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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).

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Figure 1 One World Trade Center (Wikipedia)

Figure 2 Lakhta Center (Wikipedia)

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 via aeroelastic tests. 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) mainly 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. Ilgın 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. Ilgın and Günel (2021) analyzed aerodynamic design considerations as contemporary trends in supertall building form. Ilgın (2021b) scrutinized space efficiency in supertall office towers with the primary architectural and structural considerations using 44 cases, whereas Ilgın (2021c) focused on space efficiency in supertall residential towers with the same considerations using 27 contemporary cases. Ilgın (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/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/O)
7	Greenland Jinmao International Financial Center	China / Nanjing	499	102	UC	M (H/O)
8	Shanghai World Financial Center	China / Shanghai	492	101	2008	M (H/O)
9	International Commerce Centre	China / Hong Kong	484	108	2010	M (H/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/O)
12	The Exchange 106	Malaysia / Kuala Lumpur	446	95	2019	O
13	Guangzhou International Finance Center	China / Guangzhou	438	103	2010	M (H/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 Vanderbilt	USA / New York	427	58	2020	O
18	Guangxi China Resources Tower	China / Nanning	402	86	2020	M (H/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/O)
22	Golden Eagle Tiandi Tower A	China / Nanjing	368	77	2019	M (H/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	Wilshire 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/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	R
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	2011	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	Outriggered frame	Composite	NA
2	Ping An Finance Center	Central	Outriggered frame	Composite	Tapering + tapered corner
3	Goldin Finance 117	Central	Trussed-tube	Composite	NA
4	Lotte World Tower	Central	Outriggered frame	Composite	NA
5	One World Trade Center	Central	Outriggered frame	Composite	Tapering +chamfered corner
6	Tianjin CTF Finance Centre	Central	Framed-tube	Composite	Tapering + rounded corner
7	Greenland Jinmao International Financial Center	Central	Outriggered frame	Composite	NA
8	Shanghai World Financial Center	Central	Outriggered frame	Composite	Tapering (with aerodynamic top)
9	International Commerce Centre	Central	Outriggered frame	Composite	Recessed/notched corner
10	Wuhan Greenland Center	Central	Buttressed core	Composite	Tapering + rounded corner
11	Chengdu Greenland Tower	Central	Outriggered frame	Composite	Tapering
12	The Exchange 106	Central	Outriggered frame	Composite	NA
13	Guangzhou International Finance Center	Central	Outriggered frame	Composite	Tapering + tapered and rounded corner
14	Multifunctional Highrise Complex - Akhmat Tower	Central	Framed-tube	Steel	Tapering
15	Chongqing Tall Tower	Central	Outriggered frame	Composite	NA
16	Haikou Tower 1	Central	Outriggered frame	Composite	Tapering + rounded corner
17	One Vanderbilt	Central	Outriggered frame	Composite	NA
18	Guangxi China Resources Tower	Central	Outriggered frame	Composite	NA
19	China Resources Tower	Central	Diagrid-framed-tube	Composite	Tapering
20	30 Hudson Yards	Central	Outriggered frame	Steel	NA
21	Guiyang World Trade Center Landmark Tower	Central	Framed-tube	Composite	Tapering + rounded corner
22	Golden Eagle Tiandi Tower A	Central	Outriggered frame	Composite	NA
23	Hanking Center Tower	External	Trussed-tube	Steel	NA
24	Raffles City Chongqing T4N	Central	Outriggered frame	Composite	NA
25	One Shenzhen Bay Tower 7	Central	Outriggered frame	Composite	NA
26	Tianjin World Financial Center	Central	Outriggered frame	Composite	NA
27	Wilshire Grand Center	Central	Outriggered frame	Composite	NA
28	DAMAC Heights	Central	Outriggered frame	RC	NA
29	China World Tower	Central	Outriggered frame	Composite	Tapering
30	Golden Eagle Tiandi Tower B	Central	Outriggered 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	Outriggered frame	RC	NA
35	Guangfa Securities Headquarters	Central	Outriggered frame	Composite	NA
36	The Shard	Central	Shear walled frame	Composite	NA
37	Northeast Asia Trade Tower	Central	Outriggered frame	Composite	Tapering
38	One Manhattan West	Central	Shear walled frame	Composite	NA
39	Torre Costanera	Central	Outriggered frame	RC	NA
40	Shimao Riverside Block D2b	Central	Outriggered frame	Composite	Tapering
41	Golden Eagle Tiandi Tower C	Central	Outriggered 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 Ilgın 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 (Ilgın 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 Ilgın et al. (2022b) and Ilgın (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 (Ilgın 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.

Figure 3 875 North Michigan Avenue (Wikipedia)

Figure 4 Transamerica Pyramid Center (Wikipedia)

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%**

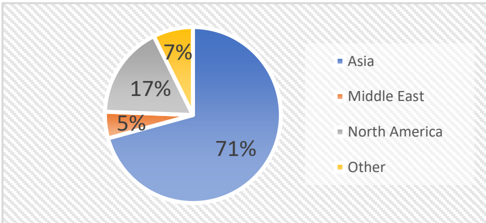

Figure 5 Tapered supertall buildings by location

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 (Ilgın 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%**

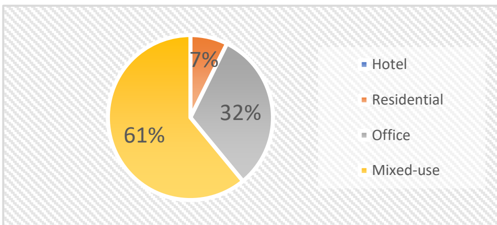

Figure 6 Tapered supertall buildings by function

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%**

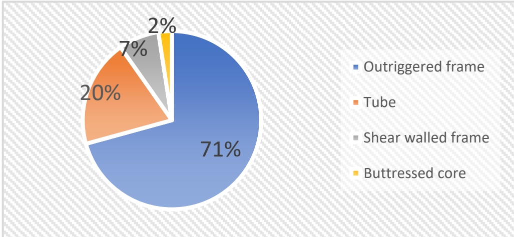

Figure 7 Tapered supertall buildings by structural system

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 system	#	%
Steel	3	7
Reinforced concrete	4	10
Composite	34	83
TOTAL	**41**	**100%**

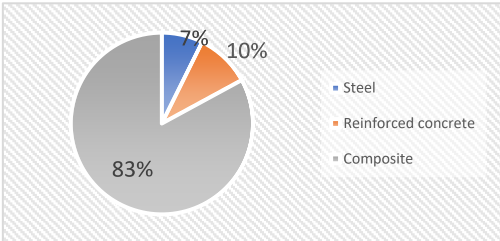

Figure 8 Tapered supertall buildings by structural material

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).

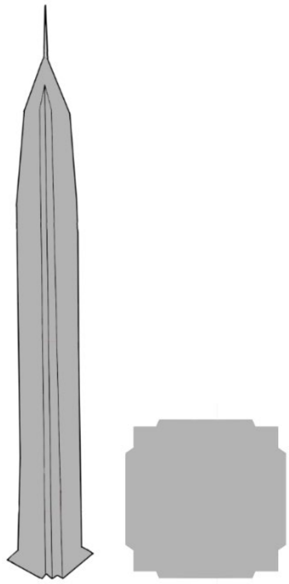

Figure 9 Tapering effects on Ping An Finance Center

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 Ilgın 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 (Ilgın et al., 2021; Ilgın, 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.

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Resume

Dr. Hüseyin Emre Ilgın received his Ph.D. (2018) in Building Sciences about tall building design in Architecture from METU. In his 15-year-professional-life, he worked in several architectural offices and companies in the building design and construction industry including design control and site supervision phases of numerous healthcare facility projects including over one million m^2 city hospitals. In academic life, he had taught in several universities as a part-time instructor for about 10 years. Since December 2019, he has been conducting post-doctoral research on wood construction at Tampere University. Now Dr. Ilgın works as a Marie Skłodowska-Curie postdoctoral research fellow on dovetailed massive wood board elements in the same university.