-tall-wood-report.pdf (accessed 18 March 2022).

Rinne, R., Ilgın, H.E. and Karjalainen, M. (2022), "Comparative study on life-cycle assessment and carbon footprint of hybrid, concrete and timber apartment buildings in Finland", *International Journal of Environmental Research and Public Health*, Vol. 19 No. 2, p. 774, doi: 10.3390/ijerph19020774.

Salvadori, V. (2017), "Development of a tall wood building", MSc thesis, TU Wien and Politecnico Milano, Wien and Milano.

Skullestad, J.L., Bohneb, R.A. and Lohne, J. (2016), "High-rise timber buildings as a climate change mitigation measure – a comparative LCA of structural system alternatives", *Energy Procedia*, Vol. 96, pp. 112-123, doi: 10.1016/j.egypro.2016.09.112.

Smith, I. and Frangi, A. (2008), "Overview of design issues for tall timber buildings", *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, Vol. 18 No. 2, pp. 141-147, doi: 10.2749/101686608784218833.

Smith, R.E., Griffin, G. and Rice, T. (2015), "Solid timber construction, process practice performance", Report sponsored by American Institute of Architects, USDA Forest Products Laboratory and FPI Innovations, available at: https://wood-works.ca/wp-content/uploads/Mass-Timber-Costing-Case-Studies.pdf (accessed 18 March 2022).

Smyth, M. (2018), "A study of the viability of cross laminated timber for residential construction", MSc thesis, Department of Civil and Architectural Engineering, School of Architecture and the Built Environment, KTH Royal Institute of Technology, Stockholm.

Tall Buildings Statement (2018), "Local plan supporting study, mayor of London", available at: https://www.london.gov.uk/sites/default/files/opdc_tall_buildings_statement_update_2021.pdf (accessed 18 March 2022).

The National Building Code of Finland – Structural Fire Safety, Decree of the Ministry of the Environment (2017), available at: https://ym.fi/en/the-national-building-code-of-finland (accessed 18 March 2022).

Thomas, D. and Ding, G. (2018), “Comparing the performance of brick and timber in residential buildings – the case of Australia”, *Energy and Buildings*, Vol. 159, pp. 136-147, doi: 10.1016/j.enbuild.2017.10.094.

Tulonen, L., Karjalainen, M. and Ilgın, H.E. (2021), *Tall Wooden Residential Buildings in Finland: What Are the Key Factors for Design and Implementation?* IntechOpen, London. doi: 10.5772/intechopen.98781.

Tupėnaitė, L., Žilėnaitė, V., Kanapeckienė, L., Sajjadian, S.M., Gečys, T., Sakalauskienė, L. and Naimavičienė, J. (2020), “Multiple criteria assessment of high-rise timber buildings”, *Engineering Structures and Technologies*, Vol. 11 No. 3, pp. 87-94, doi: 10.3846/est.2019.11952.

UNECE (the United Nations Economic Commission for Europe) Forest Products Annual Market Review (2019–2020), available at: https://unece.org/fileadmin/DAM/timber/publications/2020/SP-50.pdf (accessed 18 March 2022).

Wood Solutions Technical Design Guide issued by FWPA (2017), “Mid-rise timber buildings, class 2, 3 and 5 buildings”, available at: https://www.woodsolutions.com.au/publications (accessed 18 March 2022).

WTA – Waugh Thistleton Architects (on behalf of the Softwood Lumber Board and Forestry Innovation Investment) (2018), *100 Projects UK CLT, Canada*, available at: https://info.thinkwood.com/100-uk-clt-projects (accessed 18 March 2022).

Corresponding author
Hüseyin Emre Ilgın can be contacted at: emre.ilgin@tuni.fi

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: **permissions@emeraldinsight.com**