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SPACE EFFICIENCY IN SLENDER SUPERTALL TOWERS

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Space efficiency is one of the most significant planning concerns for creating viable supertall tower projects (≥ 300 m). This issue becomes even more important in slender skyscrapers (aspect ratio ≥ 5). Their small footprint forces service areas and structural elements to be as compact as possible. However, space efficiency in slender supertall towers is a gap in the literature. This critical subject was investigated using data from 68 case study buildings. Findings highlighted the following: (i) Mixed-use, central core, and tapered form were common. (ii) Outriggered frame system and composite had the most widespread use. (iii) Skyscrapers with 71-75% space efficiency and 7-7.9 m aspect ratio were predominant. (iv) Median aspect ratio and median space efficiency of towers were 8.1% and 72%, respectively. (v) Especially in slender buildings with high space efficiency (≥70%), space efficiency changed in direct proportion to aspect ratio. This article will assist architectural and structural designers in the sustainable development of slender supertall towers.

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INTRODUCTION

In addition to the race to build the world's tallest tower, constructing the slenderest skyscraper is also among the passions of architects. The trend of high-priced super slender building construction began in New York in 2010 (Szołomicki & Golasz-Szołomicka, 2021). This move has spread to other metropolises of the world. The main reasons for this trend were the increasing land scarcity and the demand for luxury accommodation.

The appeal of slender towers is increased because they can provide accommodation in the largest possible space in the smallest possible space. These towers can be defined as the reflection of high knowledge and advanced building materials in skyscraper construction. These structures, which emphasize the aesthetic dimension of slenderness, are often perceived as beautiful (Riad, 2016).

Today's skyscrapers, such as 432 Park Avenue with an aspect ratio of 15, continue to take slenderness to extraordinary heights. Aspect ratio or slenderness ratio can be defined as the ratio of the structural height of a tower to the narrowest structural width at the ground floor level or base (Ilgın, 2021b). In towers with a slenderness ratio above 5, aspect ratio becomes even more important as the structural design is mostly affected by lateral loads (Galsworthy et al., 2016). Additionally, excessive slenderness can exponentially increase structurally related costs.

Creating usable space becomes even more important in slender, supertall buildings that are more expensive to build and operate than traditional skyscrapers (Sev & Özgen, 2009). Space efficiency in these towers can become the focus of meeting investment value. This efficiency is directly related to the floor plan, core, and dimensions of the load-bearing components. Space efficiency plays a critical role in financial return (Kim & Elnimeiri, 2004). The small footprint of slender towers necessitates that the size of the core and load-bearing components be as compact as possible. This can put pressure on architectural and structural designers to achieve the targeted high space efficiency.

There are no studies in the literature that attempt to analyze the space efficiency in slender supertall towers. This topical topic was explored using 68 detailed cases. While doing this, basic architectural and structural planning issues were examined. In this paper, in addition to giving general information about the case studies, important analyzes (for example, the relationship between space efficiency and slenderness ratio) were made. Sustainable design issues such as energy consumption were excluded because there was not enough information to examine all sample buildings.

Objectives of this study are summarized below:

a. Data scrutiny and analysis. Examining data from 68 skyscrapers to gain meaningful insights into the relationship between space efficiency and various architectural and structural parameters.

b. Identification of dominant trends. Through analysis of case study data, identification of key trends in terms of function, form and structural system that contribute to optimum space efficiency.

c. Aspect ratio correlation. Establishing a relationship between aspect ratio and space efficiency, especially in slender buildings with high space efficiency ($\geq$70%).

d. Guidance for designers. Enabling architectural and structural designers to make informed decisions that increase space efficiency while ensuring sustainability and functionality.

e. Promotion of sustainable development. Supporting the integration of sustainability principles into skyscraper projects by emphasizing the importance of space efficiency and its impact on sustainable design.

The remainder of this study is structured as follows: First, a literature review was presented. Then, materials and methods used in the article were provided, followed by findings. After that, a comprehensive discussion was given. Finally, conclusions, future studies and limitations of the research were presented.

LITERATURE SURVEY

There are a limited number of studies in literature focusing on space efficiency in high-rise buildings. Apart from Ilgın's articles (Ilgın, 2018, 2021c; Ilgın et al., 2021), the focus was on the analysis of a small sample of buildings, as can be seen from the literature below. Additionally, the existing literature on slenderness mostly concerns its impact on structural and aerodynamic design analysis (e.g., Singh and Mandal, 2022; Cascone et al., 2021; Walsh et al., 2018). In this sense, space efficiency in slender supertall towers is a gap in the literature.

Okbaz and Sev (Okbaz & Sev, 2023) created a model for space efficiency in 11 freeform high-rise offices. They examined various design parameters such as service core and structural components. It was found that (i) building form has a significant effect, while the impact of floor-to-floor height is negligible; (ii) tapered form has the highest rate, whereas free form has the lowest ratio. Tuure and Ilgın (Tuure & Ilgın, 2023) analyzed space efficiency in 55 Finnish mid-rise wooden apartments. They reported that (a) space efficiency varies from 78% to 88% with an average of 83% and (b) there is no scientific relationship between number of stories and space efficiency. Hamid et al. (Hamid et al., 2022) interviewed architectural firms to examine the space efficiency of 60 single-family houses in Sudan. Results indicated that (i) the most efficient use of the land is the corner positioning; (ii) space efficiency is highest in parcel sizes where width is greater than depth. Suga (Suga, 2021) scrutinized space efficiency in hotels. It was found that (a) approaches focusing on space efficiency have positive effects; (b) space efficiency becomes more critical in large areas. Ilgın (Ilgın, 2021c) investigated space efficiency in office buildings, taking into account basic architectural and structural design criteria. Ilgın (Ilgın et al., 2021) examined space efficiency in residential towers, considering the same design criteria. Additionally, Ilgın (Ilgın, 2018) focused on space efficiency in mixed-use towers using 64 case study buildings. All three showed that (i) central core is the most preferred arrangement; (ii) the most employed load-bearing system is outriggered frame system; (iii) there is an inverse relationship between the height of the building and space efficiency. Arslan Kılınç (Arslan Kılınç, 2019) studied the parameters that change service core and load-bearing system in prismatic towers. Results indicated that (a) as the height of building increases, the area allocated to core and load-bearing system increases; (b) there is no scientific relationship between construction material and space efficiency. Nam and Shim (Nam & Shim, 2016) researched the effect of lease span and high-rise corner forms on space efficiency. It was highlighted that (i) square-cut corner form is the most disadvantageous; (ii) corner cuts have a negligible effect on spatial efficiency, while lease span has a substantial impact. Sev and Özgen (Sev & Özgen, 2009) explored the space efficiency of 10 office towers. They examined various design factors such as core type and load-bearing system. It was found that (a) structural system and core typology play critical roles; (b) outriggered frame systems and central core arrangement are most preferred. Saari et al. (Saari et al., 2006) examined the differences in total building cost by improving space efficiency in office towers. The results showed that when space efficiency increases significantly, measures must be taken to ensure a satisfactory indoor climate. Kim and Elnimeiri (Kim & Elnimeiri, 2004) analyzed the space efficiency of 10 mixed-use towers. It was reported that (i) in addition to space efficiency, structural efficiency and energy efficiency must also be taken into account; (ii) functional allocation and an optimum number of elevators are critical parameters.

The lack of literature on space efficiency in slender supertall towers can be attributed to several factors:

a. Emerging design focus. 'Space efficiency' in slender supertall towers is a relatively new and evolving field of study. As architectural and engineering practices constantly evolve, new aspects of building design come to the fore.

b. Niche design consideration. Slender supertall towers represent a niche category in the skyscraper world. Their unique design challenges and technical requirements distinguish them from traditional tall buildings.

c. Complexity of design. Slender supertall tower design requires complex architectural and engineering decisions due to extreme aspect ratios and sensitivity to wind loads. As these complexities come to the fore, discussion of the space efficiency aspect may be limited.

d. Limited number of case studies. The number of slender supertall towers completed worldwide is relatively limited compared to other types of tall buildings. This scarcity makes it difficult to collect sufficient data for the comprehensive literature on space efficiency.

e. Interdisciplinary nature. Space efficiency in the slender supertall tower requires collaboration between architects, structural engineers, and other professionals. The multidisciplinary nature of this topic may contribute to the lack of integrated research as different design considerations are investigated in separate areas.

f. Limited awareness. Researchers may not have fully understood the importance of space efficiency considerations in the context of slender supertall towers. This may lead to a lack of specific studies addressing this specific concern.

MATERIALS AND METHOD

In this article, case study method was applied to collect and combine data on slender supertall towers to explore space efficiency. This approach is extensively utilized in built-environment analysis, in which projects are specified for quantitative and qualitative data (e.g., Karjalainen et al., 2021; Tulonen et al., 2021; Saarinen et al., 2022; Rinne et al., 2022; Ilgın, 2021a).

Cases were 68 supertall buildings in various locations (40 in Asia, 15 in the Middle East, 9 in the USA, 3 in Russia, 1 in the United Kingdom). Detailed information was provided in Appendices A-C. Approximately half of these towers were completed in the last decade, and most (>70%) were completed in the last two decades. Supertall towers for which there is insufficient information are not included in the Appendices.

Considering the building form, a concentrated effort was made to find floor plans including ground floor or lower floor or typical floors. This allowed the generation of more reliable data for comparison of space efficiency across the sample group. Given the literature (e.g., Ilgın and Karjalainen, 2023; Gunel and Ilgın, 2007; Taranath, 2016; Ali and Al-Kodmany, 2022; Ilgın, 2006), Ilgın and Karjalainen's (Ilgın, 2006) categorizations for key architectural and structural considerations were utilized (Table 1).

Space efficiency is the ratio of net floor area (NFA) to gross floor area (GFA). To provide maximum returns to the investor, floor plans must offer sufficient usable space, i.e., high space efficiency. This efficiency depends primarily on the core design, building form, load-bearing system, and construction material (Ilgın, 2021a). Moreover, space efficiency can be increased with lease span. Lease span is the distance between fixed interior element such as service core walls and building envelope such as window (Ilgın et al., 2023).

It is worth noting that super slender tall buildings and tall buildings differ significantly in terms of architectural and engineering solutions, as detailed below:

i. Aspect ratio. Super slender towers have a larger aspect ratio than typical tall buildings. This creates challenges in terms of lateral stability and wind-induced vibrations.

ii. Structural stability. The high aspect ratio requires advanced structural engineering solutions to ensure stability against lateral forces. These solutions, unlike tall buildings, include the use of mass dampers, advanced structural systems such as trussed tube systems, and other innovative methods.

iii. Wind loads. Wind is a big concern for super slender towers due to their slender profiles. Engineers need to develop aerodynamic approaches that minimize wind effects through techniques such as tapering forms.

iv. Floorplate design. Floorplate design of super slender towers is optimized to minimize lateral deflection due to wind, which can impact occupant comfort. Innovative strategies can be employed to distribute loads effectively.

Table 1: Main architectural and structural design parameters

Architectural design parameters			Structural design parameters	
function	core design pltypology	building form	structural system	structural material
- single-use	- central	- prismatic	- shear-frame	- steel
* hotel	- atrium	- setback	* shear trussed	- reinforced concrete
* residential	- external	- tapered	* shear walled	- composite
	- peripheral	- leaning/tilted	- mega core	
		- free	- mega column	
* office			- outriggered frame	
			- tube	
- mixed-use			* framed-tube	
			* trussed-tube	
			* bundled-tube	

FINDINGS

Main architectural design considerations: function, core typology, and building form

In terms of function, mixed-use, and office use (>40% each) were dominant, followed by residential use with 16% (Figure 1). No hotel function was found in the case studies. In buildings with a slenderness ratio of 8 and above, residential preference was 30% (Figure 2). This large ratio of super slender (≥8) residential towers can be justified by the demand for luxury living at height (Besjak et al., 2022; Ilgın, 2022).

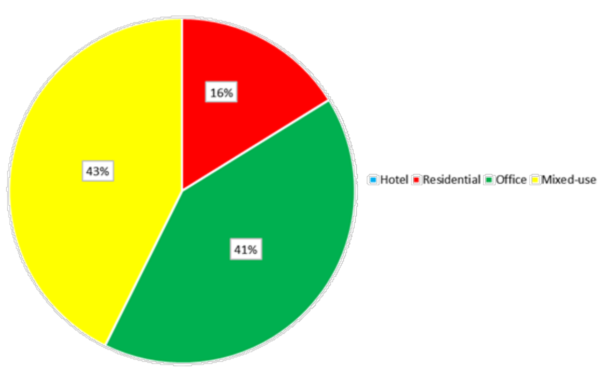

Figure 1: Slender supertall buildings by function

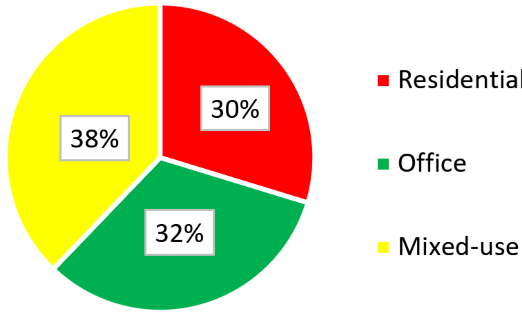

Figure 2: Slender supertall buildings with an aspect ratio of 8 and above by function

Additionally, the high demand for mixed-use towers can be explained by the 'vertical communities' approach that offers a solution to population growth. During market fluctuations, mixed-use development has become even more preferred to increase rental income and appeal to a wide customer portfolio (Ilgın, 2018). Similarly, the trend of locating business spaces as close together as possible may be driving the demand for slender office towers (Gunel & Ilgın, 2014a).

As seen in Appendix B, in skyscrapers other than 53 West 53, the central core was adopted as a uniform typology. Its suitability for compactness, its critical role in the load-bearing system and its contribution to fire safety may explain the superiority of the central core (Ilgın & Karjalainen, 2023). The reasons why the peripheral core was not preferred include the extension of circulation routes and its disadvantage in terms of fire escape (Ilgın, 2023).

Tapered forms were used the most with a ratio of 32%, followed by free forms with 23% (Figure 3). Considering that wind forces become more important in slender towers, it was not surprising that tapered form was preferred due to its aerodynamic advantages (Gunel & Ilgın, 2014b). Similarly, the aerodynamic advantages of free forms and their compatibility with architects' enthusiasm for producing iconic towers may have made these forms preferable.

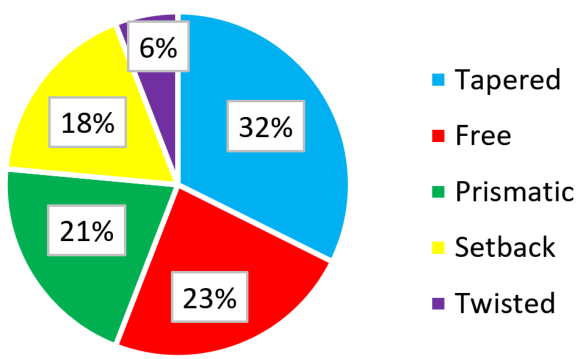

Figure 3: Slender supertall buildings by form

Main structural design considerations: structural system and structural material

As depicted in Figure 4, outriggered frame systems were mostly employed (55%), followed by tube systems (29%). Developing an efficient load-bearing system for slender supertall towers is one of the most challenging tasks for structural designers. In this sense, outriggered frame and tube systems can offer ideal solutions for these extraordinary structures (Walsh et al., 2018). Suzhou Zhongnan Center with an aspect ratio of 8.7

and Goldin Finance 117 with an aspect ratio of 9.5 are two spectacular examples. Outriggered frame system stands out with its flexibility in outer column configurations and great height potential. Tube system provides an advantage against overturning forces due to structural use of the entire facade.

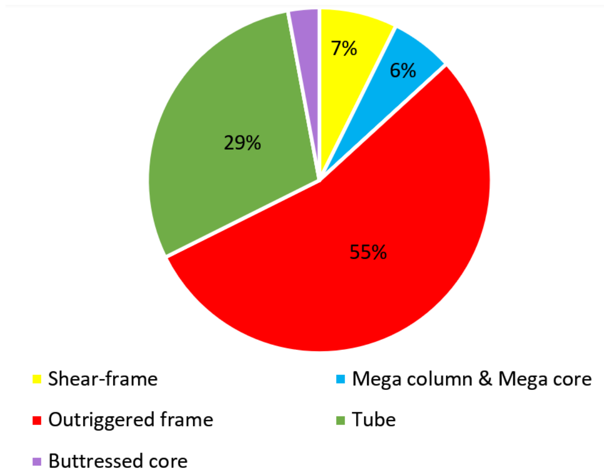

Figure 4: Slender supertall buildings by structural system

In terms of structural material, composite use was dominant (65%), followed by reinforced concrete with 32% (Figure 5). In addition, concrete preference was over 50 percent in towers with a slenderness ratio of 8 and above (Figure 6). Slender towers must have sufficient mass to perform better in damping the building's sway from wind loads. One of the most effective ways to achieve this is to use concrete.

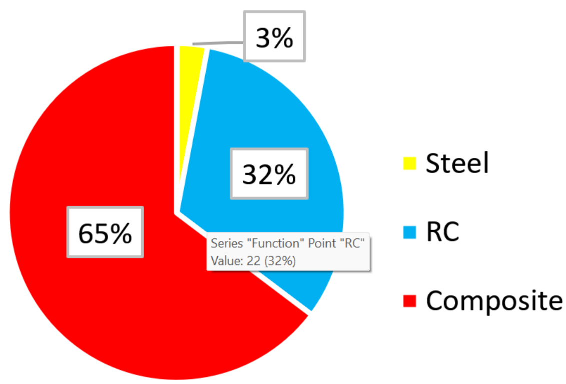

Figure 5: Slender supertall buildings by structural material

Interrelations of space efficiency and slenderness ratio

Figure 7 shows in the bar chart how space efficiency changes with aspect ratio. Skyscrapers with a space efficiency of 71-75% (Figure 7a) and an aspect ratio of 7-7.9 m (Figure 7b) were dominant groups. Median aspect ratio and median space efficiency of all cases were 8.1 and 72%, respectively. As seen in Figure 7a, slenderness ratios of 7-8.9 were mostly used in space efficiency range of 66-70%. Towers in 71-75% range were generally built in aspect ratios of 5-7.9. Skyscrapers with the highest space efficiency (>80%) were among the slenderest (10-15). As depicted in Figure 7b, space efficiency of skyscrapers with aspect ratios of 7-7.9 was mostly 66-75%.

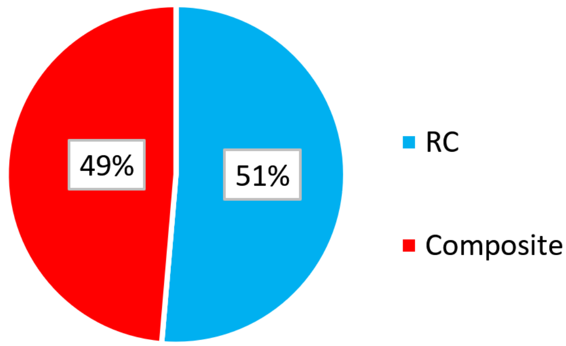

Figure 6: Slender supertall buildings with an aspect ratio of 8 and above by structural material

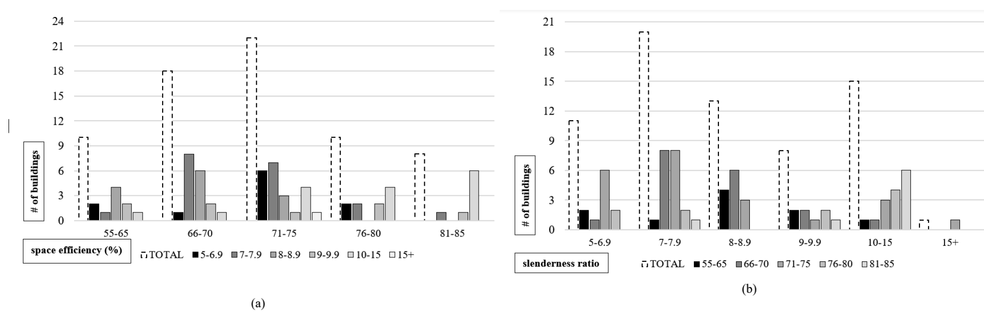

Figure 7: Interrelation of aspect ratio and space efficiency in the form of bar chart

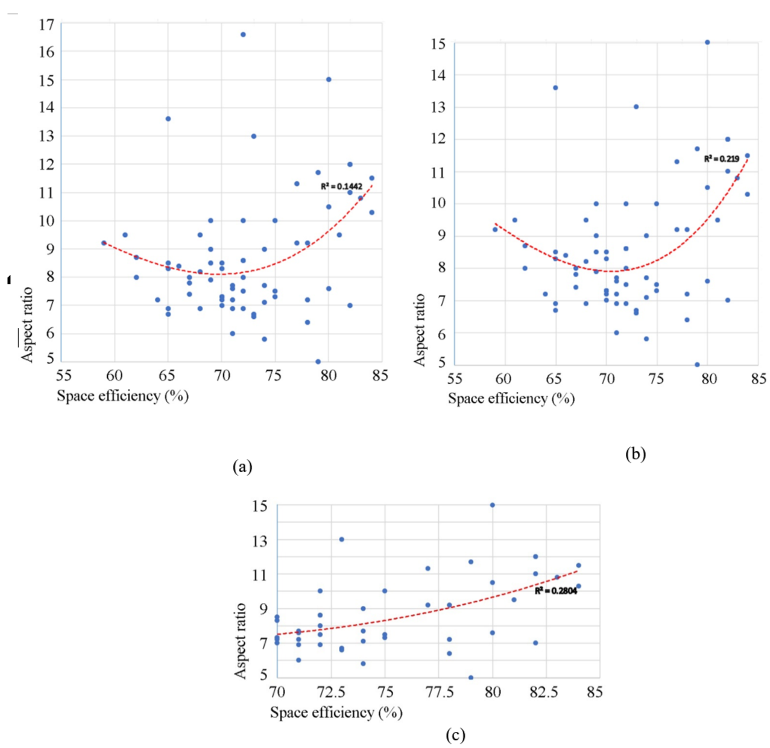

Figure 8: Interrelation of space efficiency and aspect ratio in the form of scatter chart; (a) with outlier, (b) without outlier; and (c) without outlier in building group with an aspect ratio of 70% and above

Figure 8(a-c) shows how the space efficiency differs according to the slenderness ratio in the scatter plot. Here, blue dots symbolize slender skyscrapers. Polynomial regression approach was used to obtain correlations with supertall buildings. This method was chosen because it provides a more accurate R-squared correlation coefficient compared to other approaches, such as linear. Aspire Tower with its aspect ratio of 16.6 was considered an outlier. Figure 8b indicates how the outlier quantitatively affects the regression line.

As trendline in Figure 8(a) shows, space efficiency tended to increase with aspect ratio. As seen in the slope of the trend line, this increase was more evident in towers with an aspect ratio of 70% and above. This comprised 70% of the sample group. It was observed that the slope of the trend line increased when the outlier was removed. Figure 8c focuses only on supertall buildings with space efficiency of 70% and above, excluding the selected outlier. The value of the R-squared correlation coefficient was approaching 1, and the uptrend had spread across the entire trend line.

DISCUSSION

In this article, space efficiency in slender skyscrapers was examined through 68 case studies along with key architectural and structural parameters. A comprehensive discussion was not possible due to the lack of literature. However, the results regarding function, core arrangement, form and load-bearing system are similar to the findings of other studies. The main findings are as follows:

a) Mixed-use and office use were common.

b) Central core typology was dominant.

c) Tapered form was the most prevalent form.

d) Outriggered frame systems were mostly employed, followed by tube systems.

e) Composite use was common, followed by reinforced concrete.

f) Skyscrapers with space efficiency of 71-75% and aspect ratio of 7-7.9m dominated.

g) Median aspect ratio and median space efficiency of towers were 8.1% and 72%, respectively.

h) Especially in slender buildings with high space efficiency (≥70%), space efficiency changed in direct proportion to aspect ratio.

Central core dominance was observed in the case sample group. This finding was also revealed in studies conducted by Ilgın (2021c), Ilgın et al. (2021),Ilgın and Karjalainen (2023),Oldfield and Doherty (2019). Among 68 slender supertall towers, tapered form was the most common form. This result was also supported by the results of Ilgın (2021b) and Ilgın and Karjalainen (2023). However, Ilgın et al. (2021)'s results showed that prismatic forms were most frequently employed in residential skyscrapers. Outriggered frame system was mainly utilized structural system. This result confirmed the findings of other papers e.g., Ilgın and Karjalainen (2023). The dominance of composite use was identified as in Ilgın (2021c)'s study. On the other hand, half of the super slender towers were constructed with reinforced concrete as in Ilgın et al. (2021)'s paper. Especially in slender towers with a high space efficiency (≥70%), space efficiency changed in direct proportion to aspect ratio. However, as stated in studies examining space efficiency and building height, such as Ilgın (2018), an inverse relationship was found.

CONCLUSIONS

The scientific contribution of this paper lies in the comprehensive investigation of space efficiency in slender supertall towers. This topic has received limited attention in the existing literature. Analyzing data from 68 case studies, this article highlights the critical planning concern of optimizing space in these unique structures. This research therefore provides valuable insight into the dominant architectural and engineering solutions for slender supertall towers.

Today, supertall towers with various functions and forms are being built in many capitals of the world. Considering global housing trends, in addition to luxurious living at heights, skyscrapers that push the limits of slenderness also come to the fore. These extraordinary structures present high-level challenges, including architectural, engineering, and financial considerations such as maximizing space efficiency. Tube systems that ensure the desired slenderness and efficient space use without sacrificing structural efficiency can offer solutions. In these systems, the use of concrete or composite can be preferred to provide necessary mass against wind loads. As a result, a high level of interdisciplinary collaboration is critical to ensure space efficiency as well as stiffness and occupancy comfort in slender skyscrapers.

From the extensive analysis conducted in this study, concrete recommendations for architects designing slender supertall towers are as follows:

i. Mixed-use and office. Strategically integrating mixed-use and office functions to maximize space utilization and encourage dynamic interactions within the building.

ii. Central core. Facilitating efficient circulation, enhanced stability, and effective space optimization by shaping the building's layout around a central core.

iii. Tapered forms. Considering the use of tapered designs to not only meet structural demands but also create dynamic visual impact and efficient spaces.

iv. Composite outriggered frame systems. Benefiting from these solutions in terms of both structural integrity and space efficiency.

v. Optimal space efficiency and aspect ratios. Aim for 71-75% space efficiency and 7-7.9m aspect ratio for outstanding results in terms of practical feasibility and space optimization.

vi. Holistic collaboration. Promoting a multidisciplinary and collaborative approach in which knowledge from the architectural and structural fields contributes to space-efficient, structurally sound and aesthetic designs.

vii. Incorporate vertical transportation. Optimizing elevator configurations and locations to facilitate smooth movement within the building while saving valuable space.

This study opens the door to future research in many areas. Further investigation of socio-economic and cultural factors affecting space efficiency decisions may provide a broader understanding of this issue. Comparing space efficiency between different regions and building typologies can increase the depth of knowledge in this field. Additionally, exploring how emerging technologies such as parametric design impact space efficiency in slender supertall towers could be a promising avenue.

This study has several limitations. The empirical data was limited to 68 slender skyscrapers. Much larger case study sample sizes can be examined to make the findings more reliable. In future research, a sufficient number of subgroups can be generated by including buildings lower than 300 meters in the sample.

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APPENDIX A

Table 2: Slender supertall buildings considered in this study

#	Building name	Aspect ratio	Space eff.* (%)	Location (Country / city)	Height (m)	# of story	Completion date	Function
1	Nakheel Tower	10	69	UAE / Dubai	1000+	200	NC	(M) H/R/O
2	Burj Khalifa	10.5	80	UAE / Dubai	828	163	2010	(M) H/R/O
3	Suzhou Zhongnan Center	8.7	62	China / Suzhou	729	137	UC	(M) H/R/O
4	Merdeka PNB118	6.7	65	Malaysia / Kuala Lumpur	644	118	UC	(M) H/O
5	Shanghai Tower	7.6	71	China / Shanghai	632	128	2015	(M) H/O
6	Chicago Spire	10	75	USA / Chicago	609	150	NC	R
7	Ping An Finance Center	8.3	70	China / Shenzhen	599	115	2017	O
8	Goldin Finance 117	9.5	68	China / Tianjin	596	128	OH	(M) H/O
9	Entisar Tower	9	74	UAE / Dubai	577	122	OH	(M) H/R
10	Lotte World Tower	7.9	69	South Korea / Seoul	554	123	2017	(M) H/R/O
11	One World Trade Center	8.5	70	USA / New York	541	94	2014	O
12	Guangzhou CTF Finance Centre	8.5	65	China / Guangzhou	530	111	2016	(M) H/R/O
13	Tianjin CTF Finance Centre	7.3	70	China / Tianjin	530	97	2019	(M) H/O
14	CITIC Tower	7.2	70	China / Beijing	528	108	2018	O
15	Evergrande Hefei Center 1	9.2	59	China / Hefei	518	112	OH	(M) H/R/O
16	TAIPEI 101	10	72	Taiwan / Taipei	508	101	2004	O
17	Shanghai World Financial Center	8.5	69	China / Shanghai	492	101	2008	(M) H/O
18	International Commerce Centre	9	69	China / Hong Kong	484	108	2010	(M) H/O
19	Chengdu Greenland Tower	7.5	72	China / Chengdu	468	101	UC	(M) H/O
20	Lakhta Center	7.8	67	Russia / St. Petersburg	462	87	2019	O
21	Petronas Twin Tower 1	8.6	72	Malaysia / Kuala Lumpur	452	88	1998	O
22	Petronas Twin Tower 2	8.6	72	Malaysia / Kuala Lumpur	452	88	1998	O
23	Zifeng Tower	6	71	China / Nanjing	450	66	2010	(M) H/O
24	World One	9.2	78	Mumbai / India	442	117	NC	R
25	KK 100	9.5	61	China / Shenzhen	441	98	2011	(M) H/O
26	Guangzhou International Finance Center	7.7	71	China / Guangzhou	438	103	2010	(M) H/O
27	Marina 101	12	82	UAE / Dubai	425	101	2017	(M) H/R
28	432 Park Avenue	15	80	USA / New York	425	85	2015	R
29	Trump International Hotel & Tower	8	62	USA / Chicago	423	98	2009	(M) H/R
30	Al Hamra Tower	7	70	Kuwait / Kuwait City	413	80	2011	O
31	Princess Tower	11	82	UAE / Dubai	413	101	2012	R
32	Two International Finance Center	7.2	71	China / Hong Kong	412	88	2003	O
33	China Resources Tower	6.6	73	China / Shenzhen	393	68	2018	O
34	23 Marina	9.5	81	UAE / Dubai	392	88	2012	R
35	CITIC Plaza	7.4	67	China / Guangzhou	390	80	1996	O
36	Shum Yip Upperhills Tower 1	7.2	64	China / Shenzhen	388	80	2020	(M) H/O
37	PIF Tower	6.9	65	SA / Riyadh	385	72	2021	O
38	Shun Hing Square	8	67	China / Shenzhen	384	69	1996	O
39	Burj Mohammed Bin Rashid	13	73	UAE / Abu Dhabi	381	88	2014	R
40	Elite Residence	10.3	84	UAE / Dubai	380	87	2012	R
41	Central Plaza	8.4	66	China / Hong Kong	374	78	1992	O
42	Golden Eagle Tiandi Tower A	7.3	70	China / Nanjing	368	77	2019	(M) H/O
43	Bank of China Tower	7	82	China / Hong Kong	367	72	1990	O
44	Almas Tower	9.2	77	UAE / Dubai	360	68	2008	O
45	Hanking Center Tower	7.3	70	China / Shenzhen	359	65	2018	O
46	Sino Steel Int. Plaza T2	6.9	68	China / Tianjin	358	83	OH	O
47	The Center	8.2	68	China / Hong Kong	346	73	1998	O
48	NEVA TOWERS 2	11.3	77	Russia / Moscow	345	79	2020	R
49	Comcast Technology Center	7.1	74	USA / Philadelphia	339	59	2018	(M) H/O
50	Mercury City Tower	7.6	80	Russia / Moscow	338	75	2013	(M) R/O
51	Tianjin World Financial Center	8	72	China / Tianjin	337	75	2011	O
52	Golden Eagle Tiandi Tower B	8.3	65	China / Nanjing	328	68	2019	O
53	Salesforce Tower	6.9	72	USA / San Francisco	326	61	2018	O
54	53 West 53	12	82	USA / New York	320	77	2019	R
55	New York Times Tower	7.3	75	USA / New York	319	52	2007	O
56	Chongqing IFS T1	5.8	74	China / Chongqing	316	63	2016	(M) H/O
57	MahaNakhon	13.6	65	China / Bangkok	314	79	2016	(M) H/R
58	Bank of America Plaza	6.4	78	USA / Atlanta	312	55	1992	O
59	Shenzhen Bay Innovation and Technology Centre Tower 1	6.9	71	China / Shenzhen	311	69	2020	O
60	Ocean Heights	11.5	84	UAE / Dubai	310	83	2010	R
61	Pearl River Tower	11.7	79	China / Guangzhou	309	71	2013	O
62	Guangfa Securities Headquarters	7.7	74	China / Guangzhou	308	60	2018	O
63	The Shard	5	79	UK / London	306	73	2013	(M) H/R/O
64	Cayan Tower	10.8	83	UAE / Dubai	306	73	2013	R
65	Kingdom Centre	7.2	78	SA / Riyadh	302	41	2002	(M) H/R/O
66	Shimao Riverside Block D2b	6.7	73	China / Wuhan	300	53	UC	(M) H/O
67	Aspire Tower	16.6	72	Qatar / Doha	300	36	2007	(M) H/O
68	Golden Eagle Tiandi Tower C	7.5	75	China / Nanjing	300	60	2019	O

Note on abbreviations: 'H' indicates hotel use; 'R' indicates residential use; 'O' indicates office use; 'M' indicates mixed-use; 'UAE' indicates the United Arab Emirates; 'SA' indicates Saudi Arabia; 'UC' indicates Under construction; 'NC' indicates Never completed; 'OH' indicates On hold. Space efficiency*: calculated as the ratio of the net floor area (obtained by subtracting service core and structural elements from GFA) to GFA. (see detailed Appendix C with floor plans).

APPENDIX B

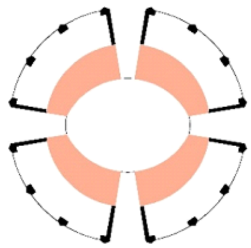
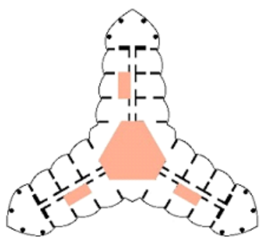
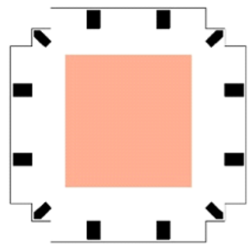
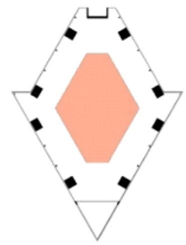
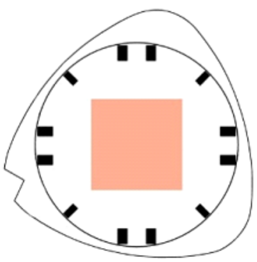
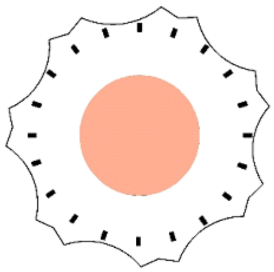
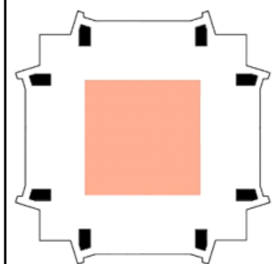
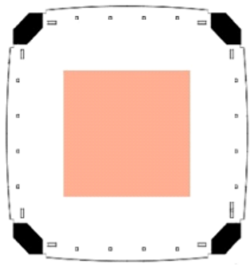
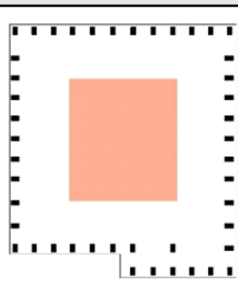
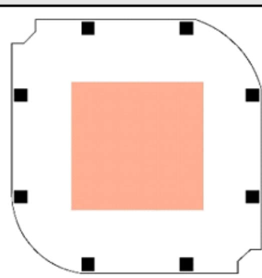
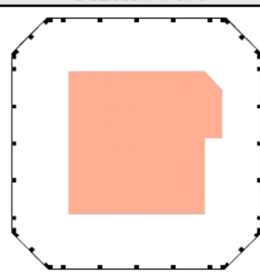
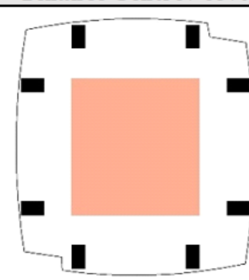
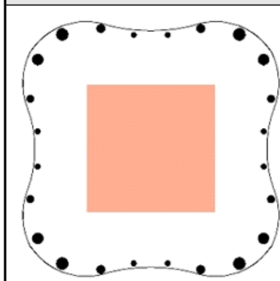
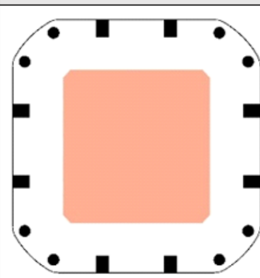
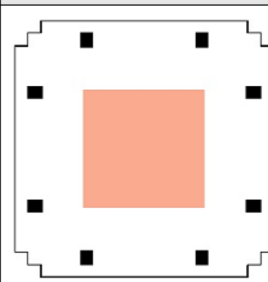
Table 3: Slender supertall buildings by core type, building form, structural system, and structural material

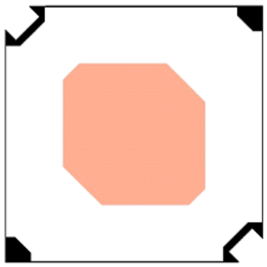
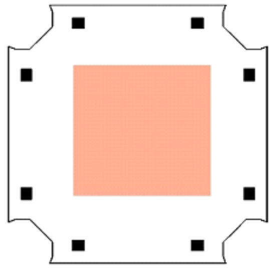
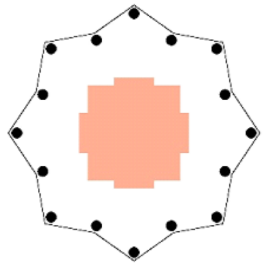
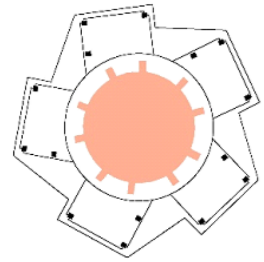
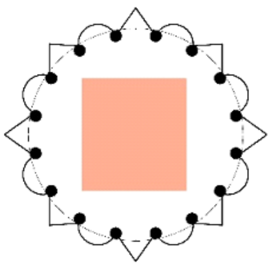
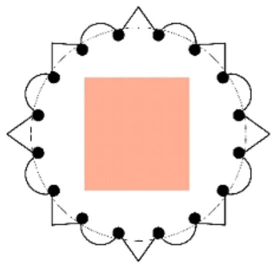
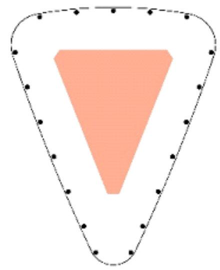
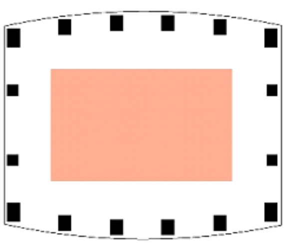
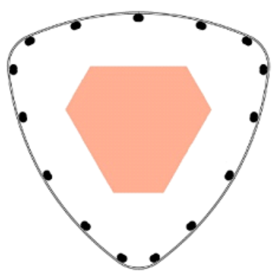
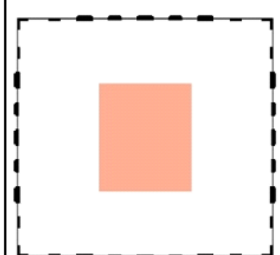
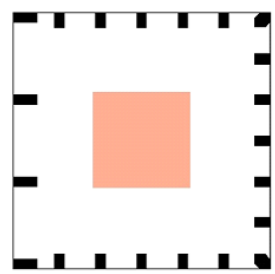
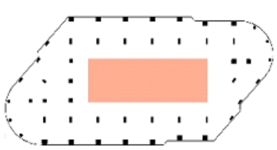
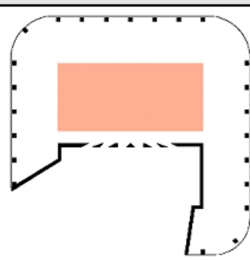
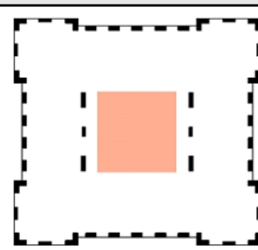
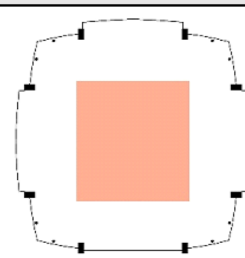
#	Building name	Core type	Building form	Structural system	Structural material
1	Nakheel Tower	Central	Free	Mega column	Composite
2	Burj Khalifa	Central	Setback	Buttressed core	RC
3	Suzhou Zhongnan Center	Central	Tapered	Outriggered frame	Composite
4	Merdeka PNB118	Central	Free	Outriggered frame	Composite
5	Shanghai Tower	Central	Twisted	Outriggered frame	Composite
6	Chicago Spire	Central	Twisted	Outriggered frame	RC
7	Ping An Finance Center	Central	Tapered	Outriggered frame	Composite
8	Goldin Finance 117	Central	Tapered	Trussed-tube	Composite
9	Entisar Tower	Central	Setback	Framed-tube	RC
10	Lotte World Tower	Central	Tapered	Outriggered frame	Composite
11	One World Trade Center	Central	Tapered	Outriggered frame	Composite
12	Guangzhou CTF Finance Centre	Central	Setback	Outriggered Frame	Composite
13	Tianjin CTF Finance Centre	Central	Tapered	Framed-tube	Composite
14	CITIC Tower	Central	Free	Trussed-tube	Composite
15	Evergrande Hefei Center 1	Central	Free	Outriggered frame	Composite
16	TAIPEI 101	Central	Free	Outriggered frame	Composite
17	Shanghai World Financial Center	Central	Tapered	Outriggered frame	Composite
18	International Commerce Centre	Central	Tapered	Outriggered frame	Composite
19	Chengdu Greenland Tower	Central	Tapered	Outriggered frame	Composite
20	Lakhta Center	Central	Twisted	Outriggered frame	Composite
21	Petronas Twin Tower 1	Central	Setback	Outriggered frame	RC
22	Petronas Twin Tower 2	Central	Setback	Outriggered frame	RC
23	Zifeng Tower	Central	Free	Outriggered frame	Composite
24	World One	Central	Setback	Buttressed core	RC
25	KK 100	Central	Free	Framed-tube	Composite
26	Guangzhou International Finance Center	Central	Tapered	Outriggered frame	Composite
27	Marina 101	Central	Prismatic	Framed-tube	RC
28	432 Park Avenue	Central	Prismatic	Framed-tube	RC
29	Trump International Hotel & Tower	Central	Setback	Outriggered frame	RC
30	Al Hamra Tower	Central	Free	Shear walled frame	Composite
31	Princess Tower	Central	Prismatic	Framed-tube	RC
32	Two International Finance Center	Central	Setback	Outriggered frame	Composite
33	China Resources Tower	Central	Tapered	Framed-tube	Composite
34	23 Marina	Central	Prismatic	Outriggered frame	RC
35	CITIC Plaza	Central	Prismatic	Shear walled frame	RC
36	Shum Yip Upperhills Tower 1	Central	Prismatic	Outriggered frame	Composite
37	PIF Tower	Central	Free	Trussed-tube	Composite
38	Shun Hing Square	Central	Free	Outriggered frame	Composite
39	Burj Mohammed Bin Rashid	Central	Free	Outriggered frame	RC
40	Elite Residence	Central	Prismatic	Framed-tube	RC
41	Central Plaza	Central	Prismatic	Trussed-tube	Composite
42	Golden Eagle Tiandi Tower A	Central	Tapered	Outriggered frame	Composite
43	Bank of China Tower	Central	Setback	Trussed-tube	Composite
44	Almas Tower	Central	Free	Outriggered frame	Composite
45	Hanking Center Tower	External	Tapered	Trussed-tube	Steel
46	Sino Steel International Plaza T2	Central	Prismatic	Framed-tube	Composite
47	The Center	Central	Prismatic	Mega column	Composite
48	NEVA TOWERS 2	Central	Prismatic	Outriggered frame	RC
49	Comcast Technology Center	Central	Setback	Trussed-tube	Composite
50	Mercury City Tower	Central	Setback	Framed-tube	RC
51	Tianjin World Financial Center	Central	Tapered	Outriggered frame	Composite
52	Golden Eagle Tiandi Tower B	Central	Tapered	Outriggered frame	Composite
53	Salesforce Tower	Central	Tapered	Shear walled frame	Composite
54	53 West 53	Peripheral	Tapered	Framed-tube	RC
55	New York Times Tower	Central	Prismatic	Outriggered frame	Steel
56	Chongqing IFS T1	Central	Prismatic	Outriggered frame	Composite
57	MahaNakhon	Central	Free	Outriggered frame	RC
58	Bank of America Plaza	Central	Setback	Mega column	Composite
59	Shenzhen Bay Innovation and Technology Centre Tower 1	Central	Prismatic	Framed-tube	Composite
60	Ocean Heights	Central	Tapered	Outriggered frame	RC
61	Pearl River Tower	Central	Free	Outriggered frame	Composite
62	Guangfa Securities Headquarters	Central	Tapered	Outriggered frame	Composite
63	The Shard	Central	Tapered	Shear walled frame	Composite
64	Cayan Tower	Central	Twisted	Framed-tube	RC
65	Kingdom Centre	Central	Free	Shear walled frame	RC
66	Shimao Riverside Block D2b	Central	Tapered	Outriggered frame	Composite
67	Aspire Tower	Central	Free	Mega core	RC
68	Golden Eagle Tiandi Tower C	Central	Tapered	Outriggered frame	Composite

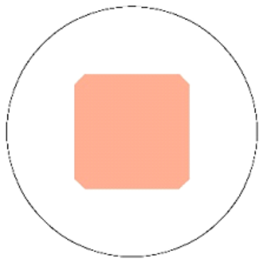
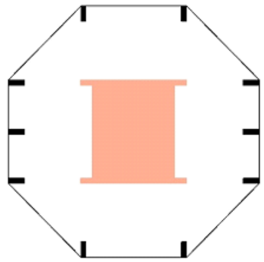
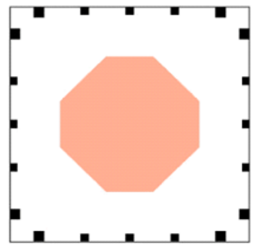
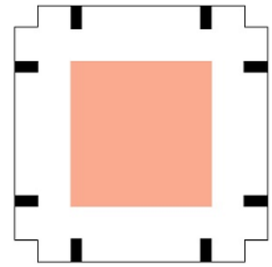
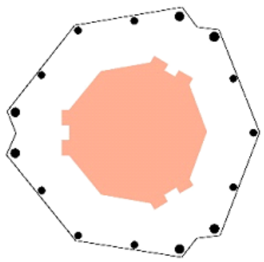
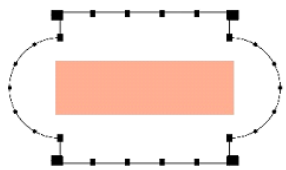
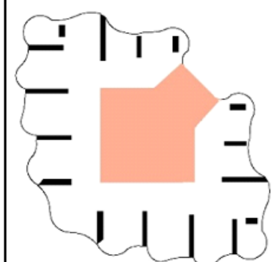
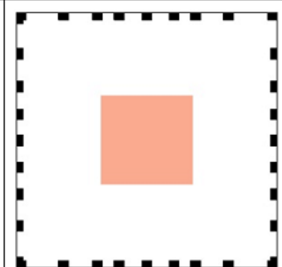
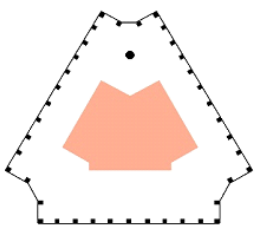
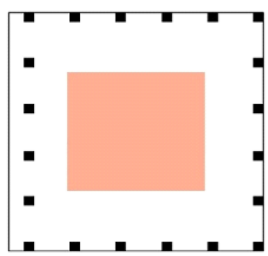
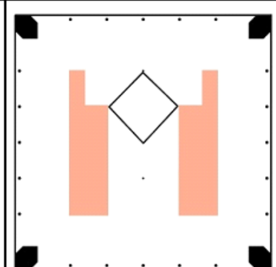
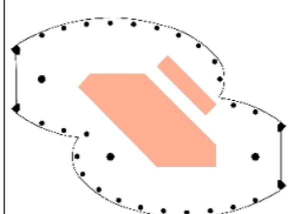
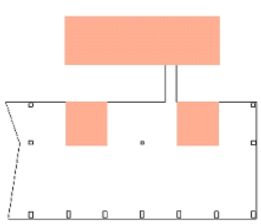
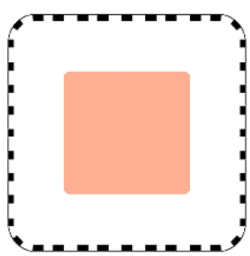
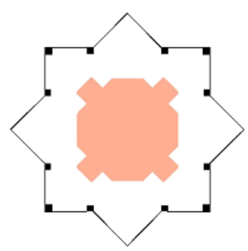
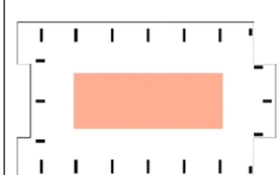
Note on abbreviation: 'RC' indicates reinforced concrete

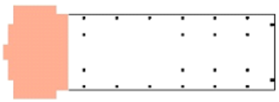
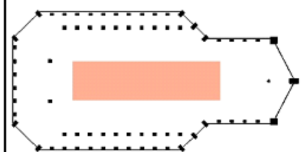
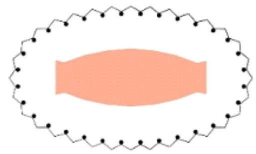
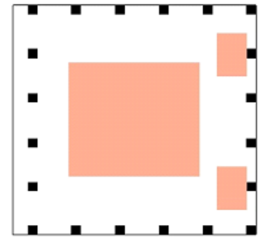
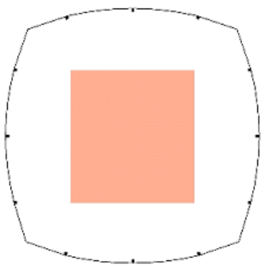
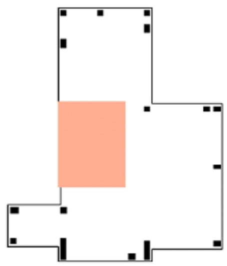
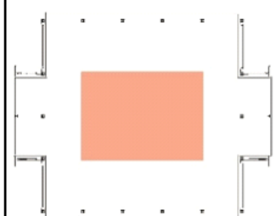
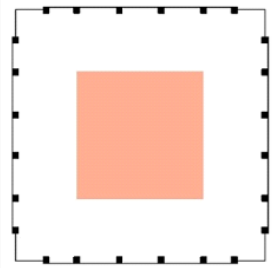
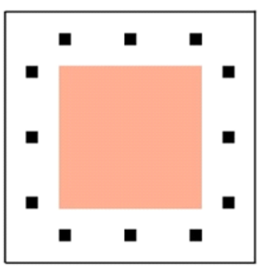
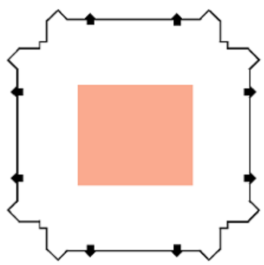
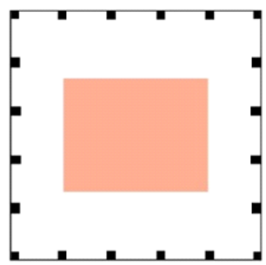
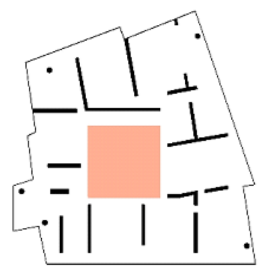
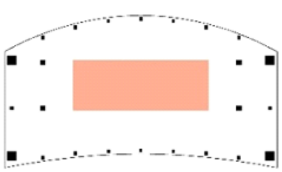
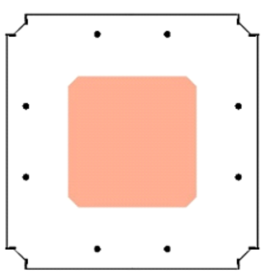
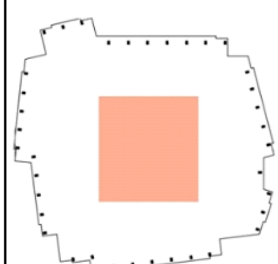
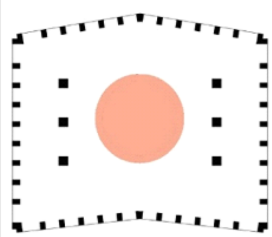
APPENDIX C

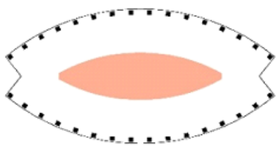
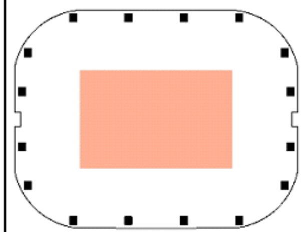
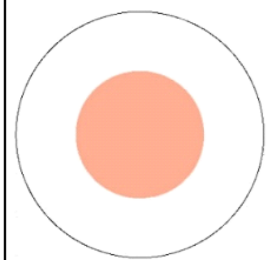
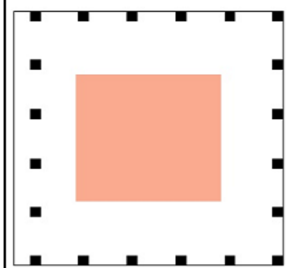
Appendix C Floor plan and space efficiency ratio of slender supertall towers

Building name / Space efficiency*			
Nakheel Tower / 69%	**Burj Khalifa** / 80%	**Suzhou Zhongnan Center** / 62%	**Merdeka PNB118** / 65%
			
Low-rise floor	Typical floor	Low-rise floor	Low-rise floor
Shanghai Tower / 71%	**Chicago Spire** / 75%	**Ping An Finance Center** / 70%	**Goldin Finance 117** / 68%
			
Low-rise floor	Low-rise floor	Low-rise floor	Ground floor
Entisar Tower / 74%	**Lotte World Tower** / 69%	**One World Trade Center** / 70%	**Guangzhou CTF Finance Centre** / 65%
			
Low-rise floor	Low-rise floor	Low-rise floor	Low-rise floor
Tianjin CTF Finance Centre / 70%	**CITIC Tower** / 70%	**Evergrande Hefei Center 1** / 59%	**TAIPEI 101** / 72%
			
Low-rise floor	Ground floor	Typical floor	Typical floor

Building name / Space efficiency			
Shanghai World Financial Center / 69%	**International Commerce Centre** / 69%	**Chengdu Greenland Tower** / 72%	**Lakhta Center** / 67%
			
Low-rise floor	Low-rise floor	Ground floor	Typical floor
Petronas Twin Tower 1 / 72%	**Petronas Twin Tower 2** / 72%	**Zifeng Tower** / 71%	**World One** / 78%
			
Typical floor	Typical floor	Ground floor	Low-rise floor
KK 100 / 61%	**Guangzhou International Finance Center** / 71%	**Marina 101** / 82%	**432 Park Avenue** / 80%
			
Low-rise floor	Typical floor	Typical floor	Typical floor
Trump International Hotel & Tower / 62%	**Al Hamra Tower** / 70%	**Princess Tower** / 82%	**Two International Finance Center** / 71%
			
Low-rise floor	Low-rise floor	Typical floor	Typical floor

Building name / Space efficiency			
China Resources Tower / 73%	**23 Marina** / 81%	**CITIC Plaza** / 67%	**Shum Yip Upperhills Tower 1** / 64%
			
Typical floor	Typical floor	Typical floor	Typical floor
PIF Tower / 65%	**Shun Hing Square** / 67%	**Burj Mohammed Bin Rashid** / 73%	**Elite Residence** / 84%
			
Typical floor	Typical floor	Low-rise floor	Typical floor
Central Plaza / 66%	**Golden Eagle Tiandi Tower A** / 70%	**Bank of China Tower** / 82%	**Almas Tower** / 77%
			
Typical floor	Typical floor	Low-rise floor	Typical floor
Hanking Center Tower / 70%	**Sino Steel Int. Plaza T2** / 68%	**The Center** / 68%	**NEVA TOWERS 2** / 77%
			
Typical floor	Typical floor	Typical floor	Typical floor

Building name / Space efficiency			
Comcast Technology Center / 74%	**Mercury City Tower** / 80%	**Tianjin World Financial Center** / 72%	**Golden Eagle Tiandi Tower B** / 65%
			
Typical floor	Low-rise floor	Typical floor	Typical floor
Salesforce Tower / 72%	**53 West 53** / 82%	**New York Times Tower** / 75%	**Chongqing IFS T1** / 74%
			
Low-rise floor	Low-rise floor	Low-rise floor	Typical floor
MahaNakhon / 65%	**Bank of America Plaza** / 78%	**Shenzhen Bay Innovation and Technology Centre Tower 1** / 71%	**Ocean Heights** / 84%
			
Low-rise floor	Typical floor	Typical floor	Low-rise floor
Pearl River Tower / 79%	**Guangfa Securities Headquarters** / 74%	**The Shard** / %79	**Cayan Tower** / 83%
			
Typical floor	Low-rise floor	Low-rise floor	Typical floor

Building name / Space efficiency			
Kingdom Centre / 78%	**Shimao Riverside Block D2b** / 73%	**Aspire Tower** / 72%	**Golden Eagle Tiandi Tower C** / 75%
			
Typical floor	Ground floor	Low-rise floor	Typical floor
Space efficiency*: calculated as the ratio of the net floor area [obtained by subtracting the service core (the pink area on the floor plan) and structural elements from GFA] to GFA.			

AUTOBIOGRAPHICAL SKETCHES

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