Interrelations of slenderness ratio and main design criteria in supertall buildings

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Abstract

Purpose – To date, there are no studies in the literature that provide a comprehensive understanding of the interrelationships between the slenderness ratio and the main design criteria in supertall towers (≥300 m). In this paper, this important issue was explored using detailed data collected from 75 cases.

Design/methodology/approach – This paper was carried out with a comprehensive literature review including the database of the Council on Tall Buildings and Urban Habitat (CTBUH) (CTBUH, 2022), peer-reviewed journals, MSc theses and PhD dissertations, conference proceedings, fact sheets, architectural and structural magazines and other Internet sources. In this study, the case study method was also used to gather and consolidate information about supertall towers to analyze the interrelationships. Cases were 75 supertall buildings in various countries [44 from Asia (37 from China), 16 from the Middle East (6 from Dubai, the United Arab Emirates), 11 from the United States of America and 3 from Russia, 1 from the UK].

Findings – The paper’s findings highlighted as follows: (1) for buildings in the height range of 300–399 m, the slenderness ratio was usually between 7 and 7.9 and megatall towers were frequently built at a slenderness ratio of 10–15; (2) the median slenderness ratio of buildings in the 400–599 m height ranges was around 8.6; (3) a trend towards supertall slender buildings (=8) was observed in Asia, the Middle East and North America; (4) residential, office and mixed-use towers had a median slenderness ratio of over 7.5; (5) all building forms were utilized in the construction of slender towers (>8); (6) the medium slenderness ratio was around 8 for supertall buildings constructed with outriggered frame and tube systems; (7) especially concrete towers reached values pushing the limits of slenderness (>10) and (8) since the number of some supertall building groups (e.g. steel towers) was not sufficient, establishing a scientific relationship between aspect ratio and related design criteria was not possible.

Originality/value – To date, there are no studies in the literature that provide a comprehensive understanding of the interrelationships between the slenderness ratio and the main design criteria in supertall towers (≥300 m). This important issue was explored using detailed data collected from 75 cases.

Keywords Slenderness ratio, Aspect ratio, Supertall building, Structural system, Location, Building form, Structural material, Building function, Building height, Interrelations

Paper type Research paper

1. Introduction

In the global race for the title of the world’s tallest tower, besides height, slenderness is among the prominent concerns. Slender skyscrapers are gaining popularity, as they can accommodate large volumes of spaces in the smallest possible footprint. These buildings are a manifestation of advanced technologies and innovative construction materials. Slenderness is perceived as an aesthetic value, and slender towers are generally considered beautiful (Riad, 2016). However, excessive slenderness can increase structural costs exponentially (Chakraborty et al., 2020; Elhegazy et al., 2021).

The history of slender towers can be divided into the following periods (Szołomicki and Golasz-Szołomicka, 2021): In the early 20th century, there was a rapid increase in the height of...
slender buildings, such as the Metropolitan Life Tower (Plate 1) due to the lack of municipal regulations. This was followed by the second period, dated to the 1920s. According to the 1916 Zoning Resolution, the building form had to be the same up to a certain height and the floor area had to be gradually reduced upwards as in the Empire State Building (Plate 2). In the mid-1980s, in the next era of slender skyscrapers, condominium towers rose in New York. These buildings used slenderness as a dominant design strategy as in City Spire (Plate 3). In the next period, several ultra-luxury skyscrapers were built between 2005 and 2010, such as the One 57 (Plate 4) in New York. Highcliff (Hong Kong, 2003) (Plate 5) was the world’s slenderest tower at that time, with a slenderness ratio of 20. This building left its mark on Hong Kong’s residential history, but in the following years such buildings were discontinued. At the beginning of 2010, a new form of a super-slim skyscraper was launched in New York, mainly due to increased land scarcity and demand for luxury housing. Today, the construction of tall slender towers is increasing rapidly all over the world, such as in Dubai, Melbourne and Guangzhou.

Today’s skyscrapers continue to take slenderness to unprecedented levels. Notable representatives of these structures are known as “pencil towers”: 432 Park Avenue (Plate 6) with an aspect ratio of 15 and 111 West 57th Street (Plate 7) with an aspect ratio of 24. The slenderness ratio or aspect ratio is defined as the ratio of the structural height of a building to the narrowest structural width at the ground floor plan or tower base (Ilgun et al., 2021). Especially in supertall buildings (≥300 m), the aspect ratio becomes more critical. This is because, at slenderness ratios exceeding 5, lateral loads often begin to dominate the structural
design (Galsworthy et al., 2016). A building with an aspect ratio greater than 7 is considered slender by New York State Building Code. Additionally, for towers with an aspect ratio greater than 8, additional damping systems should be used for occupancy comfort (Sarkisian, 2012).

Aspect ratio is one of the most important factors affecting the structural behavior of tall towers. Under wind loads, the overturning moment at the base increases with the square of the building height, and the lateral deflection is proportional to the fourth power of the building height (Almusharaf and Elnimeiri, 2010). Therefore, as the height and slenderness increase, it becomes more critical to provide adequate lateral stiffness under lateral loads (Kikuchi et al., 2014).

Developing an effective structural system is one of the biggest challenges facing the designer of tall slender buildings. In this context, outriggered frame and tube systems are among the prominent structural systems (Walsh et al., 2018). For example, in tube systems, the full width of the building is used to resist overturning forces, and this is one way to reduce the slenderness ratio. Additionally, slender skyscrapers need to have sufficient mass, and one way to achieve this is to use concrete as in the case of 432 Park Avenue.

Occupancy comfort (serviceability) is one of the most important inputs in skyscraper design (Gunel and Ilgın, 2014a). To meet the serviceability limit state design, the lateral...
displacement must not exceed the limit value (Gunel and Ilgin, 2014b). Furthermore, building sway must be kept within acceptable limits. For this reason, it is important to minimize the discomfort experienced by those living on the upper floors and to prevent negative consequences such as damage to non-structural elements.

In slender towers, aerodynamic behavior becomes an important design criterion in terms of occupancy comfort and building sway (Ilgin and Günel, 2021; Whiteman et al., 2022). In this sense, aerodynamically efficient design modifications are used to change the wind flow pattern around the building. The selection of aerodynamic building form, aerodynamic building top and corner modifications are effective methods (Arslan Seçluk and Ilgin, 2017; Sharma et al., 2018; Jafari and Alipour, 2021a). In addition to the abovementioned measures, auxiliary dumping devices can also be used as in 432 Park Avenue (Ripamonti et al., 2019; Zhong et al., 2022).

The small footprint forces the service core to become compact. This significantly increases space efficiency by optimizing the number of elevators as in 111 West 57th Street. This world’s slenderest tower has more than 80 floors and 60 apartments serviced by only two passenger elevators. Slender buildings benefit from daylight more efficiently due to their narrow lease span. Lease span is the distance between a fixed interior component (e.g. building core wall) and the facade element (e.g. window).

There is no study in the literature that comprehensively understands the interrelations of slenderness ratio and main design criteria in supertall buildings. These criteria are height, location, function, form, structural system and structural material. Their relationships to slenderness ratio were investigated multidimensionally using 75 detailed supertall cases.
In this study, besides giving general information (building name, location, height, number of stories, completion date and function), important data analyses (aspect ratio, core type, form, structural system and structural material) were also made. This article will help key construction professionals such as architects and structural designers to produce more viable slender skyscraper projects.

The remainder of the paper was structured as follows: first, a comprehensive literature review was provided; then, the research methods employed in the study were presented; this was followed by results of interrelations of slenderness ratio and main design criteria, and finally, discussion and conclusions were presented, along with recommendations and research limitations.

2. Literature review

There are a limited number of studies in the literature focusing on the slenderness ratio in tall buildings. In addition, as seen in the following studies, the current literature is mostly based on the effect of slenderness on structural and aerodynamic design. In this sense, the relationship between the slenderness ratio and the main design considerations is a gap in the literature.

Among the studies on structural and aerodynamic design, Kikuchi et al. (2014) focused on the design of seismically isolated tall slender buildings through a case study. The results showed that (1) appropriate rigidity was achieved using steel mega braces; (2) it was possible to decrease the tensile reaction forces on the corner seismic isolators. Willis (2016) highlighted the slender residential building as a new typology by analyzing financial and engineering variables. Two types of super-slim towers were identified: Manhattan’s ultra-luxury towers and all other tall slender residential buildings. Kim et al. (2018) studied aerodynamic forces on a tall building with an aspect ratio of 9. The results showed major differences in across-wind direction, but only minor differences in along-wind direction. Walsh et al. (2018) compared...
Plate 5.
Highcliff

Source(s): Wikipedia

Plate 6.
432 Park Avenue

Source(s): Wikipedia
nine different slender towers in terms of lateral deformation. The results indicated that square-based buildings could achieve greater heights than rectangular-based towers in the same area. Mele et al. (2019) investigated the effect of slenderness ratio on the structural behavior of diagrid tall buildings. The results showed that (1) for 6 to 8 aspect ratios, the structural design was mainly dominated by rigidity; (2) aspect ratios around 5 became the threshold for design solutions driven by local strength demand. Szołomicki and Golasz-Szołomicka (2021) presented the needle-like residential towers as a new typology. Their results addressed a variety of issues related to wind-induced vibrations, structural limitations and construction costs. Cascone et al. (2021) proposed a new diagrid-like model with different slenderness ratios. The results showed that the highest structural efficiency was achieved in buildings with slenderness ratios of 6.67 and 5. Ghosh and Sil (2022) analyzed the dynamic responses of tall buildings with different aspect ratios in extreme wind hazard regions of India. The aspect ratio was found to contribute greatly to the dynamic responses in terms of the base moment. Gunda and Anthugari (2022) proposed tall building models to evaluate the seismic response for various aspect ratios. Their study showed that the aspect ratio was critical in optimum outrigger location. Singh and Mandal (2022) examined wind loads for supertall towers with different aspect ratios. Across-wind loads at the tip of the tower were found to increase by up to 275% for different aspect ratios.

Overall, there is no study in the literature that comprehensively understands the interrelations of slenderness ratio and main design criteria in supertall buildings. This important issue was explored using data collected from 75 supertall cases as detailed below.

3. Research methods
This paper was carried out with a comprehensive literature review including the database of the Council on Tall Buildings and Urban Habitat (CTBUH) (CTBUH, 2022), peer-reviewed journals, MSc theses and PhD dissertations, conference proceedings, fact sheets, architectural and structural magazines and other Internet sources.
In this study, the case study method was also used to gather and consolidate information about supertall towers to analyze the interrelationships. This method is widely used in built environment assessments where projects are defined for quantitative and qualitative data (Ilgin, 2022a). In this paper, the parameters were examined as follows: (1) building height, (2) location, (3) building function, (4) building form, (5) structural system and (6) structural material. Cases were 75 supertall buildings in various countries [44 from Asia (37 from China), 16 from the Middle East (6 from Dubai, the United Arab Emirates), 11 from the United States of America, 3 from Russia and 1 from the UK]. Detailed information was provided in 75 selected case studies (see Appendixes 1 and 2). Half of these cases were completed in the last ten years and the majority in the last two decades. In addition, the selected buildings included the world’s tallest iconic skyscrapers such as the Burj Khalifa. Buildings that do not have sufficient information about the slenderness ratio and related design features were not included in the list.

In terms of functionality, supertall buildings were classified as single-use and mixed-use. In this study, hotel, residence and office were considered primary functions, while their combinations (e.g. hotel and residential) were considered mixed-use. There is no global consensus on the number of floors or heights of supertall buildings (Ali and Al-Kodmany, 2022). However, in the author’s view, taking into account the CTBUH database (CTBUH, 2022), a “supertall building” was considered equal to and taller than a 300 m building, while a “megatall” was a 600 m or higher building.

Considering existing literature (e.g. Ilgin, 2006; Gunel and Ilgin, 2007; Taranath, 2016; Ali and Moon, 2018; Chen, 2021), the classifications of Ilgin (2022b) on core typology, building form, structural system and structural material were used (see Figure 1).

4. Results
4.1 Interrelations of slenderness ratio and main design criteria
In this section, the interrelations of the slenderness ratio and the main design criteria (building height, location, building function, building form, structural system and structural material) were examined. Since the most frequently used core typology (>96%) in the study sample was the central core, no analysis was made on this subject.

4.1.1 Interrelation of slenderness ratio and building height. Figures 2 and 3 shows how the aspect ratio changes with building height where the dots correspond to supertall buildings. Considering the trend line in Figure 3, it did not seem possible to establish a strong scientific relationship between the slenderness ratio and the height.

| Core                  | Building form         | Structural system              | Structural material |
|-----------------------|-----------------------|---------------------------------|---------------------|
| Central core          | Prismatic form        | Shear-frame system              | Steel               |
| - central             | Setback form          | - shear trussed frame           | Reinforced concrete |
| - central split       | Tapered form          | - shear walled frame            |                     |
| Atrium core           | Twisted form          | Mega core system                |                     |
| - atrium              | Leaning/tilted form   | Mega column system              |                     |
| - atrium split        | Free form             | Outrigged frame system          |                     |
| External core         |                       | Tube system                     |                     |
| - attached            |                       | - framed-tube                   |                     |
| - detached            |                       | - trussed-tube                  |                     |
| - partial split       |                       | - bundled-tube                  |                     |
| - full split          |                       | Buttressed core system          |                     |
| Peripheral core       |                       |                                 |                     |
| - partial peripheral  |                       |                                 |                     |
| - full peripheral     |                       |                                 |                     |
| - partial split       |                       |                                 |                     |
| - full split          |                       |                                 |                     |

Figure 1.
Core, building form, structural system and structural material classifications used in this study.
Buildings with a height of 300–349 m constituted 33% of the entire sample. The median slenderness ratio of these buildings was 7.7. There were 16 buildings with the same median slenderness ratio in the 350–399 m height range. In the height range of 300–349 m, slenderness ratios between 7–7.9 and 10–15 were mostly used, whereas only 1 supertall building had an aspect ratio above 15. While the slenderness ratio between 7 and 7.9 was used in the 350–399 m height range in 5 cases, the slenderness ratio above 15 was not encountered.

The median slenderness ratio of 17 buildings in the 400–499 m height range was 8.6. The median slenderness ratio of 10 towers built between 500 and 599 m in height was 8.5. In the height range of 400–499 m, 5 cases were built with a slenderness ratio of 7–7.9. Slenderness ratios between 5 and 6.9 and above 15 were represented by one case for each (Figure 2). The slenderness ratio of the 10 cases in the 500–599 m height range was predominantly...
between 7 and 9.9. Megatall towers were usually built with a slenderness ratio of 10–15. Their median slenderness ratio was 10.

Burj Khalifa is the tallest building in the world with a height of 828 m. The slenderness ratio of this tower is 10.5. Additionally, 111 West 57th Street is the slenderest building with a slenderness ratio of 24.

4.1.2 Interrelation of slenderness ratio and location. Figure 4 indicates the interrelation of aspect ratio and location. The median slenderness ratio was about 8 in Asia, the lowest in Chongqing IFS T1 with 5.8 and the highest in MahaNakhon with 13.6. In the Middle East, the median was around 10, the lowest in PIF Tower with 6.9 and the highest in Aspire Tower with 16.6. The median slenderness ratio of supertall buildings in North America was 8, the lowest in Salesforce Tower with 6.9 and the highest in 111 West 57th Street with 24.

The high slenderness ratio of the three locations mentioned above (the median ≥8) can be explained by the following drivers: (1) prestige concern, (2) high demand for luxury living, (3) narrow-base construction due to scarcity of buildable areas and (4) high land prices (Willis, 2016; Szołomicki and Golasz-Szołomicka, 2021; Ilgm, 2021a, b). For example, 432 Park Avenue offered the iconic mailing address specifically targeted at the investment aspirations of the world’s ultra-wealthy buyers. Similarly, many of Dubai’s towers targeted Emirati workers.

In Russia (3 cases) and the rest (only 1 case), the number of supertall towers was too small to establish a scientific relationship between aspect ratio and location.

4.1.3 Interrelation of slenderness ratio and building function. Figure 5 depicts the interrelation of aspect ratio and building function. The median slenderness ratio was about 11 for supertall residential buildings, the lowest in World One with 9.2 and the highest in 111 West 57th Street with 24. For supertall office towers, the median was around 7.5, the lowest in Bank of America Plaza with 6.4 and the highest in Pearl River Tower with 11.7. The median slenderness ratio of supertall mixed-use buildings in the study sample was 8, the lowest in The Shard with 5 and the highest in Aspire Tower with 16.6.

The high median value of residential skyscrapers can be explained by the demand for luxury living at higher altitudes with astonishing views (Generalova and Generalov, 2018; Ilgm, 2021c; Besjak et al., 2022). The fact that the slenderest tower, 111 West 57th Street, was built for residential purposes supported this statement.

4.1.4 Interrelation of slenderness ratio and building form. Figure 6 shows the interrelation of aspect ratio and building form. The median slenderness ratio of prismatic supertall buildings was about 8.5, the lowest in Chongqing IFS T1 with 5.8 and the highest in 432 Park Avenue with 15. The median of setback towers was around 8.3, the lowest in Bank of America
Plaza with 6.4 and the highest in 111 West 57th Street with 24. The median slenderness ratio of tapered skyscrapers was 8, the lowest in The Shard with 5 and the highest in 53 West 53 with 12. Freeform supertall buildings had the median slenderness ratio of 9.2, the lowest in Zifeng Tower with 6 and the highest in Aspire Tower with 16.6.

Given the above median values, it was seen that all building forms can be constructed at high slenderness ratios. Also considering that wind loads become more critical in highly slender structures such as 111 West 57th Street, the aerodynamic advantages of setback form may be an important factor in form selection (Ilgın and Gümel, 2007; Ilgın, 2018; Mandal et al., 2022). Since the number of twisted buildings was very small, it was not possible to establish a scientific relationship between the aspect ratio and the building form in these towers.

4.1.5 Interrelation of slenderness ratio and structural system. Figure 7 illustrates the interrelation of aspect ratio and structural system. Since the number of buildings with a shear walled frame, mega core and mega column and buttressed core systems was quite small,
deriving a correlation between aspect ratio and structural systems in these towers was likely to be inaccurate. The median slenderness ratio was about 8.3 for supertall buildings with outriggered frame systems, the lowest in Chongqing IFS T1 with 5.8 and the highest in 111 West 57th Street with 24. The median for tubular towers was around 8, the lowest in China Resources Tower with 6.6 and the highest in 432 Park Avenue with 15.

Under wind loads, the overturning moment at the building base differs in proportion to the square of the height of the building; therefore, supertall slender towers are much more susceptible to these loads (Zhang et al., 2020; Jafari and Alipour, 2021b). Outriggered frame system is commonly used in tall slender towers to provide lateral stiffness against overturning. This may be the main reason why this superior system was used in the slenderest building in this study.

Since the distance between the inner mega core walls is used instead of the exterior facade in the slenderness calculation of mega core systems, the slenderness ratio is higher than expected. This might explain the unusual slenderness seen in mega core Aspire Tower. On the other hand, in buttressed core systems, the massive tower base can make these structures less slender than expected as in the Burj Khalifa.

4.1.6 Interrelation of slenderness ratio and structural material. Figure 8 indicates the interrelation of aspect ratio and structural material. The median slenderness ratio was about 10.5 for concrete supertall buildings, the lowest in Kingdom Center with 7.2 and the highest in 111 West 57th Street with 24. The median for composite towers was 7.7, the lowest in The Shard with 5 and the highest in Pearl River Tower with 11.7.

Concrete is generally preferred for tall slender towers to provide sufficient mass against wind loads. Therefore, it was not surprising that concrete was often preferred in buildings with high slenderness ratios (>10) such as 111 West 57th Street. Similarly, composite structures achieve high slenderness (with a median of 8), using concrete that performs better at damping building sway (Zhou et al., 2022). This may explain why composite was the most preferred material in the sample group.

Since the number of steel buildings was very few, it was not possible to establish a relationship between the aspect ratio and the structural material in these towers.

5. Discussion and conclusions
Due to the lack of literature, it was not possible to make a comprehensive discussion about the similarities and differences between this study and other slenderness-oriented studies. However, the findings regarding location, building form, structural system and structural
material were supported by the findings of Szolomicki and Golasz-Szolomicka (2021). The main findings of the study were as follows:

1. For buildings in the height range of 300–399 m, the slenderness ratio was usually between 7 and 7.9 and megatall towers were frequently built at a slenderness ratio of 10–15;

2. The median slenderness ratio of buildings in the 400–599 m height ranges was around 8.6;

3. A trend towards supertall slender buildings (≥8) was observed in Asia, the Middle East and North America;

4. Residential, office and mixed-use towers had a median slenderness ratio of over 7.5;

5. All building forms were utilized in the construction of slender towers (>8);

6. The medium slenderness ratio was around 8 for supertall buildings constructed with outriggered frame and tube systems;

7. Especially concrete towers reached values pushing the limits of slenderness (>10) and

8. Since the number of some supertall building groups (e.g. steel towers) was not sufficient, it was not possible to establish a scientific relationship between aspect ratio and related design criteria.

Slender supertall building construction was in demand in Asian, Middle Eastern and North American cities. This finding can be associated with the findings of Szolomicki and Golasz-Szolomicka (2021). In their study, it was noted that supertall slender buildings began to appear in Asia and the Middle East, inspired by New York’s super-slim residential towers. According to the results of the study, slender towers (>7) were built in all building forms. Furthermore, the slenderest structure in the sample group was in a setback form, probably due to the strong relationship between supertall tower design and aerodynamic considerations. This issue was also highlighted in the study by Szolomicki and Golasz-Szolomicka (2021). In addition,
their study drew attention to the use of outriggered frame and tube systems in the design of slender towers. Similarly, in this study, the median slenderness ratios were found to be high (>8) in supertall buildings where these structural systems were used. In terms of structural material, concrete supertall towers such as 111 West 57th Street reached values pushing the limits of slenderness (>10). Supporting this finding, Szolomicki and Golasz-Szolomicka (2021) stressed that concrete was an ideal material for super-slender tall buildings, especially because of its mass advantage against wind loads.

In this study, the relationships between slenderness ratio and related design considerations were examined over 75 detailed supertall cases. These design parameters were building height, location, building function, building form, structural system and structural material. The results obtained in this paper will contribute to key construction professionals such as architectural and structural designers to produce more viable slender skyscraper projects.

Today, skyscrapers of different forms and functions are being built in many cities of the world, pushing the limits of slenderness. Increasingly, the world’s metropolises are following in the footsteps of pioneering cities like New York. Such cities are notorious for offering the luxury of living in pen-like towers, especially given global residential trends. Often built as concrete residences, these skyscrapers present engineering and economic challenges to meet the desired architectural and technical requirements (Wang et al., 2017; Elhegazy, 2020). These challenges can include the overuse of structural materials for required lateral stiffness and thus high construction costs (Elhegazy et al., 2022). In this sense, combining structural efficiency and esthetics, diagrid-frame-tube systems can be an ideal structural system for slender towers (Mele et al., 2019). This system, which is more effective against lateral loads compared to the conventional framed-tube system, can be made of steel, concrete or composite (Ilgin et al., 2022). The choice of concrete or composite provides an advantage to tall slender structures by providing sufficient mass under wind loads. Additionally, interdisciplinary collaboration is critical in transforming slender tower projects into viable applications in terms of structural stiffness, occupancy comfort and space efficiency.

Several limitations of this study should be mentioned. The empirical data given were limited to 75 supertall cases. Building groups with relatively few cases such as steel towers can yield biased results. However, where necessary, it was emphasized that the analyses in these groups may not yield scientifically accurate results. In addition, much larger sample sizes can be studied to make the results more convincing. In this sense, tall buildings lower than 300 m can also be included in the sample so that a sufficient number of subclasses can be created in future studies.

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(The Appendix follows overleaf)
### Table A1.
Supertall buildings considered in this study

| #  | Building name                       | Aspect ratio | Location (Country/city)                      | Height (m) | # of story | Completion date | Function |
|----|-------------------------------------|--------------|---------------------------------------------|------------|------------|----------------|----------|
| 1  | Nakheel Tower                       | 10           | UAE/Dubai                                   | 1,000+     | 200        | NC             | H/R/O    |
| 2  | Jeddah Tower                        | 10           | SA/Jeddah                                   | 1,000+     | 167        | UC             | R        |
| 3  | Burj Khalifa                        | 10.5         | UAE/Dubai                                   | 828        | 163        | 2010           | H/R/O    |
| 4  | Suzhou Zhongnan Center              | 8.7          | China/Suzhou                                | 729        | 137        | NC             | H/R/O    |
| 5  | Merdeka PNB118                       | 6.7          | Malaysia/Kuala Lumpur                       | 644        | 118        | UC             | H/O      |
| 6  | Shanghai Tower                       | 7.6          | China/Shanghai                              | 632        | 128        | 2015           | H/O      |
| 7  | Chicago Spire                        | 10           | USA/Chicago                                 | 609        | 150        | NC             | R        |
| 8  | Ping An Finance Center              | 8.3          | China/Shenzhen                              | 599        | 115        | 2017           | O        |
| 9  | Goldin Finance 117                  | 9.5          | China/Tianjin                               | 596        | 128        | OH             | H/O      |
| 10 | Entisar Tower                       | 9            | UAE/Dubai                                   | 577        | 122        | OH             | H/R      |
| 11 | Lotte World Tower                   | 7.9          | South Korea/Seoul                           | 554        | 123        | 2017           | H/R/O    |
| 12 | One World Trade Center              | 8.5          | USA/New York                                | 541        | 94         | 2014           | O        |
| 13 | Guangzhou CTF Finance Center        | 8.5          | China/Guangzhou                             | 530        | 111        | 2016           | H/R/O    |
| 14 | Tianjin CTF Finance Center          | 7.3          | China/Tianjin                               | 530        | 97         | 2019           | H/O      |
| 15 | CITIC Tower                         | 7.2          | China/Beijing                               | 528        | 108        | 2018           | O        |
| 16 | Evergrande Hefei Center 1           | 9.2          | China/Hefei                                 | 518        | 112        | OH             | H/R/O    |
| 17 | TAIPEI 101                          | 10           | Taiwan/Taipei                               | 508        | 101        | 2004           | O        |
| 18 | Shanghai World Financial Center     | 8.5          | China/Shanghai                              | 492        | 101        | 2008           | H/O      |
| 19 | International Commerce Center       | 9            | China/Hong Kong                              | 484        | 108        | 2010           | H/O      |
| 20 | Chengdu Greenland Tower             | 7.5          | China/Chengdu                               | 468        | 101        | UC             | H/O      |
| 21 | Lakhtra Center                      | 7.8          | Russia/St. Petersburg                       | 462        | 87         | 2019           | O        |
| 22 | Petronas Twin Tower 1               | 8.6          | Malaysia/Kuala Lumpur                       | 452        | 88         | 1998           | O        |
| 23 | Petronas Twin Tower 2               | 8.6          | Malaysia/Kuala Lumpur                       | 452        | 88         | 1998           | O        |
| 24 | Zifeng Tower                        | 6            | China/Nanjing                               | 450        | 66         | 2010           | H/O      |
| 25 | World One                           | 9.2          | Mumbai/India                                | 442        | 117        | NC             | R        |
| 26 | KK 100                              | 9.5          | China/Shenzhen                              | 441        | 98         | 2011           | H/O      |
| 27 | Guangzhou International Finance Center | 7.7              | China/Guangzhou                             | 438        | 103        | 2010           | H/O      |
| 28 | 111 West 57th Street                | 24           | USA/New York                                | 435        | 84         | UC             | R        |
| 29 | Marina 101                          | 12           | UAE/Dubai                                   | 425        | 101        | 2017           | H/R      |

(continued)
| #  | Building name                          | Aspect ratio | Location (Country/city)                  | Height (m) | # of story | Completion date | Function |
|----|----------------------------------------|--------------|----------------------------------------|------------|------------|----------------|----------|
| 30 | 432 Park Avenue                         | 15           | USA/New York                           | 425        | 85         | 2015           | R        |
| 31 | Trump International Hotel and Tower    | 8            | USA/Chicago                            | 423        | 98         | 2009           | H/R      |
| 32 | Al Hamra Tower                          | 7            | Kuwait/Kuwait City                     | 413        | 80         | 2011           | O        |
| 33 | Princess Tower                          | 11           | UAE/Dubai                              | 413        | 101        | 2012           | R        |
| 34 | Two International Finance Center       | 7.2          | China/Hong                             | 412        | 88         | 2003           | O        |
| 35 | China Resources Tower                   | 6.6          | China/Shenzhen                         | 393        | 68         | 2018           | O        |
| 36 | 23 Marina                               | 9.5          | UAE/Dubai                              | 392        | 88         | 2012           | R        |
| 37 | CITIC Plaza                             | 7.4          | China/Guangzhou                        | 390        | 80         | 1996           | O        |
| 38 | Shum Yip Upperhills Tower 1            | 7.2          | China/Shenzhen                         | 388        | 80         | 2020           | H/O      |
| 39 | PIF Tower                               | 6.9          | China/Shenzhen                         | 384        | 69         | 1996           | O        |
| 40 | Sun Hing Square                         | 8            | China/Shenzhen                         | 381        | 88         | 2014           | R        |
| 41 | Burj Mohammed Bin Rashid               | 13           | UAE/Abu Dhabi                          | 380        | 87         | 2012           | R        |
| 42 | Elite Residence                        | 10.3         | Hong Kong                              | 374        | 78         | 1992           | O        |
| 43 | Central Plaza                           | 8.4          | China/Hong                             | 358        | 83         | 2019           | H/O      |
| 44 | Golden Eagle Tiandi Tower A            | 7.3          | China/Nanjing                           | 359        | 65         | 2018           | O        |
| 45 | Bank of China Tower                    | 7            | China/Shenzhen                         | 346        | 73         | 1998           | O        |
| 46 | Almas Tower                             | 9.2          | China/Shenzhen                         | 337        | 79         | 2019           | R        |
| 47 | Hankning Center Tower                  | 7.3          | China/Shenzhen                         | 328        | 68         | 2012           | O        |
| 48 | Sino Steel Int. Plaza T2              | 6.9          | China/Tianjin                          | 328        | 68         | 2019           | O        |
| 49 | Raffles City Chongqing T3N             | 9.5          | China/Shanghai                         | 319        | 79         | 2019           | R        |
| 50 | Raffles City Chongqing T4N             | 9.5          | China/Shanghai                         | 319        | 79         | 2019           | R        |
| 51 | The Center                             | 8.2          | China/Hong                             | 319        | 79         | 2019           | R        |
| 52 | NEVA TOWERS 2                          | 11.3         | Russia/Moscow                          | 319        | 79         | 2019           | R        |
| 53 | Four Seasons Place                     | 12.5         | Malaysia/Kuala Lumpur                 | 319        | 79         | 2019           | R        |
| 54 | Comcast Technology Center              | 7.1          | USA/Kuala Lumpur                       | 339        | 59         | 2018           | H/O      |
| 55 | Mercury City Tower                     | 7.6          | Russia/Moscow                          | 338        | 75         | 2013           | R/O      |
| 56 | Hengqin International Finance Center   | 7.7          | China/Zhuhai                           | 337        | 69         | 2020           | R/O      |
| 57 | Tianjin World Financial Center         | 8            | China/Tianjin                          | 337        | 75         | 2011           | O        |
| 58 | Golden Eagle Tiandi Tower B            | 8.3          | China/Nanjing                          | 328        | 68         | 2019           | O        |

(continued)
| #   | Building name                                      | Aspect ratio | Location (Country/city)                  | Height (m) | # of story | Completion date | Function |
|-----|---------------------------------------------------|--------------|----------------------------------------|------------|------------|-----------------|----------|
| 59  | Salesforce Tower                                  | 6.9          | USA/San Francisco                      | 326        | 61         | 2018            | O        |
| 60  | 53 West 53                                        | 12           | USA/New York                           | 320        | 77         | 2019            | R        |
| 61  | New York Times Tower                               | 7.3          | USA/New York                           | 319        | 52         | 2007            | O        |
| 62  | Chongqing IFS T1                                  | 5.8          | China/Chongqing                        | 316        | 63         | 2016            | H/O      |
| 63  | MahaNakhon                                         | 13.6         | China/Bangkok                          | 314        | 79         | 2016            | H/R      |
| 64  | Bank of America Plaza                             | 6.4          | USA/Atlanta                            | 312        | 55         | 1992            | O        |
| 65  | Shenzhen Bay Innovation and Technology Center Tower 1 | 6.9          | China/Shenzhen                         | 311        | 69         | 2020            | O        |
| 66  | Ocean Heights                                     | 11.5         | UAE/Dubai                              | 310        | 83         | 2010            | R        |
| 67  | Pearl River Tower                                  | 11.7         | China/Guangzhou                        | 309        | 71         | 2013            | O        |
| 68  | Guangfa Securities Headquarters                    | 7.7          | China/Guangzhou                        | 308        | 60         | 2018            | O        |
| 69  | One 57                                            | 8            | USA/New York                           | 306        | 75         | 2014            | R/H      |
| 70  | The Shard                                          | 5            | UK/London                              | 306        | 73         | 2013            | H/R/O    |
| 71  | Cayan Tower                                        | 10.8         | UAE/Dubai                              | 306        | 73         | 2013            | R        |
| 72  | Kingdom Center                                     | 7.2          | SA/Riyadh                              | 302        | 41         | 2002            | H/R/O    |
| 73  | Shimao Riverside Block D2b                         | 6.7          | China/Wuhan                            | 300        | 53         | UC              | H/O      |
| 74  | Aspire Tower                                       | 16.6         | Qatar/Doha                             | 300        | 36         | 2007            | H/O      |
| 75  | Golden Eagle Tiandi Tower C                        | 7.5          | China/Nanjing                          | 300        | 60         | 2019            | O        |

**Note(s):** “H” indicates hotel use; “R” indicates residential use; “O” indicates office use; “UAE” indicates the United Arab Emirates; “SA” indicates Saudi Arabia; “UC” indicates Under construction; “NC” indicates Never completed and “OH” indicates On hold

Table A1.
| #  | Building name                | Core type | Building form | Structural system       | Structural material |
|----|-----------------------------|-----------|---------------|-------------------------|---------------------|
| 1  | Nakheel Tower               | Central   | Free          | Mega column             | Composite           |
| 2  | Jeddah Tower                | Central   | Tapered       | Buttressed core         | RC                  |
| 3  | Burj Khalifa                | Central   | Setback       | Buttressed core         | RC                  |
| 4  | Suzhou Zhongnan Center      | Central   | Tapered       | Outriggered frame       | Composite           |
| 5  | Merdeka PNB118              | Central   | Free          | Outriggered frame       | Composite           |
| 6  | Shanghai Tower              | Central   | Twisted       | Outriggered frame       | Composite           |
| 7  | Chicago Spire               | Central   | Twisted       | Outriggered frame       | RC                  |
| 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 | Lotte World Tower           | Central   | Tapered       | Outriggered frame       | Composite           |
| 12 | One World Trade Center      | Central   | Tapered       | Outriggered frame       | Composite           |
| 13 | Guangzhou CTF Finance Center| Central   | Setback       | Outriggered frame       | Composite           |
| 14 | Tianjin CTF Finance Center  | Central   | Tapered       | Framed-tube             | Composite           |
| 15 | CITIC Tower                 | Central   | Free          | Trussed-tube            | Composite           |
| 16 | Evergrande Hefei Center 1   | Central   | Free          | Outriggered frame       | Composite           |
| 17 | TAIPEI 101                  | Central   | Free          | Outriggered frame       | Composite           |
| 18 | Shanghai World Financial Center | Central   | Tapered       | Outriggered frame       | Composite           |
| 19 | International Commerce Center| Central   | Tapered       | Outriggered frame       | Composite           |
| 20 | Chengdu Greenland Tower     | Central   | Tapered       | Outriggered frame       | Composite           |
| 21 | Lakhta Center               | Central   | Twisted       | Outriggered frame       | Composite           |
| 22 | Petronas Twin Tower 1       | Central   | Setback       | Outriggered frame       | RC                  |
| 23 | Petronas Twin Tower 2       | Central   | Setback       | Outriggered frame       | RC                  |
| 24 | Zifeng Tower                | Central   | Free          | Outriggered frame       | Composite           |
| 25 | World One                   | Central   | Setback       | Buttressed core         | RC                  |
| 26 | KK 100                      | Central   | Free          | Framed-tube             | Composite           |
| 27 | Guangzhou International Finance Center | Central | Tapered | Outriggered frame | Composite |
| 28 | 111 West 57th Street        | Peripheral| Setback       | Outriggered frame       | RC                  |
| 29 | Marina 101                  | Central   | Prismatic     | Framed-tube             | RC                  |
| 30 | 432 Park Avenue             | Central   | Prismatic     | Framed-tube             | RC                  |

Table A2. Supertall buildings by core type, building form, structural system, and structural material (continued)
| #  | Building name                          | Core type | Building form | Structural system   | Structural material |
|----|---------------------------------------|-----------|---------------|---------------------|---------------------|
| 31 | Trump International Hotel and Tower   | Central   | Setback       | Outriggered frame   | RC                  |
| 32 | Al Hamra Tower                        | Central   | Free          | Shear-walled frame  | Composite           |
| 33 | Princess Tower                        | Central   | Prismatic     | Framed-tube frame   | RC                  |
| 34 | Two International Finance Center      | Central   | Setback       | Outriggered frame   | Composite           |
| 35 | China Resources Tower                 | Central   | Tapered       | Outriggered frame   | Composite           |
| 36 | 23 Marina                             | Central   | Prismatic     | Outriggered frame   | RC                  |
| 37 | CITIC Plaza                           | Central   | Prismatic     | Shear-walled frame  | RC                  |
| 38 | Shum Yip Uppermills Tower 1           | Central   | Prismatic     | Outriggered frame   | Composite           |
| 39 | PIF Tower                             | Central   | Free          | Trussed-tube frame  | Composite           |
| 40 | Shun Hing Square                      | Central   | Free          | Outriggered frame   | Composite           |
| 41 | Burj Mohammed Bin Rashid              | Central   | Free          | Outriggered frame   | RC                  |
| 42 | Elite Residence                       | Central   | Prismatic     | Framed-tube frame   | RC                  |
| 43 | Central Plaza                         | Central   | Prismatic     | Trussed-tube frame  | Composite           |
| 44 | Golden Eagle Tiandi Tower A           | Central   | Tapered       | Outriggered frame   | Composite           |
| 45 | Bank of China Tower                   | Central   | Setback       | Trussed-tube frame  | Composite           |
| 46 | Almas Tower                           | Central   | Free          | Outriggered frame   | Composite           |
| 47 | Hanking Center Tower                  | External  | Tapered       | Trussed-tube frame  | Steel               |
| 48 | Sino Steel International Plaza T2     | Central   | Prismatic     | Framed-tube frame   | Composite           |
| 49 | Raffles City Chongqing T3N            | Central   | Tapered       | Outriggered frame   | Composite           |
| 50 | Raffles City Chongqing T4N            | Central   | Tapered       | Outriggered frame   | Composite           |
| 51 | The Center                            | Central   | Prismatic     | Mega column         | Composite           |
| 52 | NEVA TOWERS 2                         | Central   | Prismatic     | Outriggered frame   | RC                  |
| 53 | Four Seasons Place                    | Central   | Prismatic     | Outriggered frame   | RC                  |
| 54 | Comcast Technology Center             | Central   | Setback       | Trussed-tube frame  | Composite           |
| 55 | Mercury City Tower                    | Central   | Setback       | Framed-tube frame   | RC                  |
| 56 | Hengpin International Finance Center  | Central   | Free          | Outriggered frame   | Composite           |
| 57 | Tianjin World Financial Center        | Central   | Tapered       | Outriggered frame   | Composite           |
| 58 | Golden Eagle Tiandi Tower B           | Central   | Tapered       | Outriggered frame   | Composite           |
| 59 | Salesforce Tower                      | Central   | Tapered       | Shear-walled frame  | Composite           |
| 60 | 53 West 53                            | Peripheral| Tapered       | Framed-tube frame   | RC                  |
| 61 | New York Times Tower                  | Central   | Prismatic     | Outriggered frame   | Steel               |
| 62 | Chongqing IFS T1                      | Central   | Prismatic     | Outriggered frame   | Composite           |

Table A2. (continued)
| #  | Building name                        | Core type | Building form | Structural system          | Structural material |
|----|-------------------------------------|-----------|---------------|---------------------------|---------------------|
| 63 | Mahanakhon                          | Central   | Free          | Outriggered frame         | RC                  |
| 64 | Bank of America Plaza               | Central   | Setback       | Mega column               | Composite           |
| 65 | Shenzhen Bay Innovation and Technology Center Tower 1 | Central | Prismatic | Framed-tube               | Composite           |
| 66 | Ocean Heights                       | Central   | Tapered       | Outriggered frame         | RC                  |
| 67 | Pearl River Tower                   | Central   | Free          | Outriggered frame         | Composite           |
| 68 | Guangfa Securities Headquarters     | Central   | Tapered       | Outriggered frame         | Composite           |
| 69 | One 57                              | Peripheral| Setback       | Outriggered frame         | RC                  |
| 70 | The Shard                           | Central   | Tapered       | Shear-walled frame        | Composite           |
| 71 | Cayan Tower                         | Central   | Twisted       | Framed-tube               | RC                  |
| 72 | Kingdom Center                      | Central   | Free          | Shear-walled frame        | RC                  |
| 73 | Shimao Riverside Block D2b          | Central   | Tapered       | Outriggered frame         | Composite           |
| 74 | Aspire Tower                        | Central   | Free          | Mega core                 | RC                  |
| 75 | Golden Eagle Tiandi                 | Central   | Tapered       | Outriggered frame         | Composite           |

**Note(s):** “RC” indicates reinforced concrete

Table A2.

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