Use of aerodynamically favorable tapered form in contemporary supertall buildings

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Abstract

Today, supertall buildings can be constructed in unusual forms as a pragmatic reflection of advances in construction techniques and engineering technologies, together with advanced computational design tools for architectural design. As with many other buildings, architectural and practical principles play a crucial role in the form of a supertall building, where aerodynamic behavior shaped by wind-induced excitations also becomes a critical design input. Various methods are used to meet the functional needs of these towers and reduce excitations, including aerodynamic modification methods directly related to the building form. Tapered forms are one of the most frequently used and most effective methods in today's skyscrapers, which significantly affect architectural design. To date, no study has been conducted in the literature that provides an understanding of the interrelationships between tapered building forms and main planning criteria, considering the aerodynamic design concerns of the tapering effect in supertall buildings (≥300 m). This important issue is explored in this article with data gathered from 41 supertall case studies, considering location, function, structural system, and structural material as well as the aerodynamic taper effect. The main findings of the study highlighted the following: (1) Asia was where tapered towers were most favored, with a wider margin in all regions; (2) mixed-use was the most preferred function in selected supertall buildings with tapered form; (3) outriggered frame systems were mainly used; (4) tapered supertall cases were mostly built in composite; (5) the sample group included 17 cases that used the tapering effect with aerodynamic design concerns, some of which were accompanied by corner modifications. It is believed that this study will be a basic guide for design and construction professionals including architectural and structural designers, and contractors.

Keywords: supertall building, tapered form, aerodynamic design consideration, structural system, function, location, structural material

1. Introduction

Due to the ongoing urbanization and technological developments, the number of tall and supertall buildings (≥300m high) in the world is increasing exponentially (Karjalainen et al., 2021; Tulonen et al., 2021; Ilgın, 2022; Ilgın et al., 2022a; Ilgın and Karjalainen, 2022). In the initial phase of tall building construction, building designs were simple and most of the tall buildings had regular traditional configurations e.g., square, and rectangular prisms (Ilgın and Günel, 2007). However, recent tall and supertall buildings have had various unusual configurations including taper, setback, and twisted forms (Ilgın, 2021a) as in the examples of the 99-story and 541m high One World Trade Center with its tapered form (Figure 1) and the 87-story and 462m high Lakhta Center with its tapered/twisted form (Figure 2).
There are two important issues to be resolved in the wind-related design of supertall towers. First, their aerodynamic performance, particularly the reduction of across-wind response caused by
excitations due to vortex shedding, and the reduction of along-wind response. Another issue is the pedestrian level wind characteristics around supertall buildings due to downstream effects and Venturi effects, causing human discomfort issues and difficulties (Wang and Ni, 2022).

Regarding the first issue above, for buildings over 40 stories, the structural design, in general, begins to be controlled by wind loads (Günel and Ilgın, 2014a). These buildings are subject to complicated loading conditions, particularly urban aerodynamics created by neighboring clusters of high-rise structures (Micheli et al., 2019). They are wind-prone structures due to their great flexibility and low natural frequency, and their response to wind loads is a critical parameter in their structural design (Hou and Jafari, 2020). Both the structural safety and the comfort of the use of tall buildings are seriously threatened by strong winds. Additionally, the dramatic increase of wind speed with building height, and combined increases in slenderness ratios make them more flexible and therefore more susceptible to wind loads (Micheli et al., 2020). The reduction of wind-induced loads and hence wind-induced responses has always been a challenge in the design of supertall towers (Holmes, 2015). In this sense, in supertall building design, to guarantee functional performance and occupancy comfort, structural system selection, aerodynamic modifications, and supplementary damping devices play an important role (Günel and Ilgin, 2014b).

As commonly used approaches to reduce wind loads on supertall towers, aerodynamic modifications can alter the wind pattern around structures by suppressing the uniformity of vortex shedding (Sharma et al., 2018), thereby effectively mitigating wind loads on buildings (Kareem, 2007). In addition, vortex shedding poses a significant danger to the serviceability issue, especially when it reaches the natural frequency of the structure (Xie, 2014). Aerodynamic design considerations can be divided into two groups: major and minor modifications (Ilgın and Günel, 2021). Major modifications, which play a critical role in mitigating the wind effect on supertall towers, include building orientation, aerodynamic form, plan variation, and the aerodynamic top that have a significant impact on the overall architectural design. On the other hand, minor modifications including corner modifications and air passes do not significantly change the overall architectural design (Ilgın, 2006; Arslan Seçluk and Ilgın, 2017). Among major modifications, reducing the plan area through building height i.e., the use of tapered and setback forms as plan variation is an efficient method to mitigate wind loads (Ilgın, 2018).

Moreover, although the interaction of tall buildings with wind is a subject that includes many variables and needs to be examined specifically for each building (Elshaer et al., 2017), rectangular building forms are considered more sensitive to wind-induced lateral loads than aerodynamic building forms such as triangular, elliptical, and cylindrical formed structures (Günel and Ilgin, 2014b). Similarly, among major aerodynamic modifications, tapering the building in height is one of the most effective ways to the windproof design of numerous supertall towers in the world such as the 115-story and 599m high Ping An Finance Center (Ilgın, 2021b). Many studies in the literature have shown that tapered buildings can efficiently mitigate wind loads. Among them, Cooper et al. (1997) measured the unsteady wind effect on a tapered supertall tower with beveled corners as functions of reduced velocity and motion amplitude. The results showed that the frequency of local vortex shedding in each layer of the model increased with the increase of the model height. Tanagi (1999) showed that tapered towers can efficiently mitigate the across-wind motion. Nakayama et al. (2002) also reported that the tapering approach can effectively mitigate across-wind motion. Kim and You (2002) tested four types of tall buildings with different tapering ratios of 5%, 10%, and 15%, and a square-section basic building model, under two typical boundary layers representing a suburban and urban flow environment, considering the effect of wind direction. They found that tapered buildings can extend the vortex shedding range to a wider frequency range, thus mitigating the across-wind motion. Similarly, Kim et al. (2008) tested three aeroelastic, tapered tall towers with taper ratios of 5%, 10%, and 15%, and a square-section basic building model. It was found that the tapering effect appeared when wind speed was high, and the structural damping was between 2-4%. Kim and Kanda (2010) analyzed two models with 5% and 10% different taper ratios under two typical boundary layers representing (sub)urban flow...
situations. They found that the tapering effect helps mitigate the drag and fluctuating lift forces. Li et al. (2010) reported that the tapering effect could extend the frequency of vortex shedding on the tower’s across-wind surface. Xie et al. (2011) measured wind pressures in various building models with various tapering ratios of 2.2%, 4.4%, 6.6%, and a square-section basic building model under the simulated boundary layers representing a typhoon environment. Their findings showed that a tapering effect can mitigate the across-wind response under certain conditions. Tanaka et al. (2012, 2013) performed wind tunnel tests to identify the aerodynamic loads on tall towers of different configurations, including tapered forms. It was found that the tapered forms show better aerodynamic performance compared to the square section. Deng et al. (2015) performed wind tunnel tests on supertall buildings with tapering ratios of 2.2%, 4.4%, and 6.6%. Their results showed that the global strategy of tapered elevation resulted in reduced aerodynamic loads and responses to the wind. Lo et al. (2017) studied the interference effects of tapered and helical tapered shapes on interference forces and responses. Tapered with helical taper were the forms found to be more sensitive to overall reduced velocity and interference positions. Daemei et al. (2019) examined seven triangular buildings through computational fluid dynamics analysis, including the tapering effect as a major modification. Their results showed that tapering modification can result in significant mitigation in the building’s drag coefficient. Jafari and Alipour (2021) reviewed past work on the double-skinned facades from an aerodynamic point of view, and one of the highlights of the review was that tapered forms, together with the setback forms in the triangular case, perform best for aerodynamic performance. Li et al. (2022) performed a series of pressure measurements in a boundary layer wind tunnel for four rigid models with various tapering ratios of 5%, 10%, 15%, and 20%. They concluded that the aerodynamic efficiency of high-rise buildings with rectangular forms is enhanced by the increased tapering ratio.

Additionally, a limited number of studies have been done in the literature analyzing the tall building form, considering the main design parameters. Among prominent studies, Elnimeiri and Almusaraf (2010) scrutinized the interrelation between structural efficiency and tall building form to indicate that efficient buildings are sustainable, and that efficiency is at the center of the structural design together with the economic structure. Alaghmandan et al. (2014) explored the architectural and structural assessments of more than 70 supertall buildings to predict the future trend in form and load-bearing systems and to make new design proposals. While Szolomicki and Golasz-Szolomicka (2019) investigated structural and architectural solutions for selected high-rise towers over the last decade, considering building form, structural system, damping systems, and sustainability, Golasz-Szolomicka and Szolomicki (2019) studied the constructional and architectural features of the most prominent twisted tall buildings with different functions, considering advances in computer technologies, the building information modeling system, and contemporary architectural trends and sustainability to evaluate innovative material applications and construction techniques. Ilgin et al. (2021) examined the contemporary developments in main architectural and structural design concerns and a variety of related interrelations using 93 supertall towers to provide insight for architects and structural engineers. Ilgin and Günel (2021) analyzed aerodynamic design considerations as contemporary trends in supertall building form. Ilgin (2021b) scrutinized space efficiency in supertall office towers with the primary architectural and structural considerations using 44 cases, whereas Ilgin (2021c) focused on space efficiency in supertall residential towers with the same considerations using 27 contemporary cases. Ilgin (2022) explored the interrelationships of load-bearing systems and key design parameters in supertall towers using 140 contemporary cases.

Overall, there is no comprehensive study in the literature providing an understanding of the interrelationships between tapered building forms and main planning criteria, considering the aerodynamic design concerns of the tapering effect in supertall buildings. This critical topic was examined in detail in this paper using 41 supertall buildings, considering location, function, structural system, and structural material as well as the aerodynamic taper effect. It is believed that this study will be a basic guide for design and construction professionals such as architects, engineers, and contractors.
2. Research Methods

This article was conducted through a comprehensive literature survey including the database of the Council on Tall Buildings and Urban Habitat / CTBUH (CTBUH, 2022), peer-reviewed journals, MSc and Ph.D. dissertations, conference papers, architectural and structural magazines, and other internet sources.

Furthermore, the case study method was utilized to gather and consolidate data on supertall buildings to analyze the interrelations of tapered form and key design considerations. These towers were 41 cases from different locations [29 from Asia (26 from China), 2 from the Middle East, 7 from North America (USA), 1 from South America, 1 from Europe, and 1 from Russia]. Detailed information about these buildings was given in Table 1. In the 41 selected case studies (see Tables 1 and 2), exceptionally detailed information was provided and tapered supertall buildings with insufficient information on related design features were not included in the building list.

### Table 1 Contemporary tapered supertall buildings

| #  | Building name                             | Location (country / city) | Height (m) | # of stories | Completion date | Function |
|----|------------------------------------------|---------------------------|------------|-------------|----------------|----------|
| 1  | Suzhou Zhongnan Center                    | China / Suzhou            | 729        | 137         | NC             | M(H/R/O) |
| 2  | Ping An Finance Center                    | China / Shenzhen          | 599        | 115         | 2017           | O        |
| 3  | Goldin Finance 117                       | China / Tianjin           | 596        | 128         | OH             | M(H/R/O) |
| 4  | Lotte World Tower                         | South Korea / Seoul       | 554        | 123         | 2017           | M(H/R/O) |
| 5  | One World Trade Center                    | USA / New York            | 541        | 94          | 2014           | O        |
| 6  | Tianjin CTF Finance Centre                | China / Tianjin           | 530        | 97          | 2019           | M(H/R/O) |
| 7  | Greenland Jimmao International Financial Center | China / Nanjing     | 499        | 102         | UC             | M(H/R/O) |
| 8  | Shanghai World Financial Center           | China / Shanghai          | 492        | 101         | 2008           | M(H/R/O) |
| 9  | International Commerce Centre             | China / Hong Kong         | 484        | 108         | 2010           | M(H/R/O) |
| 10 | Wuhan Greenland Center                    | China / Wuhan             | 475        | 97          | UC             | M(H/R/O) |
| 11 | Chengdu Greenland Tower                   | China / Chengdu           | 468        | 101         | UC             | M(H/R/O) |
| 12 | The Exchange 106                          | Malaysia / Kuala Lumpur   | 446        | 95          | 2019           | O        |
| 13 | Guangzhou International Finance Center    | China / Guangzhou         | 438        | 103         | 2010           | M(H/R/O) |
| 14 | Multifunctional Highrise Complex - Akhmat Tower | Russia / Grozny     | 435        | 102         | OH             | M(R/O)  |
| 15 | Chongqing Tall Tower                      | China / Chongqing         | 431        | 101         | OH             | M(H/R/O) |
| 16 | Haikou Tower 1                           | China / Haikou            | 428        | 94          | OH             | M(H/R/O) |
| 17 | One Vanderbil                           | USA / New York            | 427        | 58          | 2020           | O        |
| 18 | Guangxi China Resources Tower             | China / Nanning           | 402        | 86          | 2020           | M(H/R/O) |
| 19 | China Resources Tower                    | China / Shenzhen          | 393        | 68          | 2018           | O        |
| 20 | 30 Hudson Yards                          | USA / New York            | 387        | 73          | 2019           | O        |
| 21 | Guiyang World Trade Center Landmark Tower | China / Guiyang          | 380        | 92          | UC             | M(H/R/O) |
| 22 | Golden Eagle Tiandi Tower A               | China / Nanjing           | 368        | 77          | 2019           | M(H/R/O) |
| 23 | Hanking Center Tower                     | China / Shenzhen          | 359        | 65          | 2018           | O        |
| 24 | Raffles City Chongqing T4N               | China / Chongqing         | 354        | 74          | 2019           | M(H/O)  |
| 25 | One Shenzhen Bay Tower 7                 | China / Shenzhen          | 341        | 78          | 2018           | M(H/R/O) |
| 26 | Tianjin World Financial Center           | China / Tianjin           | 337        | 75          | 2011           | O        |
| 27 | Wildshire Grand Center                   | USA / Los Angeles         | 335        | 62          | 2017           | M(H/O)  |
| 28 | DAMAC Heights                            | UAE / Dubai               | 335        | 88          | 2018           | R        |
| 29 | China World Tower                        | China / Beijing           | 330        | 74          | 2010           | M(H/R/O) |
| 30 | Golden Eagle Tiandi Tower B              | China / Nanjing           | 328        | 68          | 2019           | O        |
| 31 | Salesforce Tower                         | USA / San Francisco       | 326        | 61          | 2018           | O        |
| 32 | 53 West 53                               | USA / New York            | 320        | 77          | 2019           | O        |
| 33 | CITIC Financial Center Tower 1           | China / Shenzhen          | 312        | -           | UC             | M(R/O)  |
| 34 | Ocean Heights                            | UAE / Dubai               | 310        | 83          | 2010           | R        |
| 35 | Guangfa Securities Headquarters           | China / Guangzhou         | 308        | 60          | 2018           | O        |
| 36 | The Shard                                 | UK / London               | 306        | 73          | 2013           | M(H/R/O) |
| 37 | Northeast Asia Trade Tower               | South Korea / Incheon     | 305        | 68          | 2021           | M(H/R/O) |
| 38 | One Manhattan West                       | USA / New York            | 303        | 67          | 2019           | O        |
| 39 | Torre Costanera                          | Chile / Santiago          | 300        | 62          | 2014           | M(H/O)  |
| 40 | Shimao Riverside Block D2b               | China / Wuhan             | 300        | 53          | UC             | M(H/O)  |
| 41 | Golden Eagle Tiandi Tower C              | China / Nanjing           | 300        | 60          | 2019           | O        |

**Note on abbreviations:** ‘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.
This paper analyzed the following considerations that play a significant role in the planning of tapered supertall towers: (1) location; (2) function; (3) structural system; (4) structural material and (5) aerodynamic modification (Table 2).

Table 2 Tapered supertall buildings by core type, structural system, structural material, and aerodynamic modification

| #  | Building name                      | Core type       | Structural system | Structural material | Aerodynamic modification               |
|----|-----------------------------------|-----------------|-------------------|---------------------|----------------------------------------|
| 1  | Suzhou Zhongnan Center            | Central         | Outrigged frame   | Composite           | NA                                     |
| 2  | Ping An Finance Center            | Central         | Outrigged frame   | Composite           | Tapering + tapered corner               |
| 3  | Goldin Finance 117                | Central         | Trussed-tube      | Composite           | NA                                     |
| 4  | Lotte World Tower                 | Central         | Outrigged frame   | Composite           | NA                                     |
| 5  | One World Trade Center            | Central         | Outrigged frame   | Composite           | Tapering + chamfered corner            |
| 6  | Tianjin CTF Finance Centre        | Central         | Framed-tube       | Composite           | Tapering + rounded corner              |
| 7  | Greenland Jinmoo International Financial Center | Central | Outrigged frame   | Composite           | NA                                     |
| 8  | Shanghai World Financial Center   | Central         | Outrigged frame   | Composite           | Tapering (with aerodynamic top)        |
| 9  | International Commerce Centre     | Central         | Outrigged frame   | Composite           | Recessed/notched corner                |
| 10 | Wuhan Greenland Center            | Central         | Buttressed core   | Composite           | Tapering + rounded corner              |
| 11 | Chengdu Greenland Tower           | Central         | Outrigged frame   | Composite           | Tapering                              |
| 12 | The Exchange 106                  | Central         | Outrigged frame   | Composite           | NA                                     |
| 13 | Guangzhou International Finance Center | Central | Outrigged frame   | Composite           | Tapering + tapered and rounded corner  |
| 14 | Multifunctional Highrise Complex - Akhmat Tower | Central | Framed-tube       | Steel               | Tapering                              |
| 15 | Chongqing Tall Tower              | Central         | Outrigged frame   | Composite           | NA                                     |
| 16 | Haikou Tower 1                    | Central         | Outrigged frame   | Composite           | Tapering + rounded corner              |
| 17 | One Vanderbilt                    | Central         | Outrigged frame   | Composite           | NA                                     |
| 18 | Guangxi China Resources Tower     | Central         | Outrigged frame   | Composite           | NA                                     |
| 19 | China Resources Tower             | Central         | Diagrid-framed-tube | Composite    | Tapering                              |
| 20 | 30 Hudson Yards                   | Central         | Outrigged frame   | Steel               | NA                                     |
| 21 | Guiyang World Trade Center Landmark Tower | Central | Framed-tube       | Composite           | Tapering + rounded corner              |
| 22 | Golden Eagle Tiandi Tower A       | Central         | Outrigged frame   | Composite           | NA                                     |
| 23 | Hancocking Center Tower           | External        | Trussed-tube      | Steel               | NA                                     |
| 24 | Raffles City Chongqing T4N        | Central         | Outrigged frame   | Composite           | NA                                     |
| 25 | One Shenzhen Bay Tower 7          | Central         | Outrigged frame   | Composite           | NA                                     |
| 26 | Tianjin World Financial Center    | Central         | Outrigged frame   | Composite           | NA                                     |
| 27 | Wiltshire Grand Center            | Central         | Outrigged frame   | Composite           | NA                                     |
| 28 | DAMAC Heights                     | Central         | Outrigged frame   | RC                   | NA                                     |
| 29 | China World Tower                 | Central         | Outrigged frame   | Composite           | Tapering                              |
| 30 | Golden Eagle Tiandi Tower B       | Central         | Outrigged frame   | Composite           | NA                                     |
| 31 | Salesforce Tower                  | Central         | Shear walled frame | Composite           | NA                                     |
| 32 | 53 West 53                        | Peripheral      | Diagrid-framed-tube | RC                   | NA                                     |
| 33 | CITIC Financial Center Tower 1    | Central         | Diagrid-framed-tube | Composite           | Tapering                              |
| 34 | Ocean Heights                     | Central         | Outrigged frame   | RC                   | NA                                     |
| 35 | Guangfa Securities Headquarters   | Central         | Outrigged frame   | Composite           | NA                                     |
| 36 | The Shard                         | Central         | Shear walled frame | Composite           | NA                                     |
| 37 | Northeast Asia Trade Tower        | Central         | Outrigged frame   | Composite           | Tapering                              |
| 38 | One Manhattan West                | Central         | Shear walled frame | Composite           | NA                                     |
| 39 | Torre Costanera                   | Central         | Outrigged frame   | RC                   | NA                                     |
| 40 | Shimao Riverside Block D2b        | Central         | Outrigged frame   | Composite           | Tapering                              |
| 41 | Golden Eagle Tiandi Tower C       | Central         | Outrigged frame   | Composite           | NA                                     |

*Note on abbreviation: ‘RC’ indicates reinforced concrete; ‘NA’ indicates not available.*

Although there is still no global consensus on the number of floors or heights of tall and supertall buildings, 'supertall building' and 'megatall' were considered buildings 300 m and higher and 600 m and higher, respectively (CTBUH, 2022). In this study, the following core arrangement classification of Ilgin and Karjalainen (2022) was used: (i) central core; (ii) atrium core, (iii) external core, and (iv) peripheral core. In addition, hotel, residential, and office uses were considered the basic functions in supertall buildings, while their combinations were considered mixed-use (Ilgin et al., 2021). In this article, considering existing literature (e.g., Taranath, 2016; Ali and Moon, 2018; Fu, 2018; Moon, 2018; Ali and Al-Kodmany, 2022), the following structural system categorization...
of Ilgin et al. (2022b) and Ilgin (2022) were used: (i) shear-frame system (shear trussed frame and shear walled frame); (ii) mega core system; (iii) mega column; (iv) outriggered frame system; (v) tube system (framed-tube including diagrid-framed-tube, trussed-tube, and bundled-tube); and (vi) buttressed core system, while the following structural material classification was used: (i) steel, (ii) reinforced concrete and (iii) composite. Furthermore, the following classification of aerodynamic design considerations (Ilgin and Günel, 2021) was used: (i) major modifications - noticeably changing the overall architectural design - (building orientation, aerodynamic form, plan variation, and aerodynamic top); (ii) minor modifications - not considerably change the overall architectural design – (corner modifications and air pass).

The tapering effect can be defined as floor plans and surface areas that decrease along the building height, where the size of the floor plan decreases continuously as the building goes up. The pyramidal form can be considered the most essential type of tapered form, together with the ancient pyramids, the first example of which was in Egypt.

The 100-story and 344m high 875 North Michigan Avenue, formerly known as John Hancock Centre with tapering ratio of long side 9.1% and short side 5.5% (Figure 3), the 73-story and 297m high Landmark Tower (1993) with tapering ratio of 5.7% on both sides and the 48-story and 260m high Transamerica Pyramid Center (Figure 4) are prominent examples of tapering modifications in real-time (Sharma et al., 2018). Here, the tapering ratio is defined as (bottom width - top width) / height × 100.

When a tower is tapered, its outer surface area, where the wind load is exposed, decreases at higher levels, and increases at lower levels. As wind pressure increases slowly upwards and decreases rapidly downwards, lateral shear forces and overturning moments decrease as the tapered angle increases.

For tall buildings, the lock-in phenomenon caused by vortex shedding is often the most important structural design condition. Tapered forms help prevent tall and supertall towers from shedding organized alternating vortices, due to the constantly changing plan dimensions across the
height of the building. Thus, tapered structures are less sensitive to across-wind direction vibrations than high-rise towers with square cross sections.

Tapered forms mitigate the drag force owing to their geometric properties. Due to the increased size in the downward direction, the downwash phenomenon slows down less rapidly, and the upward flow accelerates at a higher speed due to the smaller width. This results in a lower pressure coefficient near the bottom and a larger pressure coefficient at the upper level compared to the reference square form.

3. Findings

3.1. Interrelations of tapered form and main planning considerations

Interrelations of tapered form and key design parameters associated with it, location, function, structural system, structural material, and aerodynamic modifications were analyzed in this part. As the most common core arrangement (>95%) in the sample group was central core typology (Table 2), no studies were conducted on it.

3.1.1. Location

Figure 5 shows that Asia was where tapered towers are most preferred (>70%), with a wider margin in all regions, followed by North America with 17%. Lateral loads from earthquakes and typhoons pose a great risk in Asia, especially in densely populated coastal cities such as Hong Kong and Shanghai. It is therefore crucial that structures in these Asian cities are designed to withstand a major earthquake or wind-induced loads, especially supertall buildings whose structural designs are governed by lateral loads, mostly wind (Günel and Ilgin, 2014b). Therefore, the reason why the tapered form was mostly used in Asian cities may be its superior structural and aerodynamic efficiency against lateral loads.

| Location   | #  | %  |
|------------|----|----|
| Asia       | 29 | 71%|
| Middle East | 2  | 5% |
| North America | 7  | 17%|
| Other      | 3  | 7% |
| TOTAL      | 41 | 100%|

Figure 5 Tapered supertall buildings by location

3.1.2. Function

Figure 6 shows that among 41 tapered supertall buildings, mixed-use with a ratio of 61% is the most favored function, followed by office function with 32%. The reason for the high rate of mixed-use can be explained by the fact that the tapered form narrows as it rises, allowing different functional needs that demand various structural spans to be accommodated (Ilgin et al., 2021). On the other hand, from a financial point of view, the fact that it enables a wide customer portfolio with its 24-hour visitor potential and thus maximizes rentals may be the reason why mixed-use in tapered forms is most preferred (Ali and Al-Kodmany, 2012).

| Function   | #  | %  |
|------------|----|----|
| Hotel      | -  | -  |
| Residential | 3  | 7% |
| Office     | 13 | 32%|
| Mixed-use  | 25 | 61%|
| TOTAL      | 41 | 100%|

Figure 6 Tapered supertall buildings by function
3.1.3. Structural system

Figure 7 indicates that outriggered frame systems are mostly used (>70%) in supertall towers in the sample group, followed by tube systems with 20%. The predominance of outrigger frame system can be explained by the fact that this system allows the exterior columns to be widely spaced, thereby minimizing the obstruction created by closely spaced column arrangement, opening the exterior of the building so that architects can articulate the facade freely (Ali and Al-Kodmany, 2022).

| Structural system         | #   | %  |
|---------------------------|-----|----|
| Outriggered frame         | 29  | 71 |
| Tube                      | 8   | 20 |
| Shear walled frame        | 3   | 7  |
| Buttressed core           | 1   | 2  |
| TOTAL                     | 41  | 100|

Figure 7 Tapered supertall buildings by structural system

3.1.4. Structural material

Figure 8 highlights that among 41 tapered supertall buildings, composite structures with 83%, with a wider margin, is the most common material, followed by reinforced concrete use with 10%. The use of composite structure can mainly be attributed to the benefits of both structural materials, namely the superiority of the (tensile) strength of steel and the fire resistance of concrete. Hence, it may come as no surprise that more than 80% of supertall cases were designed as composites.

| Structural material        | #   | %  |
|---------------------------|-----|----|
| Steel                     | 3   | 7  |
| Reinforced concrete       | 4   | 10 |
| Composite                 | 34  | 83 |
| TOTAL                     | 41  | 100|

Figure 8 Tapered supertall buildings by structural material

3.2. Analysis of the use of tapering as an aerodynamic modification

There are 17 buildings in the sample group, which are known to use the tapering effect in their designs (see Table 2). In 7 cases, the tapering effect is accompanied by corner modifications, making the role of aerodynamic considerations in the design more evident. Among them, the 115-story and 599m high Ping An Finance Center utilized tapering and tapered corners, and according to Chinese regulation, these strategies provide a 32% and 35% reduction in the overturning moment and wind load, respectively (Malott, 2014) (Figure 9).
Similarly, the 99-story and 541m high One World Trade Center, when combined with chamfered corners, tapers as it rises, creating an aerodynamically and structurally effective form (Lewis and Holt, 2011). In the 97-story and 530m high Tianjin CTF Finance Centre, tapering was combined with rounded corners. In this supertall structure, tapering contributed significantly to performing well in wind tunnel tests and minimizing the surface area exposed to wind, and due to rounded corners, not only can wind loads at the corners be mitigated but structural spans can also be reduced (Lee et al., 2020). Tapering form and an aerodynamic top played a critical role in the architectural design of the 101-story and 492m high Shanghai World Financial Center (Moon, 2015). The 97-story and 475m high Wuhan Greenland Center has a unique form that unites three key form concepts including a tapering effect through the building height, rounded corners, and a domed top to mitigate wind load and vortex shedding (Adrian Smith + Gordon Gill Architecture LLP, 2022). The 101-story and 468m high Chengdu Greenland Tower’s tapering form together with a high-performance damper support system deflects the wind and contributes to the building’s stability (Binder, 2015). The aerodynamic shaping of the 103-story and 438m high Guangzhou International Finance Center was designed as an efficient means of reducing the wind forces. Additionally, the corner tapering spreads vortex-shedding and thus helps the across-wind responses, the rounded building corners change the flow pattern around the building and mitigate wind-induced excitation (Kwok and Lee, 2016). The design of the final shape of the 102-story and 435m high Multifunctional Highrise Complex - Akhmat Tower was influenced by wind performance. The building, which was thought to have a square plan from the concept stage of the project, made the building elements more efficient thanks to its tapered form obtained by aerodynamic optimizations while providing significant tonnage and cost savings in steel, while at the same time reducing wind loads (Beardsley et al., 2018).

4. Discussion and conclusions

The findings obtained in this paper showed similarities and differences with other studies in the literature such as Ilgin et al. (2021). Among the 41 tapered supertall cases, central core planning was the most preferred arrangement, as reported in several studies in the literature (Ilgin et al., 2021; Ilgin, 2021b, c). In terms of location, it was observed that mostly tapered supertall structures were constructed in Asian cities. This finding can be attributed to Moon’s (2015) finding that Asia was home to many tapering supertall buildings, such as the Lotte World Tower. It was expected to remain a dynamic supertall development area where building heights tend to increase. In this study,
supported by the finding of Ilgın et al. (2021), the most preferred function was mixed-use, followed closely by office use. In terms of the load-bearing system, the fact that outriggered frame system was predominantly utilized in selected supertall towers confirms the findings of other studies including Ilgın et al. (2021), Ilgın (2021b), and Ilgın (2021c). On the other hand, as in the findings of Ilgın et al. (2021) and Ilgın (2021b), the use of composite was much more common than reinforced concrete and steel construction.

Although the supertall building forms are primarily determined by site conditions, economic parameters, and architectural and engineering features, the design should be made by considering the aerodynamic properties of the building form. This is because even a small change in geometric shape can provide a significant advantage over wind-induced lateral loads. In this context, the tapered form is one of the most preferred building forms and enables the supertall tower to exhibit an effective behavior against wind loads. To provide this, the sample group included 17 cases that used the tapering effect with aerodynamic design concerns, some of which were accompanied by corner modifications.

In this study, using 41 supertall buildings, interrelationships between tapered building forms and main planning criteria, considering the aerodynamic design concerns of the tapering effect in contemporary supertall buildings were analyzed. In conclusion, it is believed that the findings obtained in this paper will be a basic guide for key professionals e.g., architects, engineers, and developers.

The empirical data given in this paper were limited to supertall towers (≥300 m). In addition, analysis of supertall cases using tapered forms in their aerodynamic designs was limited to the number of buildings (17) for which this information was available. However, given that the number of supertall buildings has increased significantly in recent years, it can be predicted that there will be a sufficient number of cases for analysis of aerodynamic issues in the near future. Moreover, buildings lower than 300 m might be included in the sample study group so that an adequate number of subclasses can be generated in future studies.

References
Adrian Smith + Gordon Gill Architecture LLP, (2022). Wuhan Greenland Center, Retrieved from: http://smithgill.com/work/wuhan_greenland_center/
Alaghmandan, M., Bahrami, P., and Elnimeiri, M. (2014). The Future Trend of Architectural Form and Structural System in High-Rise Buildings, Architecture Research, 4(3), 55-62, 10.5923/j.arch.20140403.01.
Ali, M., and Al-Kodmany, K. (2012). Tall Buildings and Urban Habitat of the 21st Century: A Global Perspective. Buildings, 2(4), 384–423.
Ali, M.M. and Al-Kodmany, K. (2022). Structural Systems for Tall Buildings, Encyclopedia, 2, 1260-1286. doi.org/10.3390/encyclopedia2030085
Ali, M. M. and Moon, K.S. (2018). Advances in structural systems for tall buildings: Emerging developments for contemporary urban giants. Buildings 8 (104): 1–34.
Beardsley, S., Stochetti, A. and Cerone, M. (2018). The Design of Akhmat Tower, E3S Web of Conferences, HRC 2017, 33, 01022, doi.org/10.1051/e3sconf/20183301022
Binder, G. (ed.) (2015). Tall Buildings of China, Images Publishing, CTBUH, Victoria, Australia.
Cooper, K.R., Nakayama, M., Sasaki, Y., Fediw, A.A., Resende-Ide, S. and Zan, S.J. (1997). Unsteady aerodynamic force measurements on a super-tall building with a tapered cross section Journal of Wind Engineering and Industrial Aerodynamics, 72, 199–212.
CTBUH (2022), Council on Tall Buildings and Urban Habitat; Illinois Institute of Technology, S.R. Crown Hall: 3360 South State Street, Chicago, IL, USA, available at: https://www.ctbuh.org.
Daemei, A. B., Khotehsara, E. M., Nobarani, E. M. and Bahrami, P. (2019). Study on wind aerodynamic and flow characteristics of triangular-shaped tall buildings and CFD simulation in order to assess drag coefficient. Ain Shams Engineering Journal, 10, 541–548.
Deng, T., Yu, X. and Xie, Z. (2015). Aerodynamic measurements of across-wind loads and responses of tapered super high-rise buildings. Wind and Structures an International Journal, 21, 3, 331–352.
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Elnimeiri, M. and Almusharaf, A. (2010). The interaction between sustainable structures and architectural form of tall buildings, International Journal of Sustainable Building Technology and Urban Development, Vol. 1 No. 1, pp. 35-41, 10.5390/SUSB.2010.1.1.035.

Elshaer, A., Bitsuamlak, G. and El Damatty, A. (2017). Enhancing wind performance of tall buildings using corner aerodynamic optimization, Engineering Structures, 136, 133–148, dx.doi.org/10.1016/j.engstruct.2017.01.019.

Fu, F. (2018). Design and Analysis of Tall and Complex Structures. Oxford and Cambridge: Butterworth-Heinemann, Elsevier.

Golasz-Szolomicka, H. and Szolomicki, J. (2019). Architectural and Structural Analysis of Selected Twisted Tall Buildings. IOP Conference Series. Materials Science and Engineering, 471(5), S2050–, 10.1088/1757-899X/471/5/052050.

Holmes, J.D. (2015). Wind Loading of Structures, CRC Press, Boca Raton.

Hou, F. and Jafari, M. (2020). Investigation approaches to quantify wind-induced load and response of tall buildings: A review. Sustainable Cities and Society, 62, Article 102376. doi.org/10.1016/j.scs.2020.102376

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

Günel, M.H. and Ilgin, H.E. (2014b). Tall Buildings: Structural Systems and Aerodynamic Form, Routledge, London; New York, NY.

Ilgın, H.E. (2006). A Study on Tall Buildings and Aerodynamic Modifications against Wind Excitation, MSc Thesis, Department of Architecture, Middle East Technical University, Ankara, Turkey.

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

Ilgın, H.E. (2021a). A search for a new tall building typology: structural hybrids, Livenarch VII Livable Environments and Architecture 7th International Congress OTHER ARCHITECT/URE(S), September 28-30, Trabzon, Turkey, Vol. 1, pp. 95-107.

Ilgın, H.E. (2021b). Space efficiency in contemporary supertall office buildings, Journal of Architectural Engineering, 27(3), 4021024, 10.1061/(ASCE)AE.1943-5568.0000486.

Ilgın, H.E. (2021c). Space efficiency in contemporary supertall residential buildings, Architecture, 1(1), 25-37, 10.3390/architecture1010004.

Ilgın, H.E. (2022). A study on interrelations of structural systems and main planning considerations in contemporary supertall buildings, International Journal of Building Pathology and Adaptation, Vol. ahead-of-print No. ahead-of-print, doi.org/10.1108/IJBPA-12-2021-0172

Ilgın, H.E., Ay, B.Ö., Gunel, M.H. (2021). A study on main architectural and structural design considerations of contemporary supertall buildings, Architectural Science Review, 64(3), 212-224, 10.1080/00038628.2020.1753010.

Ilgın, H.E. and Karjalainen, M. (2022). Tallest Timber Buildings: Main Architectural and Structural Design Considerations, IntechOpen: London, UK, 10.5772/intechopen.105072.

Ilgın, H.E. and Günel, M.H. (2021). Contemporary trends in supertall building form: aerodynamic design considerations, Livenarch VII Livable Environments and Architecture 7th International Congress Other Architect/Ure(S), September 28-30, Trabzon, Turkey, Vol. 1, pp. 61-81.

Ilgın, H.E. and Günel, M.H. (2007). The role of aerodynamic modifications in the form of tall buildings against wind excitation, METU Journal of the Faculty of Architecture, 24(2), 17-25.

Ilgın, H.E., Karjalainen, M. and Pelsmakers, S. (2022a). Finnish Architects’ Attitudes Towards Multi-Storey Timber Residential Buildings, International Journal of Building Pathology and Adaptation, Vol. ahead-of-print No. ahead-of-print, doi.org/10.1108/IJBPA-04-2021-0059.

Ilgın, H.E., Karjalainen, M. and Pelsmakers, S. (2022b). Contemporary Tall Timber Residential Buildings: What are the Main Architectural and Structural Design Considerations?, International Journal of Building Pathology and Adaptation, Vol. ahead-of-print No. ahead-of-print, doi.org/10.1108/IJBPA-10-2021-0142

Jafari, M. and Alipour, A. (2021). Review of approaches, opportunities, and future directions for improving aerodynamics of tall buildings with smart facades. Sustainable Cities and Society, 72, 102979–. doi.org/10.1016/j.scs.2021.102979
Karjalainen, M., Ilgin, H.E., and Tulonen, L. (2021). Main Design Considerations and Prospects of Contemporary Tall Timber Apartment Buildings: Views of Key Professionals from Finland, Sustainability 13(12), 6593-, doi.org/10.3390/su13126593.

Kareem, A. (2007). Control of wind induced response of structure, in: Proceeding of the 3rd International Advanced School on Structural Wind Engineering, Tongji University, Shanghai, 99–108.

Kim, Y.C. and Kanda, J. (2010). Characteristics of aerodynamic forces and pressures on square plan buildings with height variations, Journal of Wind Engineering and Industrial Aerosdynamics, 98(8-9), 449–465.

Kim, Y.M. and You, K.P. (2002). Dynamic responses of a tapered tall building to wind loads, Journal of Wind Engineering and Industrial Aerosdynamics, 90, 1771–1782.

Kim, Y.M., You, K.P. and Ko, N.H. (2008). Across-wind responses of an aeroelastic tapered tall building, Journal of Wind Engineering and Industrial Aerosdynamics, 96, 1307–1319.

Kwok, M. and Lee, A. (2016). Engineering of Guangzhou International Finance Centre, International Journal of High-Rise Buildings, 5(4), 49-72, dx.doi.org/10.21022/IJHRB.2016.5.4.49

Lee, B., Kinzl, T., Rhee, I. and Johnson, R. (2020). Determinism, Integration, and Articulation Lead Up to a Landmark, CTBUH Journal, Issue I.

Lewis, K. and Holt, N. (2011). Case Study: One World Trade Center, CTBUH Journal, Issue III.

Li, Y., Song, Q., Li, C., Huang, X. and Zhang, Y. (2022). Reduction of wind loads on rectangular tall buildings with different taper ratios, Journal of Building Engineering, 45, 103588-, doi.org/10.1016/j.jobe.2021.103588.

Li, B., Yang, Q.S., Tian, Y.J. and Chen, X.Z. (2010). Fluctuating wind load characteristics of taper super tall buildings, Journal of Building Structures, 31(10), 8–16.

Lo, Y., Kim, Y. C. and Yoshida, A. (2017). Effects of aerodynamic modification mechanisms on interference from neighboring buildings. Journal of Wind Engineering and Industrial Aerosdynamics, 168, 271–287. doi.org/10.1016/j.jweia.2017.06.018

Malott, D. (2014). Designing Chine’s Tallest: DNA of the Ping An Finance Center, September 16-19, Shanghai, CTBUH World Conference 2014.

Micheli, L., Alipour, A., Laflamme, S. and Sarkar, P. (2019). Performance-based design with life-cycle cost assessment for damping systems integrated in wind excited tall buildings. Engineering Structures, 195, 438-451, doi.org/10.1016/j.engstruct.2019.04.009

Micheli, L., Hong, J., Laflamme, S. and Alipour, A. (2020). Surrogate models for high performance control systems in wind-excited tall buildings. Applied Soft Computing, 90, doi.org/10.1016/j.asoc.2020.106133

Moon, K.S. (2015). Supertall Asia/Middle East: Technological Responses and Contextual Impacts, Buildings, 5(3), 814-833.

Moon, K. S. (2018). Developments of structural systems toward mile-high towers, International Journal of High-Rise Buildings, 7(3), 197–121.

Nakayama, M., Tanaka, T. and Tanaka, K. (2002). An aeroelastic study on a super-tall building with tapered section, in: Proceedings of the 11 the National Symposium on Wind Engineering, Texas Tech University, Lubbock, 249–254.

Arslan Sekluk, S. and Ilgin, H. (2017). Performative Approaches in Tall Buildings: Pearl River Tower, Eurasian Journal of Civil Engineering and Architecture, 1(2), 11-20.

Sharma, A., Mittal, H. and Gairola, A. (2018). Mitigation of wind loads on tall buildings through aerodynamic modifications: Review, Journal of Building Engineering, 18, 180–194.

Szolomicki, J. and Golasz-Szolomicka, H. (2019). Technological advances and trends in modern high rise buildings, Buildings, 9(9), 193-, 10.3390/buildings9090193.

Tanagi, Y. (1999). Experimental study on wind response of tapered tall buildings: Part 1: force measurement, in: Proceedings of AIJ Kyoto, Kyoto University, 33–34.

Tanaka, H., Tamura, Y., Ohtake, K., Nakai, M. and Kim, Y.C. (2012). Experimental investigation of aerodynamic forces and wind pressures acting on tall buildings with various unconventional configurations, Journal of Wind Engineering and Industrial Aerosdynamics, 107–108, 179–191.

Tanaka, H., Tamura, Y., Ohtake, K., Nakai, M., Kim, Y.C. and Bandi, E.K. (2013). Aerodynamic and flow characteristics of tall buildings with various unconventional configurations, International Journal of High-Rise Buildings, 2(3), 213–228.

Taranath, B.S. (2016). Structural Analysis and Design of Tall Buildings: Steel and Composite Construction, CRC Press, Taylor & Francis Group, Boca Raton, FL, 2016.
Tulonen, L., Karjalainen, M. and Ilgın, H.E. (2021). Tall Wooden Residential Buildings in Finland: What Are the Key Factors for Design and Implementation?, IntechOpen: London, UK, 10.5772/intechopen.98781.

Wang, Y. and Ni, Y. (2022). Full-scale monitoring of wind effects on a supertall structure during six tropical cyclones, Journal of Building Engineering, 45, 103507–, 10.1016/j.jobe.2021.103507

Xie, J. (2014). Aerodynamic optimization of super-tall buildings and its effectiveness assessment, Journal of Wind Engineering and Industrial Aerodynamics, 130, 88–98, dx.doi.org/10.1016/j.jweia.2014.04.004.

Xie, Z.N. and Li, J. (2011). Experimental research on across wind effect on tapered super-tall buildings under action of strong wind, Journal of Building Structures, 32(12), 118–126.

Resume

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