A study on interrelations of structural systems and main planning considerations in contemporary supertall buildings

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Hüseyin Emre Ilgın
Faculty of Built Environment, School of Architecture, Tampere University, Tampere, Finland

Abstract

Purpose – The aim of the study is to provide a comprehensive understanding of interrelations of structural systems and main planning considerations in supertall buildings (≥300 m).

Design/methodology/approach – Data were collected from 140 contemporary supertall towers using the case study method to analyze structural systems in the light of the key design considerations to contribute to the creation of more viable supertall building projects.

Findings – Central core typology, outriggered frame system, composite material and tapered prismatic and free forms were the most preferred features in supertall building design. Shear walled frame and tube systems occurred mostly in the 300–400 m height range, while outriggered frame systems were in the range of 300–600 m in height. Asia, the Middle East and North America mainly preferred outriggered frame systems, followed by tube systems. Considering the building function and form, the most preferred structural system in each of these groups was outriggered frame system, while mixed-use function stood out in all structural systems except in shear walled frame system.

Originality/value – To date, there has been no comprehensive study in the literature of the interrelations of structural systems and important planning considerations in the design of contemporary supertall towers through a large set of study samples. This critical issue was multidimensionally explored in this paper in light of 140 detailed case studies of supertall buildings around the world.

Keywords Supertall building, Interrelations, Structural system, Building height, Building form, Core planning, Structural material

Paper type Research paper

1. Introduction

The increasing rate of urbanization in recent years, along with the race to win the title of the tallest building, has seen an accelerating trend in the construction of supertall buildings around the world, especially in developing economies (Al-Kodmany, 2012, 2018a; Gabel, 2016; Gerges *et al.*, 2017; Ilgın, 2021a). The world continues to witness an explosion of growth in the number of skyscrapers above 200 m with record-breaking completions for three consecutive years (2014–2016), and an over 400% increase in the total number of such towers in the 21st century (Gabel, 2018; Khallaf and Khallaf, 2021). According to the Council on Tall Buildings and Urban Habitat (CTBUH) database (CTBUH, 2022), the number of supertall buildings under construction and completed in the last decade is close to 250. The rapidly increasing global

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demand for supertall buildings in the world brings up the parameters that play a critical role in the design and implementation of these giant projects as in the cases of Burj Khalifa (Dubai, 828 m) (Figure 1a) (Abdelrazaq, 2010), Merdeka PNB118 (Kuala Lumpur, under construction) (Figure 1b) (Fender *et al.*, 2016), Shanghai Tower (Shanghai, 2015) (Figure 1c) (Wu *et al.*, 2019) and One Vanderbilt Avenue (New York, 2020) (Figure 1d) (Klemperer, 2015).

Since a supertall building is feasible by the structure itself, the structural system is the most important design parameter, and many planning criteria depend on the structural

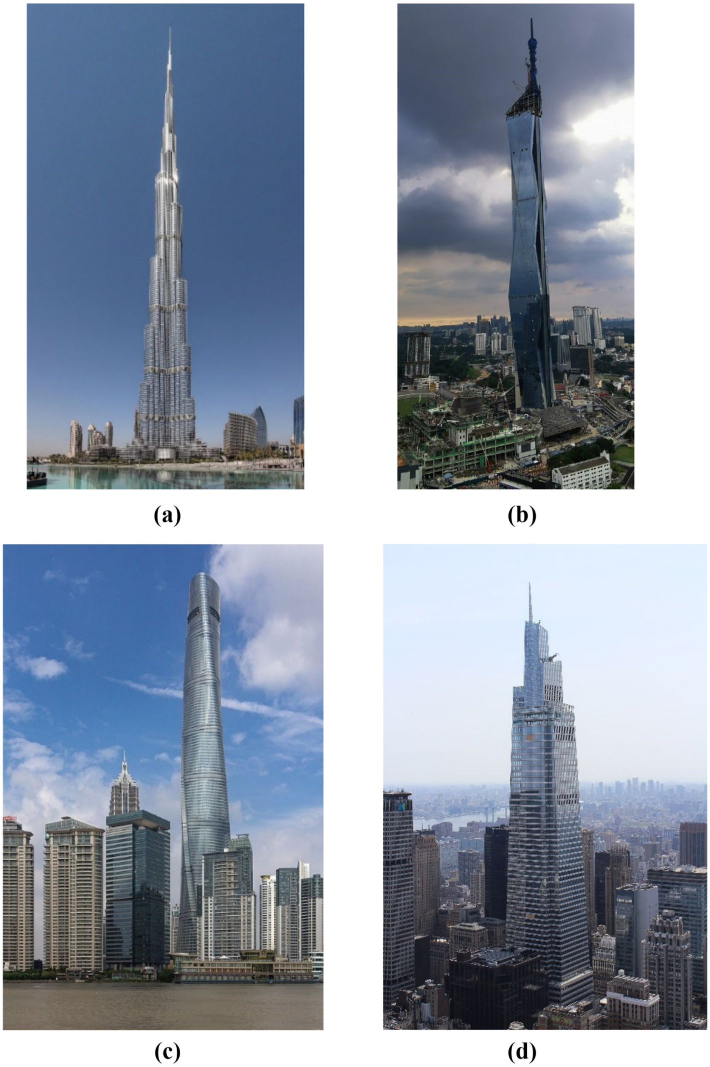

Figure 1. Contemporary supertall building examples

Note(s): (a) Burj Khalifa (source: Wikipedia); (b) Merdeka PNB118 (source: Wikipedia); (c) Shanghai Tower (source: Wikipedia); (d) One Vanderbilt Avenue (source: Percival Kestreltail/Wikipedia) system in terms of its performance (Ilgın, 2018). The selection of an optimal building structural system is also critical to improving building construction (Chakraborty *et al.*, 2020; Zhong *et al.*, 2022). Structural systems play a key role in determining a cost-effective supertall building form. Moreover, the structural cost of tall buildings can constitute approximately 30% of the total construction cost, and this cost increases as the building rises (Almusharaf and Elnimeiri, 2010; Wang *et al.*, 2017; Mubarek *et al.*, 2019; Elmousalami, 2019). Due to the current trend of the pluralistic architectural style, the structural systems have become more diverse and have somehow lost their natural logic, adapting to the formatting predetermined by the architect (Ali and Al-Kodmany, 2012). The style and aesthetics of the buildings are integrally related to the horizontal and vertical configurations.

It should be noted here that many studies in the literature raise concerns about the sustainability and ecological dimensions of construction projects (e.g. Chakraborty *et al.*, 2016; Swei *et al.*, 2017; Kumar and Gururaj, 2019; Opoku, 2019; Elhegazy *et al.*, 2021a) including supertall towers (e.g. Yeang, 2008; Al-Kodmany, 2018b, c; Borrallo-Jiménez *et al.*, 2020; Zhang, 2020). According to Al-Kodmany (2018b, c), these buildings have elements that threaten their social, economic and environmental sustainability. In this sense, from a social perspective, supertall buildings can cause social isolation due to their vertical composition and therefore are generally not assessed suitable for raising children and family life. They are also thought to be self-referential and vertically stratified objects devoid of cultural and social references to their surroundings (Scheeren, 2014; Henn and Fleischmann, 2015; Safarik, 2016). From an economic point of view, supertall towers are costly to build due to their complex structure and their mechanical and electrical systems (DeJong and Wamelink, 2008). In addition, far greater amounts of materials and energy, and far greater amounts of embodied energy, must be involved in their construction and operation than in low-rise buildings (Ali and Al-Kodmany, 2012). From an environmental perspective, the construction and maintenance of supertall buildings generate large amounts of carbon dioxide emissions (Dong *et al.*, 2015; Gan *et al.*, 2017). It should also be underlined here that building management, evaluating its performance and assessing tenant satisfaction are key components of achieving more sustainable skyscrapers (Safarik *et al.*, 2016).

Although there are many studies on tall and supertall building structural systems in the literature (e.g. Ali and Moon, 2007; Taranath, 2016; Ali and Moon, 2018; Fu, 2018), limited studies examine the relationship between the structural system and other design parameters. Among these studies, Sev and Özgen (2009) analyzed the space efficiency in 10 high-rise office buildings from Turkey and the world in the light of various parameters such as leasing depth, gross and net floor areas, core integrity, structural material, floor-to-floor height and structural system. Elnimeiri and Almusaraf (2010) scrutinized the historical development of the relationship between the structural system and tall building form. Alaghmandan *et al.* (2014) examined architectural and structural trends in the design of tall buildings through 73 case studies. Ilgın (2021b) focused on space efficiency in 44 contemporary supertall office buildings with the main architectural and structural parameters (i.e. core planning, building form, structural system and structural material), while Ilgın (2021c) studied space efficiency in 27 contemporary supertall residential buildings with the same parameters. On the other hand, Ilgın *et al.* (2021) analyzed the contemporary trends in main architectural and structural design considerations and several corresponding interrelations through 93 case studies.

To date, there has been no comprehensive study in the literature of the interrelations of structural systems and important planning considerations in the design of contemporary supertall towers through a large set of study samples. This critical issue was multidimensionally explored in this paper in light of 140 detailed case studies of supertall buildings around the world.

In this study, besides giving general information (building name, country and city, height, number of storys, completion date, function), key planning considerations (core design, building forms, structural systems and structural materials) and interrelations of the structural system and main design considerations including building height, location, function, building form and structural material were analyzed. By doing so, this paper, which reveals the current state of the art of supertall applications, is believed to provide insight into making more viable design decisions for future supertall towers.

The remainder of this paper was structured as follows. First, an explanation of the materials and methods used in the study was provided. This was followed by results of interrelations of structural system and main planning considerations. Finally, discussion and conclusions were presented, with research limitations and suggestions for future studies.

2. Materials and methods

In this study, the case study method was employed to collect and consolidate information about contemporary supertall buildings to examine the interrelationships of structural systems and major planning considerations. This method is a widely used approach in built environment assessments, where projects are identified and documented for quantitative and qualitative data through in-depth literature review (Kuzmanovska *et al.*, 2018).

In this paper, the following parameters, which have an important role in the planning of supertall buildings and are associated with the structural system, were discussed: (1) building height, (2) location, (3) building function, (4) building form and (5) structural material.

Cases which included 140 supertall buildings in a variety of countries [78 from Asia (58 from China), 31 from the Middle East (22 from Dubai, the United Arab Emirates), 20 from North America (14 from the United States), 7 from Russia, 2 from Australia, 1 from South America (Chile), 1 from Europe (UK)]. Appendices 1 and 2 show detailed information of 140 contemporary supertall towers.

Functionally supertall buildings are divided into single-use or mixed-use. In supertall tower design, hotels, residential buildings and offices are considered as the primary functions in this paper.

Based on the CTBUH database (CTBUH, 2022), a single-use building is considered a building where 85% or more of its total height is devoted to a single function, whereas a mixed-use building is assumed to contain two or more functions, occupying a significant part of the total area of the tower in this study. It was also assumed that a supertall building is equal to and higher than a 300 m building (CTBUH, 2022). Additionally, the following core classification of Ilgın *et al.* (2021) was used because of its more comprehensive structure in the literature (e.g. Trabucco, 2010; Oldfield and Doherty, 2019): (1) central core (central and central split), (2) atrium core (atrium and atrium split), (3) external core (attached, detached, partial split and full split) and (4) peripheral core (partial peripheral, full peripheral, partial split and full split).

Furthermore, compared to other studies in the literature (e.g. Al-Kodmany and Ali, 2016; Szolomicki and Golasz-Szolomicka, 2019), the following forms of classification were used in this study (Ilgın *et al.*, 2021): (1) prismatic, (2) setback, (3) tapered, (4) twisted, (5) leaning/tilted and (6) free forms.

Since it is more comprehensive than the existing structural system classification in the literature (e.g. Gunel and Ilgın, 2007; Gunel and Ilgın, 2014a, b; Taranath, 2016; Ali and Moon, 2018), the author used the following classification for supertall buildings (Ilgın *et al.*, 2021):

(1) shear-frame system consisting of shear wall/truss and frame with subsets of shear trussed frame and shear walled frame;

(2) mega core system consisting of a mega core with much larger cross-sections than normal, running continuously along the height of the building as a main load-bearing element;

(3) mega column system consisting of mega columns or shear walls with much larger cross-sections than normal, running continuously along the height of the building as main load-bearing elements;

(4) outriggered frame system consisting of at least one-story deep outriggers added to shear-frame system;

(5) tube system:

- framed-tube system consisting of closely spaced exterior columns with spandrel beams at the facade,
- trussed-tube system consisting of exterior columns with exterior multistory braces,
- bundled-tube system consisting of a combination of more than one tube; and

(6) buttressed core system, an advanced "shear wall system," consisting of shear walls directly supporting the central core.

In this article, the following classification was used for structural materials for supertall building construction: (1) steel, (2) reinforced concrete and (3) composite. Considering vertical structural members – columns, beams, shear trusses, shear walls and outriggers – as the main structural elements, "composite" referred to the buildings in which some structural elements were made of reinforced concrete and other structural elements were made of steel, or to those in which some structural elements were made of both structural steel and concrete together or to both the first and the second categories (e.g. Chen, 2021; Elhegazy *et al.*, 2021b).

3. Results

Figure 2 shows the relationship between the building height and the number of storys of supertall towers examined. As seen in the red trendline in Figure 2, it can be said that there is a directly proportional relationship between the height of the building and the number of storys.

It is worth noting here that a building can also have symbolic functions besides its main function(s), which is divided into regular floors with typical floor heights. This could make the building an outlier, as in the case of the 36-story, 300 m high Aspire Tower (see Figure 2) comprising both hotel and office functions. The tower, which resembles a hand holding a flaming torch, became the most important symbol of the 15th Asian Games held in Qatar in 2006 (Chikaher and Hirst, 2007; Gunel and Ilgin, 2014b). Similarly, as in the 62-story, 427 m high One Vanderbilt Avenue in New York, a part of a supertall building may have been designed not for purely human occupation in the form of an office, hotel or residence, but for other purposes, such as an observation deck on the upper floors (Klemperer, 2015). This approach can also make the building an outlier (see Figure 2).

Additionally, in Figures 3–5, the bars demonstrate the total number of supertall buildings (right axis of the chart) by function, form and structural material, respectively, while dots correspond to the heights of supertall buildings (left axis of the chart) by function, form and structural material, respectively. As seen in Figure 3, building functions other than hotel either reached the level of megatall buildings (≥600 m) or were very close to it, while megatall building limit exceeded in all building forms as shown in Figure 4. Considering the wind loads that become more critical as the building height increases (e.g. Wang and Ni, 2022), the aerodynamic efficiency of the tapered, setback, free and twisted forms may have contributed to the skyscrapers built with these forms to break through the megatall height limits (Ilgın and Günel, 2007; Sharma *et al.*, 2018; Ilgın and Gunel, 2021; Li *et al.*, 2022; Mandal *et al.*, 2022). As highlighted in Figure 5, many composite buildings were built beyond the megatall building height. This can be explained by the superiority of composite structure, which

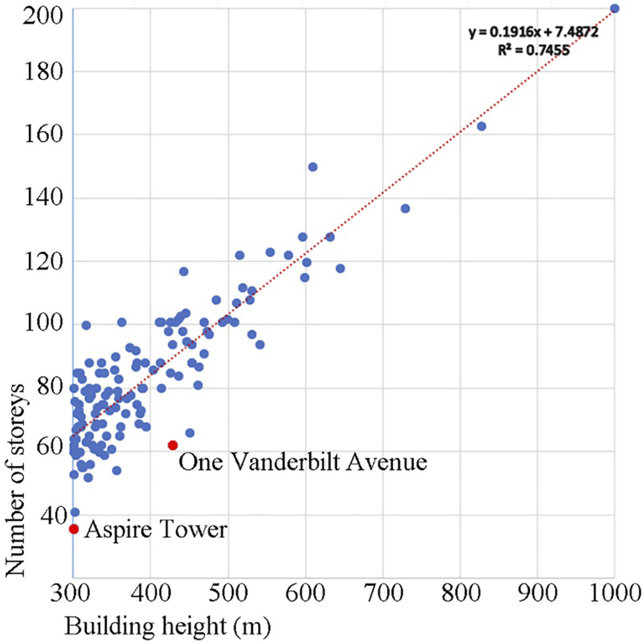

Figure 2.
Interrelation of the building height and the number of stories

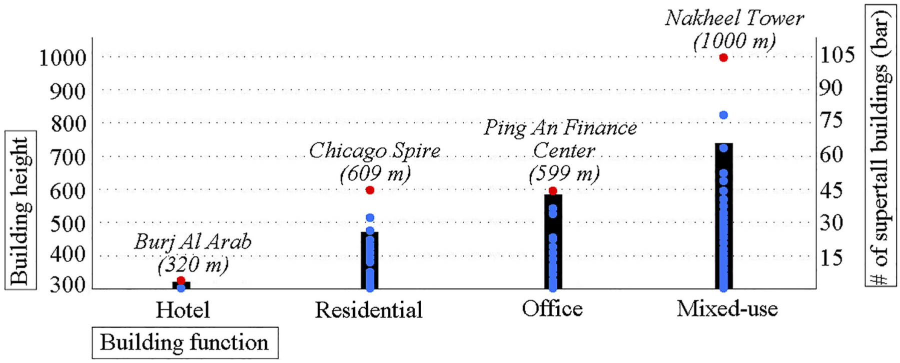

Figure 3.
Interrelation of building height and function

combines the advantages of both materials, such as the high strength of steel and the rigidity and fire resistance of reinforced concrete (e.g. Du *et al.*, 2022). Megatall limit was exceeded only with the Burj Khalifa (Figure 1a) as reinforced concrete, and these structures were generally built in the range of 300–600 m. At the Burj Khalifa, high-performance, high-strength concrete with strengths of up to 80 MPa may have contributed significantly to the tower's attainment of this extraordinary height (Weismantle *et al.*, 2007; Aldred, 2010). On the other hand, the tallest building in steel was 435 m in the study sample.

3.1 Interrelations of structural system and main planning considerations

Interrelations of structural system and main planning considerations associated with it, such as building height, location, building function, building form and structural material, were examined in this section. Since the most used core typology by a wide margin (>96%) in the study sample was the central core, no analysis was made on this issue.

3.1.1 Interrelation of structural system and building height. In Figure 6, the bars demonstrate the total number of supertall buildings (right axis of the chart) by structural system, while dots correspond to the heights of supertall buildings (left axis of the chart) with such a structural system.

Shear walled frame systems occurred 92% in the 300–400 m height range, and only Al Hamra Tower, whose height exceeds 400 m, was built with this system. According to the study example, buttressed core systems were rarely preferred in supertall building construction, but Burj Khalifa (Figure 1a), the world's tallest completed building, was built with a buttressed core system. Outriggered frame systems with a ratio of 95% were in the height range of 300–600 m, while only 5 of them can be called megatall towers (≥600 m). By January 2022, 9 of the 10 tallest buildings completed in the CTBUH database (CTBUH, 2022) used an outriggered frame system: Shanghai Tower with 128-storys and 632 m height (Figure 1c), Makkah Royal Clock Tower with 120-storys and 601 m height, Ping An Finance Center with 115-storys and 599 m height, Lotte World Tower with 123-storys and 554 m height, One World Trade Center with 94-storys and 541 m height, Guangzhou CTF Finance Centre with 111-storys and 530 m height, Tianjin CTF Finance Centre with 97-storys and 530 m height, CITIC Tower with 109-storys and 528 m height and Taipei 101 with 101-storys and 508 m height. Tube systems, which occurred at a rate of 59%, were in the height range of 300–400 m; only 4 of them exceed 500 meters. In the sample group, while framed-tube system

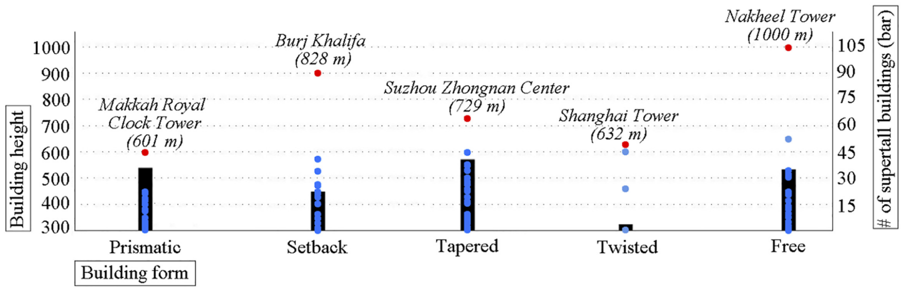

Figure 4.
Interrelation of building height and building form

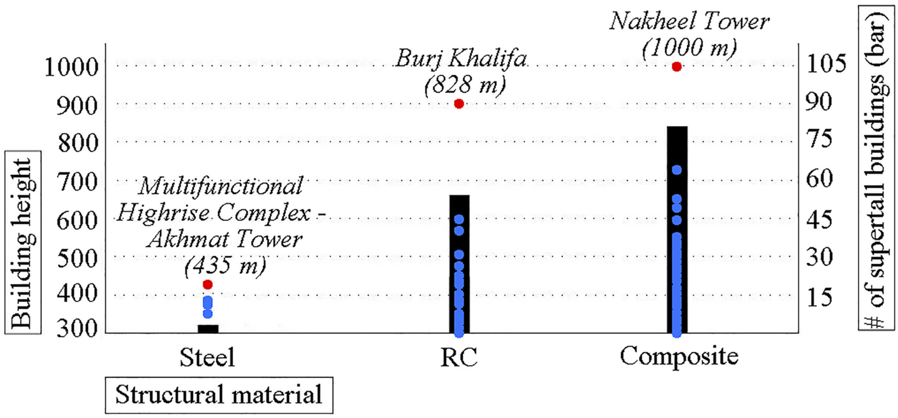

Figure 5.
Interrelation of building height and structural material

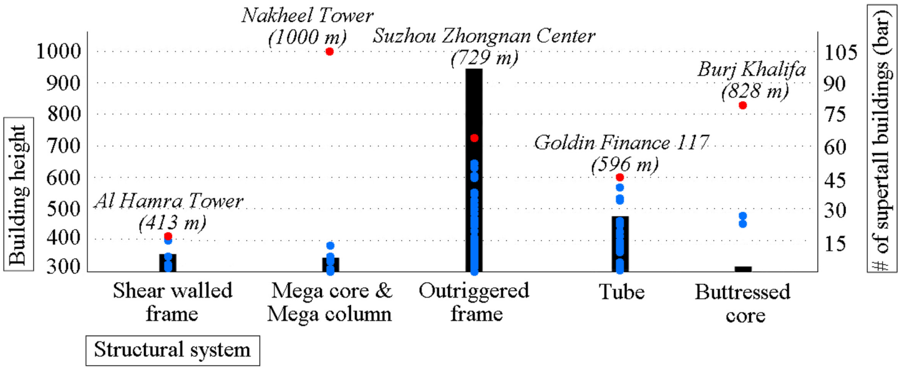

Figure 6.
Interrelation of building height and structural system

was preferred most (63%) among tube systems, trussed-tube system was employed in Goldin Finance 117 with 596 m height, the tallest building in which the tube system was used.

3.1.2 Interrelation of structural system and location. Figures 7 and 8 show the interrelation of structural system and location. Asia preferred outriggered frame system in a wide margin (76%), followed by tube system with a ratio of 18%. Similarly, the Middle East and North America utilized outriggered frame systems mostly, with ratios of 48 and 65%, respectively. As the number of supertall buildings in the sample group was relatively small in Russia (7 cases) and the remaining locations (4 cases), it was difficult to establish a scientific relationship between structural system and location.

3.1.3 Interrelation of structural system and building function. Figure 9 compares the use of alternative structural systems for a given building function. Although outrigger frame system was the most preferred structural system in all building functions, followed by tube system apart from hotel function, outrigger frame system's dominance became more pronounced (>70%) especially in mixed-use development. On the other hand, Figure 10 compares the use of alternative functions for a given structural system. While mixed-use function stood out in all structural systems except shear walled frame, this situation became even more evident in outriggered frame systems. Since the number of buildings with buttressed core system and hotel function was very few, deriving a correlation between structural system and building function of those buildings was likely to be inaccurate.

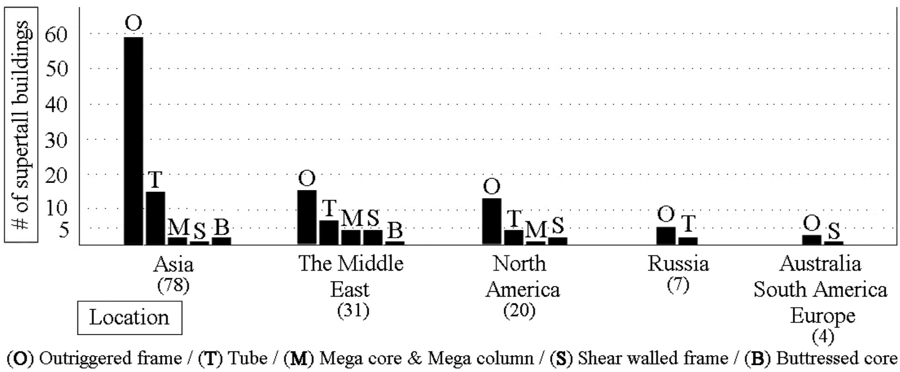

Figure 7.
Interrelation of structural system and location – 1

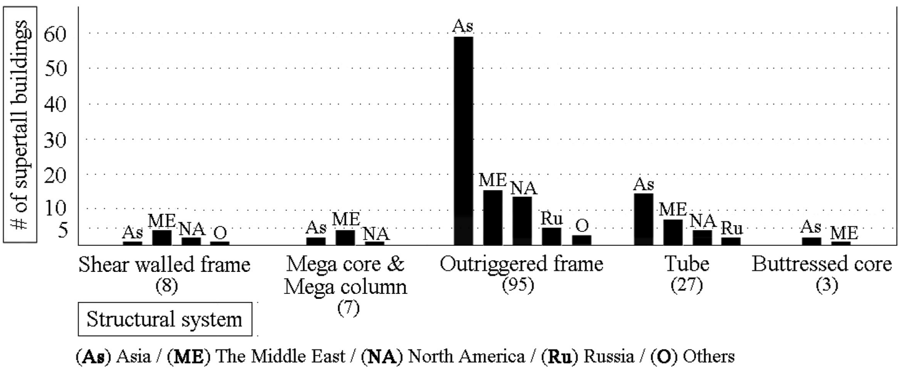

Figure 8. Interrelation of structural system and location – 2

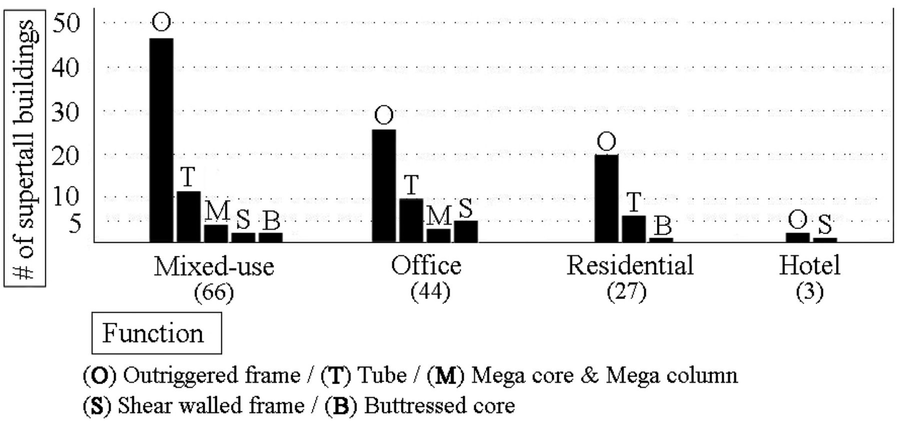

Figure 9. Interrelation of structural system and building function – 1

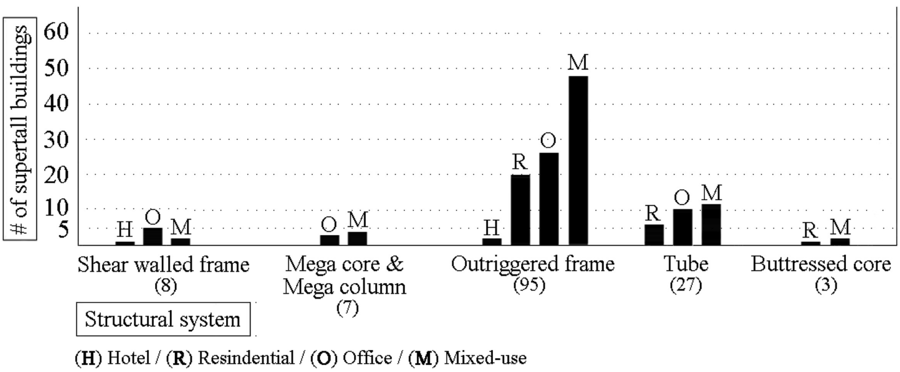

Figure 10. Interrelation of structural system and building function – 2

3.1.4 Interrelation of structural system and building form. Figure 11 compares the use of alternative structural systems for a given building form. Even though outrigger frame system was the most used structural system in all building forms, followed by tube system apart from free form, outrigger frame system's dominance became more pronounced especially in tapered and free forms (>70%). On the other hand, Figure 12 compares the use of alternative building forms for a given structural system. While tapered, free and prismatic forms were preferred in outriggered frame systems; prismatic, tapered and setback forms were employed in tube systems according to the order of frequent use. Since the number of buildings with twisted form and buttressed core was very low, it did not seem possible to establish a relationship between the building form and structural system of those buildings.

3.1.5 Interrelation of structural system and structural material. Figures 13 and 14 show the interrelation of structural system and structural material. As seen in Figure 13, composite was the most preferred material, followed by reinforced concrete, in all types of structural systems except buttressed core system. When the subject was considered in terms of structural material classification, outriggered frame system was the most preferred structural system in terms of all types of materials, followed by tube system. Since the number of buildings made of steel and with buttressed core system was very few, deriving a correlation between structural systems and structural materials of those buildings was likely to be inaccurate.

4. Discussion and conclusions

The results obtained in this study showed similarities and dissimilarities with other studies in the literature (e.g. Oldfield and Doherty, 2019; Ilgın *et al.*, 2021). In this paper, central core arrangement was the most used typology, as noted in similar studies (Oldfield and Doherty, 2019; Ilgın, 2021b, c; Ilgın *et al.*, 2021). Among the 140 supertall towers, tapered, prismatic and free forms were the most frequent, and this finding was verified by the findings in the studies of Ilgın *et al.* (2021) on 93 supertall towers, Ilgın (2021b) on 44 supertall office buildings and Ilgın (2021c) on 27 supertall residential towers. In terms of structural systems, outriggered frame system was mainly used in supertall buildings, which confirmed the findings of other studies such as Ilgın *et al.* (2021), Ilgın (2021b) and Ilgın (2021c), while the use of composite

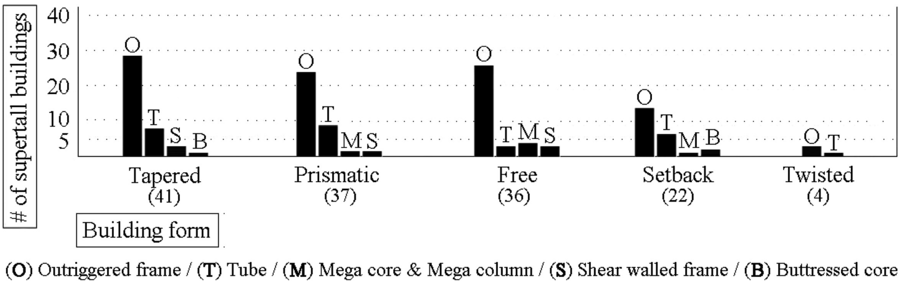

Figure 11.
Interrelation of structural system and building form – 1

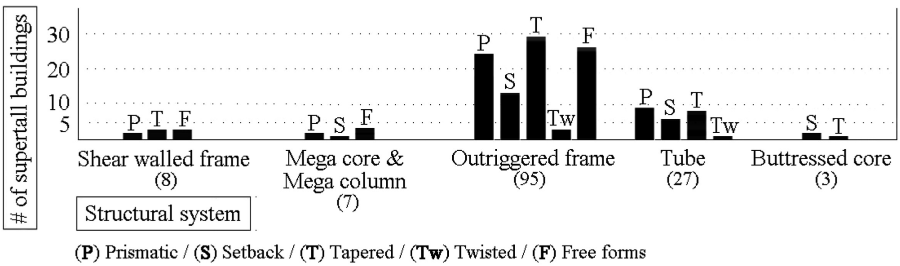

Figure 12.
Interrelation of structural system and building form – 2

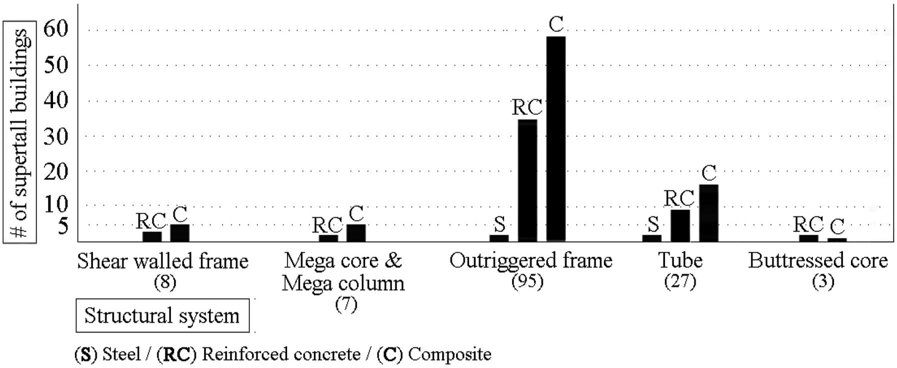

Figure 13. Interrelation of structural system and structural material – 1

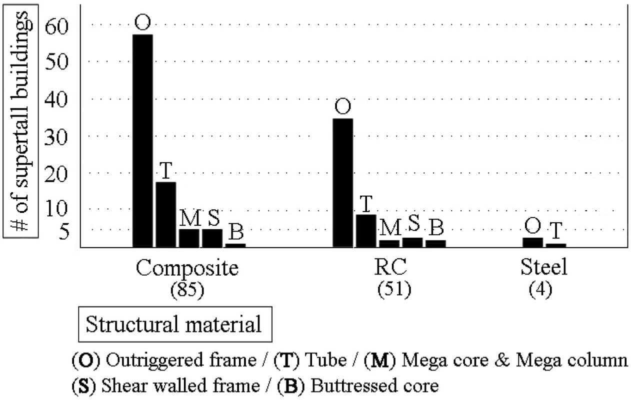

Figure 14. Interrelation of structural system and structural material – 2

was more prevalent than steel and reinforced concrete as in the studies of Ilgın *et al.* (2021) and Ilgın (2021b).

Regarding the interrelations of the structural system and the main planning considerations associated with it, this study analyzed building height, location, building function, building form and structural material to provide an introductory design guide for key construction professionals in supertall building projects. Shear walled frame and tube systems mostly occurred in the 300–400 m height range, while outriggered frame systems were primarily in the height range of 300–600 m. Asia, the Middle East and North America mainly preferred outriggered frame systems, followed by tube systems, in supertall building construction. Similarly, considering building function and building form, outrigger frame system was the most prevalent structural system in all building function and form groups. Additionally, mixed-use function came to the fore in all structural systems except shear walled frame. On the other hand, while tapered, free and prismatic forms were preferred in outriggered frame systems, prismatic, tapered and setback forms were employed in tube systems according to the order of frequent use. In terms of the interrelation of the structural system and structural material, composite was the most used material, followed by reinforced concrete, in all structural systems except buttressed core system.

It is also worth noting that supertall buildings have come under serious criticism that they are unsustainable in many ways, including social, financial and ecological considerations.

Solutions to these important issues should be considered from the initial planning phase of supertall towers. In this context, architects should be aware that the design of these gigantic projects, like many other complex structures, is a multidimensional issue that requires interdisciplinary collaboration and high-level teamwork.

In this paper, through 140 supertall cases, main design considerations (i.e. core planning, building forms, structural systems and structural materials) and interrelations of structural system and main design considerations (i.e. building height, location, building function, building form and structural material) were analyzed.

In conclusion, the results obtained in this study on interrelations of structural systems and main planning considerations in contemporary supertall buildings are expected to provide design guidelines for key professional stakeholders such as architects, engineers and developers.

The empirical data presented in this paper are limited to buildings taller than or equal to 300 meters. Additional categorization levels for 140 supertall buildings in the study sample set especially relatively may give biased results for a small number of building groups such as hotel function buildings and steel buildings; it was emphasized that, where appropriate, it would probably be inaccurate to extract correlations from these building groups. However, considering the significantly increasing number of buildings in the scope of this study in the last decade, it can be foreseen that there will be a sufficient number of buildings in subcategories in the near future.

In addition, buildings below 300 m can also be included in the study sample to create a sufficient number of subcategories. On the other hand, as innovative structural systems are developed for the next generation of sustainable, ultra-tall buildings and megastructures, the relationships between the structural system and other design parameters may change, which will require further research. In particular, future research should delve deeper into the structural system-sustainability relationship of supertall towers, and in this context, supertall timber building projects may come to the fore (Johnson *et al.*, 2014; Foster and Ramage, 2017; Ramage *et al.*, 2017).

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Appendix 1

Table A1. Contemporary supertall buildings considered in this study

#	Building name	Country	City	Height (meters)	# of storeys	Completion date	Function
1	Nakheel Tower	UAE	Dubai	1,000	200	NC	M (H/R/O)
2	Burj Khalifa	UAE	Dubai	828	163	2010	M (H/R/O)
3	Suzhou Zhongnan Center	China	Suzhou	729	137	NC	M (H/R/O)
4	Merdeka PNB118	Malaysia	Kuala Lumpur	644	118	UC	M (H/O)
5	Shanghai Tower	China	Shanghai	632	128	2015	M (H/O)
6	Chicago Spire	USA	Chicago	609	150	NC	R
7	Makkah Royal Clock Tower	Saudi Arabia	Mecca	601	120	2012	M (H/R)
8	Ping an Finance Center	China	Shenzhen	599	115	2017	O
9	Goldin Finance 117	China	Tianjin	596	128	OH	M (H/O)
10	Entisar Tower	UAE	Dubai	577	122	OH	M (H/R)
11	Lotte World Tower	South Korea	Seoul	554	123	2017	M (H/R/O)
12	One World Trade Center	USA	New York	541	94	2014	O
13	Guangzhou CTF Finance Centre	China	Guangzhou	530	111	2016	M (H/R/O)
14	Tianjin CTF Finance Centre	China	Tianjin	530	97	2019	M (H/O)
15	CITIC Tower	China	Beijing	528	108	2018	O
16	Evergrande Hefei Center 1	China	Hefei	518	112	OH	M (H/R/O)
17	Pentominium Tower	UAE	Dubai	515	122	OH	R

(continued)

#	Building name	Country	City	Height (meters)	# of storeys	Completion date	Function
18	Busan Lotte Town Tower	South Korea	Busan	510	107	NC	M (H/R/O)
19	TAIPEI 101	Taiwan	Taipei	508	101	2004	O
20	Greenland Jinmao International Financial Center	China	Nanjing	499	102	UC	M (H/O)
21	Shanghai World Financial Center	China	Shanghai	492	101	2008	M (H/O)
22	International Commerce Centre	China	Hong Kong	484	108	2010	M (H/O)
23	Wuhan Greenland Center	China	Wuhan	475	97	UC	M (H/R/O)
24	Central Park Tower	USA	New York	472	98	2020	R
25	Chengdu Greenland Tower	China	Chengdu	468	101	UC	M (H/O)
26	R&F Guangdong Building	China	Tianjin	468	91	OH	M (H/R/O)
27	Lakhta Center	Russia	St. Petersburg	462	87	2019	O
28	Vincom Landmark 81	Vietnam	Ho Chi Minh City	461	81	2018	M (H/R)
29	Changsha IFS Tower T1	China	Changsha	452	94	2018	M (H/O)
30	Petronas Twin Tower 1	Malaysia	Kuala Lumpur	452	88	1998	O
31	Petronas Twin Tower 2	Malaysia	Kuala Lumpur	452	88	1998	O
32	Zifeng Tower	China	Nanjing	450	66	2010	M (H/O)
33	The Exchange 106	Malaysia	Kuala Lumpur	446	95	2019	O
34	Marina 106	UAE	Dubai	445	104	OH	R
35	World One	Mumbai	India	442	117	NC	R
36	KK 100	China	Shenzhen	441	98	2011	M (H/O)
37	Guangzhou International Finance Center	China	Guangzhou	438	103	2010	M (H/O)
38	Multifunctional Highrise Complex– Akhmat Tower	Russia	Grozny	435	102	OH	M (R/O)
39	111 West 57th Street	USA	New York	435	84	UC	R
40	Chongqing Tall Tower	China	Chongqing	431	101	OH	M (H/R/O)
41	Haikou Tower 1	China	Haikou	428	94	OH	M (H/R/O)
42	One Vanderbilt Avenue	USA	New York	427	62	2020	O
43	Marina 101	UAE	Dubai	425	101	2017	M (H/R)
44	432 Park Avenue	USA	New York	425	85	2015	R
45	Trump International Hotel and Tower	USA	Chicago	423	98	2009	M (H/R)
46	Al Hamra Tower	Kuwait	Kuwait City	413	80	2011	O
47	Princess Tower	UAE	Dubai	413	101	2012	R

(*continued*)

Table A1.

#	Building name	Country	City	Height (meters)	# of storeys	Completion date	Function
48	Two International Finance Center	China	Hong Kong	412	88	2003	O
49	LCT The Sharp Landmark Tower	South Korea	Busan	411	101	2019	M (H/R)
50	Guangxi China Resources Tower	China	Nanning	402	86	2020	M (H/O)
51	China Resources Tower	China	Shenzhen	393	68	2018	O
52	23 Marina	UAE	Dubai	392	88	2012	R
53	CITIC Plaza	China	Guangzhou	390	80	1996	O
54	Dynamic Tower	UAE	Dubai	388	80	NC	M (H/R)
55	Shum Yip Upperhills Tower 1	China	Shenzhen	388	80	2020	M (H/O)
56	30 Hudson Yards	USA	New York	387	73	2019	O
57	PIF Tower	Saudi Arabia	Riyadh	385	72	ATO	O
58	Shun Hing Square	China	Shenzhen	384	69	1996	O
59	Autograph Tower	Indonesia	Jakarta	382	75	UC	M (H/O)
60	Burj Mohammed Bin Rashid	UAE	Abu Dhabi	381	88	2014	R
61	Guiyang World Trade Center Landmark Tower	China	Guiyang	380	92	UC	M (H/O)
62	Elite residence	UAE	Dubai	380	87	2012	R
63	Central Plaza	China	Hong Kong	374	78	1992	O
64	Federation Tower	Russia	Moscow	373	93	2016	M (R/O)
65	Golden Eagle Tiandi Tower A	China	Nanjing	368	77	2019	M (H/O)
66	Bank of China Tower	China	Hong Kong	367	72	1990	O
67	St. Regis Chicago	USA	Chicago	362	101	2020	M (H/R)
68	Almas Tower	UAE	Dubai	360	68	2008	O
69	Hanking Center Tower	China	Shenzhen	359	65	2018	O
70	Greenland Group Suzhou Center	China	Suzhou	358	77	UC	M (H/O)
71	Sino Steel International Plaza T2	China	Tianjin	358	83	OH	O
72	II Primo Tower 1	UAE	Dubai	356	79	UC	R
73	Emirates Tower One	UAE	Dubai	355	54	2000	O
74	OKO–Residential Tower	Russia	Moscow	354	90	2015	M (H/R)
75	Raffles City Chongqing T4N	China	Chongqing	354	74	2019	M (H/O)
76	The Torch	UAE	Dubai	352	86	2011	R
77	Spring City 66	China	Kunming	349	61	2019	O
78	The Center	China	Hong Kong	346	73	1998	O
79	Neva Towers 2	Russia	Moscow	345	79	2020	R
80	ADNOC Headquarters	UAE	Abu Dhabi	342	65	2015	O
81	One Shenzhen Bay Tower 7	China	Shenzhen	341	78	2018	M (H/R/O)

Table A1. (*continued*)

#	Building name	Country	City	Height (meters)	# of storeys	Completion date	Function
82	Comcast Technology Center	USA	Philadelphia	339	59	2018	M (H/O)
83	LCT The Sharp Residential Tower A	Korea	Busan	339	85	2019	R
84	Mercury City Tower	Russia	Moscow	338	75	2013	M (R/O)
85	Hengqin International Finance Center	China	Zhuhai	337	69	2020	M (R/O)
86	Tianjin World Financial Center	China	Tianjin	337	75	2011	O
87	Wilshire Grand Center	USA	Los Angeles	335	62	2017	M (H/O)
88	DAMAC heights	UAE	Dubai	335	88	2018	R
89	Shimao International Plaza	China	Shanghai	333	60	2006	M (H/O)
90	LCT The Sharp Residential Tower B	Korea	Busan	333	85	2019	R
91	China World Tower	China	Beijing	330	74	2010	M (H/O)
92	Hon Kwok City Center	China	Shenzhen	329	80	2017	M (R/O)
93	3 World Trade Center	USA	New York	329	69	2018	O
94	Keangnam Hanoi Landmark Tower	Vietnam	Hanoi	328	72	2012	M (H/R/O)
95	Golden Eagle Tiandi Tower B	China	Nanjing	328	68	2019	O
96	Salesforce Tower	USA	San Francisco	326	61	2018	O
97	Deji Plaza	China	Nanjing	324	62	2013	M (H/O)
98	Q1 Tower	Australia	Gold Coast	322	78	2005	R
99	Burj Al Arab	UAE	Dubai	321	56	1999	H
100	Nina Tower	China	Hong Kong	320	80	2006	M (H/O)
101	Sinar Mas Center 1	China	Shanghai	320	65	2017	O
102	Palace Royale	Mumbai	India	320	88	OH	R
103	53 West 53	USA	New York	320	77	2019	R
104	New York Times Tower	USA	New York	319	52	2007	O
105	Chongqing IFS T1	China	Chongqing	316	63	2016	M (H/O)
106	Australia 108	Australia	Melbourne	316	100	2020	R
107	Mahanakhon	China	Bangkok	314	79	2016	M (H/R)
108	CITIC Financial Center Tower 1	China	Shenzhen	312	–	UC	M (R/O)
109	Bank of America Plaza	USA	Atlanta	312	55	1992	O
110	Shenzhen Bay Innovation and Technology Centre Tower 1	China	Shenzhen	311	69	2020	O
111	Menara TM	Malaysia	Kuala Lumpur	310	55	2001	O
112	Ocean Heights	UAE	Dubai	310	83	2010	R
113	Pearl River Tower	China	Guangzhou	309	71	2013	O
114	Fortune Center	China	Guangzhou	309	68	2015	O
115	Emirates Tower Two	UAE	Dubai	309	56	2000	H

(*continued*)

Table A1.

#	Building name	Country	City	Height (meters)	# of storeys	Completion date	Function
116	Guangfa Securities Headquarters	China	Guangzhou	308	60	2018	O
117	The One	Canada	Toronto	308	85	UC	R
118	Burj Rafal	Saudi Arabia	Riyadh	307	68	2014	M (H/R)
119	Amna Tower	UAE	Dubai	307	75	2020	R
120	Noora Tower	UAE	Dubai	307	75	2019	R
121	The Shard	UK	London	306	73	2013	M (H/R/O)
122	Cayan Tower	UAE	Dubai	306	73	2013	R
123	Northeast Asia Trade Tower	South Korea	Incheon	305	68	2011	M (H/R/O)
124	35 Hudson Yards	USA	New York City	304	72	2019	M (H/R)
125	Baiyoke Tower II	Thailand	Bangkok	304	85	1997	H
126	One ManhaTan West	USA	New York	303	67	2019	O
127	Two Prudential Plaza	USA	Chicago	303	64	1990	O
128	Jiangxi Nanchang Greenland Central Plaza, Parcel A	China	Nanchang	303	59	2015	O
129	Jiangxi Nanchang Greenland Central Plaza, Parcel B	China	Nanchang	303	59	2015	O
130	Leatop Plaza	China	Guangzhou	303	64	2012	O
131	Kingdom Centre	Saudi Arabia	Riyadh	302	41	2002	M (H/R/O)
132	Capital City Moscow Tower	Russia	Moscow	301	76	2010	R
133	Supernova Spira	India	Noida	300	80	UC	M (H/R)
134	Al Wasl Tower	UAE	Dubai	300	64	UC	M (H/R/O)
135	Torre Costanera	Chile	Santiago	300	62	2014	M (H/O)
136	Abeno Harukas	Japan	Osaka	300	60	2014	M (H/O)
137	Shimao Riverside Block D2b	China	Wuhan	300	53	UC	M (H/O)
138	Aspire Tower	Qatar	Doha	300	36	2007	M (H/O)
139	NBK Tower	Kuwait	Kuwait City	300	61	2019	O
140	Golden Eagle Tiandi Tower C	China	Nanjing	300	60	2019	O

Note(s): “M” indicates mixed-use; “H” indicates hotel use; “R” indicates residential use; “O” indicates office use; “UAE” indicates the United Arab Emirates; “UC” indicates under construction; “NC” indicates never completed; “OH” indicates on hold

Table A1.

Appendix 2

Table A2. Supertall buildings by core type, building form, structural system and structural material

#	Building name	Core type	Building form	Structural system	Structural material
1	Nakheel Tower	Central	Free	Mega column	Composite
2	Burj Khalifa	Central	Setback	Buttressed core	RC
3	Suzhou Zhongnan Center	Central	Tapered	Outriggered frame	Composite
4	Merdeka PNB118	Central	Free	Outriggered frame	Composite
5	Shanghai Tower	Central	Twisted	Outriggered frame	Composite
6	Chicago Spire	Central	Twisted	Outriggered frame	RC
7	Makkah Royal Clock Tower	Central	Prismatic	Outriggered frame	Composite
8	Ping an Finance Center	Central	Tapered	Outriggered frame	Composite
9	Goldin Finance 117	Central	Tapered	Trussed-tube	Composite
10	Entisar Tower	Central	Setback	Framed-tube	RC
11	LoTe World Tower	Central	Tapered	Outriggered frame	Composite
12	One World Trade Center	Central	Tapered	Outriggered frame	Composite
13	Guangzhou CTF Finance Centre	Central	Setback	Outriggered frame	Composite
14	Tianjin CTF Finance Centre	Central	Tapered	Framed-tube	Composite
15	CITIC Tower	Central	Free	Trussed-tube	Composite
16	Evergrande Hefei Center 1	Central	Free	Outriggered frame	Composite
17	Pentominium Tower	Central	Free	Outriggered frame	RC
18	Busan LoTe Town Tower	Central	Free	Outriggered frame	Composite
19	TAIPEI 101	Central	Free	Outriggered frame	Composite
20	Greenland Jinmao International Financial Center	Central	Tapered	Outriggered frame	Composite
21	Shanghai World Financial Center	Central	Tapered	Outriggered frame	Composite
22	International Commerce Centre	Central	Tapered	Outriggered frame	Composite
23	Wuhan Greenland Center	Central	Tapered	Buttressed core	Composite
24	Central Park Tower	Central	Setback	Outriggered frame	RC
25	Chengdu Greenland Tower	Central	Tapered	Outriggered frame	Composite
26	R&F Guangdong building	Central	Setback	Outriggered frame	Composite
27	Lakhta Center	Central	Twisted	Outriggered frame	Composite
28	Vincom Landmark 81	Central	Setback	Bundled-tube	Composite

(*continued*)

#	Building name	Core type	Building form	Structural system	Structural material
29	Changsha IFS Tower T1	Central	Prismatic	Outriggered frame	Composite
30	Petronas Twin Tower 1	Central	Setback	Outriggered frame	RC
31	Petronas Twin Tower 2	Central	Setback	Outriggered frame	RC
32	Zifeng Tower	Central	Free	Outriggered frame	Composite
33	The Exchange 106	Central	Tapered	Outriggered frame	Composite
34	Marina 106	Central	Prismatic	Framed-tube	RC
35	World one	Central	Setback	Buttressed core	RC
36	KK 100	Central	Free	Framed-tube	Composite
37	Guangzhou International Finance Center	Central	Tapered	Outriggered frame	Composite
38	Multifunctional Highrise Complex – Akhmat Tower	Central	Tapered	Framed-tube	Steel
39	111 West 57th Street	Peripheral	Setback	Outriggered frame	RC
40	Chongqing Tall Tower	Central	Tapered	Outriggered frame	Composite
41	Haikou Tower 1	Central	Tapered	Outriggered frame	Composite
42	One Vanderbilt Avenue	Central	Tapered	Outriggered frame	Composite
43	Marina 101	Central	Prismatic	Framed-tube	RC
44	432 Park Avenue	Central	Prismatic	Framed-tube	RC
45	Trump International Hotel and Tower	Central	Setback	Outriggered frame	RC
46	Al Hamra Tower	Central	Free	Shear walled frame	Composite
47	Princess Tower	Central	Prismatic	Framed-tube	RC
48	Two International Finance Center	Central	Setback	Outriggered frame	Composite
49	LCT The Sharp Landmark Tower	Central	Prismatic	Outriggered frame	RC
50	Guangxi China Resources Tower	Central	Tapered	Outriggered frame	Composite
51	China Resources Tower	Central	Tapered	Framed-tube	Composite
52	23 Marina	Central	Prismatic	Outriggered frame	RC
53	CITIC Plaza	Central	Prismatic	Shear walled frame	RC
54	Dynamic Tower	Central	Free	Mega core	RC
55	Shum Yip Upperhills Tower 1	Central	Prismatic	Outriggered frame	Composite
56	30 Hudson Yards	Central	Tapered	Outriggered frame	Steel
57	PIF Tower	Central	Free	Trussed-tube	Composite
58	Shun Hing Square	Central	Free	Outriggered frame	Composite
59	Autograph Tower	Central	Prismatic	Outriggered frame	Composite

Table A2.

(continued)

#	Building name	Core type	Building form	Structural system	Structural material
60	Burj Mohammed Bin Rashid	Central	Free	Outriggered frame	RC
61	Guiyang World Trade Center Landmark Tower	Central	Tapered	Framed-tube	Composite
62	Elite Residence	Central	Prismatic	Framed-tube	RC
63	Central Plaza	Central	Prismatic	Trussed-tube	Composite
64	Federation Tower	Central	Free	Outriggered frame	Composite
65	Golden Eagle Tiandi Tower A	Central	Tapered	Outriggered frame	Composite
66	Bank of China Tower	Central (split)	Setback	Trussed-tube	Composite
67	St. Regis Chicago	Central	Free	Outriggered frame	RC
68	Almas Tower	Central	Free	Outriggered frame	Composite
69	Hanking Center Tower	External	Tapered	Trussed-tube	Steel
70	Greenland Group Suzhou Center	Central	Free	Outriggered frame	Composite
71	Sino Steel International Plaza T2	Central	Prismatic	Framed-tube	Composite
72	II Primo Tower 1	Central	Prismatic	Outriggered frame	RC
73	Emirates Tower One	Central	Prismatic	Mega column	Composite
74	OKO–Residential Tower	Central	Free	Outriggered frame	RC
75	Raffles City Chongqing T4N	Central	Tapered	Outriggered frame	Composite
76	The Torch	Central	Prismatic	Outriggered frame	RC
77	Spring City 66	Central	Free	Outriggered frame	Composite
78	The Center	Central	Prismatic	Mega column	Composite
79	NEVA TOWERS 2	Central	Prismatic	Outriggered frame	RC
80	ADNOC Headquarters	External	Prismatic	Shear walled frame	RC
81	One Shenzhen Bay Tower 7	Central	Tapered	Outriggered frame	Composite
82	Comcast Technology Center	Central	Setback	Trussed-tube	Composite
83	LCT The Sharp Residential Tower A	Central	Prismatic	Outriggered frame	RC
84	Mercury City Tower	Central	Setback	Framed-tube	RC
85	Hengqin International Finance Center	Central	Free	Outriggered frame	Composite
86	Tianjin World Financial Center	Central	Tapered	Outriggered frame	Composite
87	Wilshire Grand Center	Central	Tapered	Outriggered frame	Composite
88	DAMAC Heights	Central	Tapered	Outriggered frame	RC
89	Shimao International Plaza	Central	Free	Mega column	Composite
90	LCT The Sharp Residential Tower B	Central	Prismatic	Outriggered frame	RC

(*continued*)

Table A2.

#	Building name	Core type	Building form	Structural system	Structural material
91	China World Tower	Central	Tapered	Outriggered frame	Composite
92	Hon Kwok City Center	Central	Prismatic	Outriggered frame	Composite
93	3 World Trade Center	Central	Setback	Trussed-tube	Composite
94	Keangnam Hanoi Landmark Tower	Central	Setback	Outriggered frame	RC
95	Golden Eagle Tiandi Tower B	Central	Tapered	Outriggered frame	Composite
96	Salesforce Tower	Central	Tapered	Shear walled frame	Composite
97	Deji Plaza	Central	Prismatic	Outriggered frame	Composite
98	Q1 Tower	Central	Prismatic	Outriggered frame	RC
99	Burj Al Arab	Central	Free	Shear walled frame	Composite
100	Nina Tower	Central	Prismatic	Outriggered frame	RC
101	Sinar Mas Center 1	Central	Free	Outriggered frame	Composite
102	Palace Royale	Central	Prismatic	Outriggered frame	RC
103	53 West 53	Peripheral	Tapered	Framed-tube	RC
104	New York Times Tower	Central	Prismatic	Outriggered frame	Steel
105	Chongqing IFS T1	Central	Prismatic	Outriggered frame	Composite
106	Australia 108	Central	Free	Outriggered frame	RC
107	Mahanakhon	Central	Free	Outriggered frame	RC
108	CITIC Financial Center Tower 1	Central	Tapered	Framed-tube	Composite
109	Bank of America Plaza	Central	Setback	Mega column	Composite
110	Shenzhen Bay Innovation and Technology Centre Tower 1	Central	Prismatic	Framed-tube	Composite
111	Menara TM	Central	Free	Outriggered frame	RC
112	Ocean Heights	Central	Tapered	Outriggered frame	RC
113	Pearl River Tower	Central	Free	Outriggered frame	Composite
114	Fortune Center	Central	Free	Outriggered frame	Composite
115	Emirates Tower Two	Atrium	Prismatic	Outriggered frame	RC
116	Guangfa Securities Headquarters	Central	Tapered	Outriggered frame	Composite
117	The One	Central	Prismatic	Outriggered frame	Composite
118	Burj Rafal	Central	Prismatic	Outriggered frame	Composite

Table A2. (*continued*)

#	Building name	Core type	Building form	Structural system	Structural material
119	Amna Tower	Central	Prismatic	Outriggered frame	RC
120	Noora Tower	Central	Prismatic	Outriggered frame	RC
121	The Shard	Central	Tapered	Shear walled frame	Composite
122	Cayan Tower	Central	Twisted	Framed-tube	RC
123	Northeast Asia Trade Tower	Central	Tapered	Outriggered frame	Composite
124	35 Hudson Yards	Central	Setback	Outriggered frame	RC
125	Baiyoke Tower II	Central	Setback	Outriggered frame	RC
126	One ManhaTan West	Central	Tapered	Shear walled frame	Composite
127	Two Prudential Plaza	Central	Setback	Outriggered frame	RC
128	Jiangxi Nanchang Greenland Central Plaza, Parcel A	Central	Free	Outriggered frame	Composite
129	Jiangxi Nanchang Greenland Central Plaza, Parcel B	Central	Free	Outriggered frame	Composite
130	Leatop Plaza	Central	Prismatic	Trussed-tube	Composite
131	Kingdom Centre	Central	Free	Shear walled frame	RC
132	Capital City Moscow Tower	Central	Free	Outriggered frame	RC
133	Supernova Spira	Central	Prismatic	Outriggered frame	RC
134	Al Wasl Tower	Central	Free	Outriggered frame	Composite
135	Torre Costanera	Central	Tapered	Outriggered frame	RC
136	Abeno Harukas	Central	Setback	Outriggered frame	Composite
137	Shimao Riverside Block D2b	Central	Tapered	Outriggered frame	Composite
138	Aspire Tower	Central	Free	Mega core	RC
139	NBK Tower	Central	Free	Outriggered frame	Composite
140	Golden Eagle Tiandi Tower C	Central	Tapered	Outriggered frame	Composite

Note(s): "RC" indicates reinforced concrete

Table A2.

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