buildings

MDPI

Article

Space Efficiency in Tapered Super-Tall Towers

Hüseyin Emre Ilgın

School of Architecture, Faculty of Built Environment, Tampere University, P.O. Box 600, FI-33014 Tampere, Finland; emre.ilgin@tuni.fi

Abstract: In modern skyscraper architecture, the preference for incorporating tapered building configurations is on the rise, constituting a prominent trend in the industry, particularly due to their structural and aerodynamic benefits. The efficient utilization of space is a critical consideration in the design of tapered skyscrapers, holding significant importance for sustainability. Nevertheless, the existing body of scholarly work falls short in providing an all-encompassing investigation into the space efficiency of super-tall towers featuring tapered configurations, despite their prevalent adoption. This research endeavors to rectify this notable void by undertaking an exhaustive examination of data derived from 40 case studies. The key findings are as follows: (1) average space efficiency was about 72%, with values fluctuating between a minimum of 55% and a maximum of 84%; (2) average ratio of core area to the gross floor area (GFA) registered about 26%, encompassing a spectrum ranging from 11% to 38%; (3) most tapered skyscrapers employed a central core design, primarily tailored for mixed-use purposes; (4) an outriggered frame system was the prevailing structural system, while composite materials were the most commonly used structural materials; and (5) significant differences in the influence of function and load-bearing systems on the space efficiency of tapered towers were not observed. The author anticipates that these results will offer valuable direction, particularly to architectural designers, as they work towards advancing the sustainable development of tapered skyscrapers.

Keywords: super-tall tower; tapered skyscrapers; space efficiency; core area to the gross floor area; main architectural design considerations; main structural design considerations

check for updates

Citation: Ilgın, H.E. Space Efficiency in Tapered Super-Tall Towers. *Buildings* **2023**, *13*, 2819. https://doi.org/10.3390/buildings13112819

Received: 17 September 2023
Revised: 26 October 2023
Accepted: 9 November 2023
Published: 10 November 2023

1. Introduction

Skyscrapers represent remarkable human achievements and have been subject to intense scrutiny and criticism since their introduction in the late 19th century, initially in the United States [1]. Concerns have arisen regarding whether these towering structures are the results of sound economic decisions or merely fleeting symbols of social and economic value. As the 21st century began, the competition to construct the world's tallest skyscraper appeared endless [2]. The title passed from the Petronas Twin Towers, completed in 1998 (452 m), to Taipei 101 in 2004 (508 m), and then to Burj Khalifa in 2010 (828 m).

Since 2000, there has been a notable shift in the primary location for constructing skyscrapers, transitioning from North America to Asia [3]. According to annual reports published by the Council on Tall Buildings and Urban Habitat (CTBUH) between 2013 and 2018, China alone accounted for more than 50% of newly completed skyscrapers, defined as buildings exceeding 200 m in height, each year [4]. This surge in skyscraper construction in China began in the early 2000s, resulting in a substantial increase in their numbers. By the conclusion of 2018, China boasted a total of 545 skyscrapers, with the majority having been built in the past 10 to 20 years [5]. Currently, China, which boasts the largest quantity of tall buildings, possesses more than 3100 buildings exceeding a height of 150 m, surpassing 1000 buildings exceeding 200 m, and a total of 116 buildings that soar past the 300 m mark [6]. Following closely behind, the United States secures the second spot, with a notable count of 887 structures towering over 150 m, 242 of them extending past the 200 m mark, and 31 super-tall buildings within its skyline. Meanwhile, the United Arab Emirates is in close pursuit, with a total of 331 buildings exceeding the 150 m threshold, 150 of them surpassing 200 m, and 33 towers that exceed a height of 300 m [6].

As a result of the ongoing urbanization and advancements in technology, the global count of tall and super-tall buildings is experiencing exponential growth [7]. Initially, during the early stages of tall building construction, designs were straightforward, and most tall buildings adhered to conventional configurations such as squares and rectangular prisms [8]. However, more recent tall structures have adopted a variety of unconventional forms, including tapering, setbacks, and twisted designs [9,10], as in the One World Trade Center, a 99-story, 541 m-high tower with a tapered shape, and the Lakhta Center, an 87-story, 462 m-high skyscraper featuring both tapering and twisting elements.

The use of a tapered form in skyscrapers offers several advantages, making it an attractive architectural and engineering choice [11,12]. Some of these advantages include:

a. Enhanced aesthetics: Tapered skyscrapers often feature a striking and iconic design, which can become a distinctive landmark in a city's skyline. The narrowing profile towards the top creates a visually appealing and dynamic structure.
b. Maximizing views: Tapered designs allow for larger and unobstructed views from upper floors. This can be particularly advantageous in urban settings with scenic surroundings or where panoramic views are a key selling point, such as residential or hotel buildings.
c. Natural lighting: Tapered buildings can optimize natural lighting by reducing shadowing effects on neighboring structures. This can enhance the quality of indoor spaces, reduce the need for artificial lighting, and contribute to energy efficiency.
d. Wind resistance: Tapered forms are aerodynamically efficient and can minimize wind loads on the building. This can lead to improved structural stability, reduced sway, and a more comfortable experience for occupants.
e. Structural efficiency: Tapered designs can allow for a reduction in structural materials and weight towards the top of the building. This can result in cost savings during construction and a more efficient use of materials.
f. Iconic landmarks: Tapered skyscrapers often become iconic landmarks that contribute to a city's identity and tourism appeal. They can serve as symbols of innovation and progress.
g. Flexibility in use: Tapered designs can accommodate various uses within a single structure, such as commercial, residential, and mixed-use spaces, allowing for greater flexibility in urban planning.

The concept of space efficiency within the context of super-tall towers is multifaceted, encompassing the optimization of usable floor area, the allocation of core space, and the selection of structural systems and materials [13]. Therefore, analyzing the spatial efficiency in tall buildings is of paramount importance for a multitude of rationales, which are as follows:

a. Limited land resources: Space efficiency becomes vital as urban areas face limited available land for development. Tall buildings allow for the vertical expansion of a city, which conserves valuable land resources. This approach optimizes land use and minimizes urban sprawl, helping to reduce environmental impact and maintain green spaces.
b. Infrastructure optimization: Tall buildings enable the efficient use of infrastructure, such as water supply, sewage systems, and transportation networks. Concentrating people and activities in a smaller area reduces the per capita burden on these systems and minimizes resource consumption, resulting in saved costs and environmental benefits.

c. Energy Efficiency: Efficient space design in tall buildings can lead to significant energy savings. For instance, compact designs reduce heat loss and gain, which is essential for temperature control and energy efficiency. Well-designed tall buildings can have lower energy consumption per capita compared to sprawled low-rise alternatives.
d. Sustainable building practices: Space efficiency in tall buildings often goes hand-in-hand with sustainable design practices. This includes incorporating green building technologies, materials, and energy-efficient systems, which are scientifically proven to reduce environmental impacts and contribute to a sustainable urban environment.
e. Economic considerations: Efficient space use in tall buildings can lead to higher property values, rental yields, and a better return on investment. This is backed by economic analyses and research that demonstrate the economic advantages of space-efficient designs, attracting developers and investors.

There is a notable dearth of scientific exploration regarding the space efficiency of tall and super-tall buildings. Existing research predominantly focuses on their utilitarian aspects or their architectural composition (please see the Literature survey). Remarkably, a conspicuous void exists within scholarly investigations when it comes to conducting a comprehensive examination of space efficiency in tapered configurations, which are the predominant design in super-tall towers. The primary goal of this research initiative is to bridge this substantial gap in the contemporary academic literature.

This paper conducted an extensive analysis of 40 case study towers, detailed in Appendices A–C, with meticulous consideration of their functional characteristics, structural systems, and materials utilized. Although sustainable planning aspects such as energy consumption were omitted from the analysis due to insufficient data for all the towers, the primary focus of this research centers on space efficiency.

It is important to emphasize that the primary criterion for selecting these specific buildings for the study was the availability of crucial data, including floor plans, core type, structural system, and building materials. Significantly, the aftermath of the tragic events surrounding the World Trade Center incident in the United States on 11 September 2001 has considerably impeded data collection efforts due to heightened security concerns in skyscraper-related research.

The findings of this research endeavor are anticipated to provide valuable insights not only to architects, engineers, and urban planners, but also to investors and stakeholders engaged in the development of these iconic vertical tapered structures. Moreover, the outcomes of this study hold the potential to inform future design paradigms, setting the stage for the creation of more efficient, sustainable, and visually captivating urban environments.

The following sections were structured in the subsequent sequence. Firstly, a thorough review of the existing scholarly literature within the field was performed. Next, the research methodology employed in the study was elucidated, and the resulting outcomes were explicated. This was succeeded by an investigation into 40 case studies, which provided pertinent insights into the key attributes and space efficiency considerations of these noteworthy examples. Finally, a conclusion was formulated as well as potential future research avenues and the limitations of this study.

2. Literature Survey

The scientific literature lacks extensive research efforts aimed at fully understanding the complexities of space efficiency in the context of tall structures. Previous studies in this field have been limited in their focus, typically scrutinizing only a small subset of tall buildings.

Tuure and Ilgın [14] conducted an analysis using data gathered from 55 mid-rise wooden residential structures in Finland. The primary findings can be summarized as follows. 1. Among the examined case study samples, space efficiency ranged from approximately 78% to 88%, with an average of 83%. 2. The construction systems and materials of shear walls did not exhibit significant variations concerning space efficiency. Moreover, there was no scientifically discernible correlation between the number of floors and space efficiency. 3. The highest average space efficiency was achieved when employing a central core architectural typology.

In a study conducted by Okbaz and Sev [15], they embarked on an examination involving 11 office towers with freeform designs, with the objective of shedding light on the concept of space efficiency. Their extensive analysis considered multiple planning factors, including the layout of the service core and load-bearing elements. The results indicated that freeform structures displayed a reduced level in space efficiency in comparison to conical forms. This result emphasized the substantial impact of building form on space utilization, while the vertical spacing between floors was observed to have minimal influence.

Goessler and Kaluarachchi [16] conducted research to explore how smart technologies can impact compact urban residences, rendering them more versatile, adaptable, and tailored to individual needs. The investigation was grounded in the premise that the integration of adaptive housing design and smart technology has the potential to enhance efficiency and space utilization by two to threefold when contrasted with traditional apartment configurations. The findings indicated that the incorporation of smart and adaptable technology can enhance space efficiency by diminishing the necessity for distinct physical areas designated for various activities.

Ibrahimy et al. [17] examined the efficiency of space utilization in residential properties within Kabul City. The findings revealed that a significant proportion of residential buildings do not conform to the prescribed regulations and standards related to space utilization. This lack of compliance was primarily attributed to the insufficient emphasis on the interior design process and a failure to adhere to government-mandated construction guidelines. A substantial portion of the constructed structures displayed deficiencies in the proper implementation of architectural design principles.

Hamid et al. [18] conducted interviews with architectural firms with the objective of investigating the concept of space efficiency in 60 single-family residences in Sudan. They examined various factors, such as the placement of courtyards and the configuration of vertical circulation components. The findings revealed that positioning buildings at the corners of the land plot led to the most efficient use of space. Additionally, it was determined that the most advantageous location for vertical circulation elements was at the midpoint along the building edges.

In a different inquiry centered on the field of hotel construction, Suga [19] delved into the sphere of space efficiency. The research highlighted the favorable influence of space-efficient design in hotel developments, with specific attention directed toward the efficient layout of communal spaces in relation to the dimensions of guest accommodations.

Ilgın [20] conducted an examination of core design and space efficiency in modern super-tall office buildings, drawing insights from a selection of ten case study towers to explore critical determinants of the service core design's effects. The author acknowledged that contemporary service core design trends have been undergoing constant evolution, and the study provides crucial design principles that take into account these fluid trends.

Ilgın [21] initiated a research endeavor to investigate the notion of space efficiency in 44 office skyscrapers, considering vital architectural and structural planning elements. Concurrently, a parallel undertaking involved the assessment of space efficiency in 27 residential skyscrapers, incorporating analogous design criteria [22]. Furthermore, Ilgın [23] investigated the space efficiency of 64 towers featuring mixed-use functions. The combined results obtained from Ilgın's papers above revealed a prevalent inclination toward adopting a central core architectural typology, with outriggered frame systems emerging as frequently utilized load-bearing structures. Additionally, a significant inverse correlation between space efficiency and building height was identified.

Using regression analysis methodologies, Arslan Kılınç [24] examined the determinants impacting the design of service core and load-bearing systems in tall buildings with prismatic shapes. The research unveiled a connection between the height of the building and the allocation of greater spaces for both the structural system and the service core. Nevertheless, no substantial scientific or technical association was established between space efficiency and the choice of construction materials.

Von Both [25] introduced an approach designed for the initial planning stages, rooted in stakeholder analysis. This approach aids in the delineation of process-related user functions and well-defined functional interconnections. It actively prompts the planner to contemplate potential enhancements in terms of area and space efficiency. Furthermore, it enables the translation of the topological function structure into a floor plan concept that optimizes space usage. A prototype of this method was showcased as a web-based tool, which facilitates a participatory planning process involving users and stakeholders.

Höjer and Mjörnell [26] initiated a discourse on the impact of digitalization on the dynamics of interior space demand and supply within pre-existing structures. The discussion also delves into how policy measures can be instrumental in promoting more resource-efficient utilization of space. Drawing from the concepts promoting adaptable utilization of digitally enabled building spaces and innovative measurement techniques, a four-stage construction guideline is suggested: the initial phase involves diminishing the space requisites; the subsequent step entails optimizing the utilization of already available space; the third stage focuses on the renovation and adaptation of existing structures to meet contemporary requirements; and the final phase centers on the creation of new buildings.

Zhang et al. [27] suggested an approach for designing a free-form structure in cold regions of China, aiming to enhance solar radiation absorption through space use optimization employing a multi-objective genetic algorithm. The results revealed that, in contrast to the reference building with a cube-shaped design, the optimized free-form structure experiences a notable increase in total solar radiation gain, ranging from 30% to 53%. Simultaneously, the shape coefficient value decreases by 15% to 20%, while the reduction in space-efficiency values remains under 5%.

Nam and Shim [28] focused their research endeavors on the investigation of space efficiency in high-rise buildings, particularly concerning corner forms and lease spans. The study determined that square-cut corner forms adversely affected space efficiency. In contrast, lease spans played a significant role in space efficiency, while corner cuts were observed to have a minimal impact.

Sev and Özgen [29] undertook an exploration of spatial efficiency with a specific focus on ten tall office buildings. Their examination encompassed various factors, including structural materials, core configurations, floor-to-floor heights, and lease spans. The results emphasized the significance of core arrangement and load-bearing systems in attaining the highest level of spatial efficiency. Core planning strategies displayed significant divergences contingent upon occupant needs, with the central core design emerging as the preferred approach for tall office developments.

Saari et al. [30] analyzed the interaction between space efficiency and the overall cost of tall office structures. Their results revealed a noteworthy impact of improved space efficiency in achieving the desired standards of indoor climate comfort.

Finally, Kim and Elnimeiri [31] performed an evaluation of space efficiency ratios within a set of 10 mixed-use tall buildings. They emphasized the critical role played by elevator optimization methods and the strategic allocation of functional zones in enhancing space efficiency. Additionally, they underscored the profound importance of integrating building design and load-bearing systems as fundamental elements that contribute significantly to improving space efficiency.

Based on the literature review presented earlier, it is evident that there is a lack of scientific inquiry into the space efficiency of tall and super-tall buildings. Most existing studies primarily concentrate on their functional aspects (for example, as demonstrated by [21]) or their architectural design (as seen in the work of [15]). Notably, there is an evident void in scholarly investigations when it comes to conducting comprehensive research on space efficiency in skyscrapers with a tapered form, which is the prevailing form in the design of super-tall towers. The main objective of this research endeavor is to address this significant gap in the current academic literature.

In this context, the subsequent section presents research methodologies centered on case studies, which specifically examine architectural and structural design factors and their relationship with space efficiency. The research is based on a dataset comprising 40 skyscrapers with tapered forms (refer to Appendices A–C).

3. Method

To investigate the concept of space efficiency in tapered super-tall towers, a case study methodology was adopted, drawing inspiration from established practices in the assessment of built-environment projects. This approach, widely endorsed within the scientific community, enables the collection of both quantitative and qualitative data, facilitating a comprehensive analysis of the subject matter [32]. A rigorous selection process resulted in the inclusion of a total of 40 super-tall towers characterized by tapered forms, each of which underwent a thorough examination.

The chosen sample for this study was geographically diverse, encompassing 28 towers in Asia (with 25 situated in China), seven towers in the United States, two towers in the Middle East, and one tower each in Russia, Chile, and UK (as detailed in Appendix A). Extensive information regarding each case was diligently documented and can be referenced in Appendix B.

The author at times utilized publicly available data and alternatively collaborated with architectural and structural design companies of tapered super-tall towers within the research cohort to obtain architectural and structural PDF drawings. After acquiring these design documents, the PDF drawings were processed using AutoCAD 2023 (24.2) software to transform them into a vector format and independently generate floor plans and assess the space efficiency of the selected case study towers. This approach facilitated precise measurements of the towers' dimensions and their structural elements.

It is worth noting that AutoCAD software [33] stands out as an exceptionally robust choice for my primary goal of converting PDFs to vector formats and meticulously crafting 2D floor plans. Its prowess in vectorization is exemplified by its capacity to seamlessly import PDFs as underlays or even employ specialized raster-to-vector conversion tools for precise transformation of scanned images into editable vector entities, making it ideal for working with existing designs. The software's strength lies in its customization capabilities, facilitating the creation of tailor-made templates, thereby ensuring adherence to specific drafting standards and preferences. This comprehensive toolset is underpinned by a versatile text and annotation system with multi-line text support, further enhancing the clarity and detail of floor plans. Additionally, AutoCAD facilitates easy output, offering a plethora of plotting and printing options as well as support for various export formats, including DWG and PDF, enhancing the sharing and distribution of finalized floor plans with collaborators and stakeholders.

In a thorough undertaking, the researcher meticulously examined the floor plans of a diverse array of tapered super-tall towers, encompassing low-rise and ground floors. This rigorous approach ensured the acquisition of reliable and precise data, forming a robust basis for the evaluation of space efficiency within the sample group. It is crucial to emphasize that super-tall towers that did not provide adequate and accessible data regarding space efficiency or floor plans were purposefully omitted from the case study selection.

The foremost design considerations that impact space efficiency include the following.

- Concerning architectural design considerations:
  - Core planning influences the arrangement of vertical circulation and, in specific instances, the distribution of shafts;
  - Building form impacts the dimensions and configuration of floor slabs.
- Concerning structural design considerations:
  - Structural system influences the layout and dimensions of structural components, and;
  - Structural material affects the size of structural elements.

Furthermore, the building's function has a pronounced impact on architectural and structural design parameters.

Core planning categorization proposed by [34] was embraced for its broader framework, encompassing the subsequent classifications: (1) central core, (2) atrium core, (3) external core, and (4) peripheral core.

Considering its comprehensive scope, the research encompassed various building form arrangements [35], as depicted in Figure 1:

a. Prismatic configurations refer to buildings characterized by symmetrical and parallel shapes at both ends, featuring identical sides and vertical axes perfectly aligned orthogonally to the ground. This arrangement guarantees that the building preserves uniform geometric proportions across its entirety.
b. Setback configurations refer to buildings with horizontally indented segments positioned at different elevations along the vertical axis of the edifice. These recessed portions generate distinct terraces within the structure, leading to a tiered or cascading visual effect. The intent behind setback designs is to introduce visual diversity, augment architectural aesthetics, and offer functional advantages like enhanced exposure to natural light and improved vistas.
c. Tapered configurations refer to buildings that display a gradual reduction in their floor plans and surface areas as they rise vertically. This phenomenon gives rise to either linear or non-linear profiles, where the building's dimensions and proportions progressively decrease towards the upper levels. The utilization of tapered forms aims to craft a visually dynamic and aesthetically pleasing structure, departing from a monolithic or uniform appearance. This design strategy enables variations in scale, enriches architectural character, and may provide functional benefits like enhanced structural performance.
d. Twisted configurations refer to buildings that undergo a gradual rotation or torsion of their floors or façades as they ascend along a central axis. This rotation occurs progressively, resulting in a twisted or spiraling effect that imparts a sense of dynamism and visual fascination to the edifice. The degree of rotation between each floor or façade element, known as the twist angle, is employed to achieve the intended architectural expression. The application of twisted forms enables the creation of distinctive building profiles, enhancing aesthetic allure and setting the structure apart from its surroundings.
e. Leaning/tilted configurations refer to buildings characterized by an inclined layout. These structures deviate from the conventional vertical orientation and intentionally feature a tilt in their design. This inclination can be achieved through various architectural techniques, including cantilevering. The deliberate leaning imparts a distinctive visual allure and dynamic presence to the edifice, introducing a sense of movement and asymmetry. Leaning forms offer architectural designers the chance to craft visually captivating structures that challenge the conventions of verticality.

f. Freeform designs are born through the application of transformative operations on geometrically fundamental elements, such as lines or volumes. These operations encompass a sequence of manipulations and alterations orchestrated by the architect, culminating in a final form that diverges from the established categories mentioned earlier. The creative journey involved in shaping freeform architecture may lack well-defined and preconceived sequences, as it involves a more exploratory approach. The resultant form often embodies an essence of unpredictability and uniqueness that sets it apart from conventional architectural classifications. The absence of explicit guidelines or predefined frameworks empowers architects to push the boundaries of design and venture into unexplored realms, giving rise to unconventional architectural expressions.

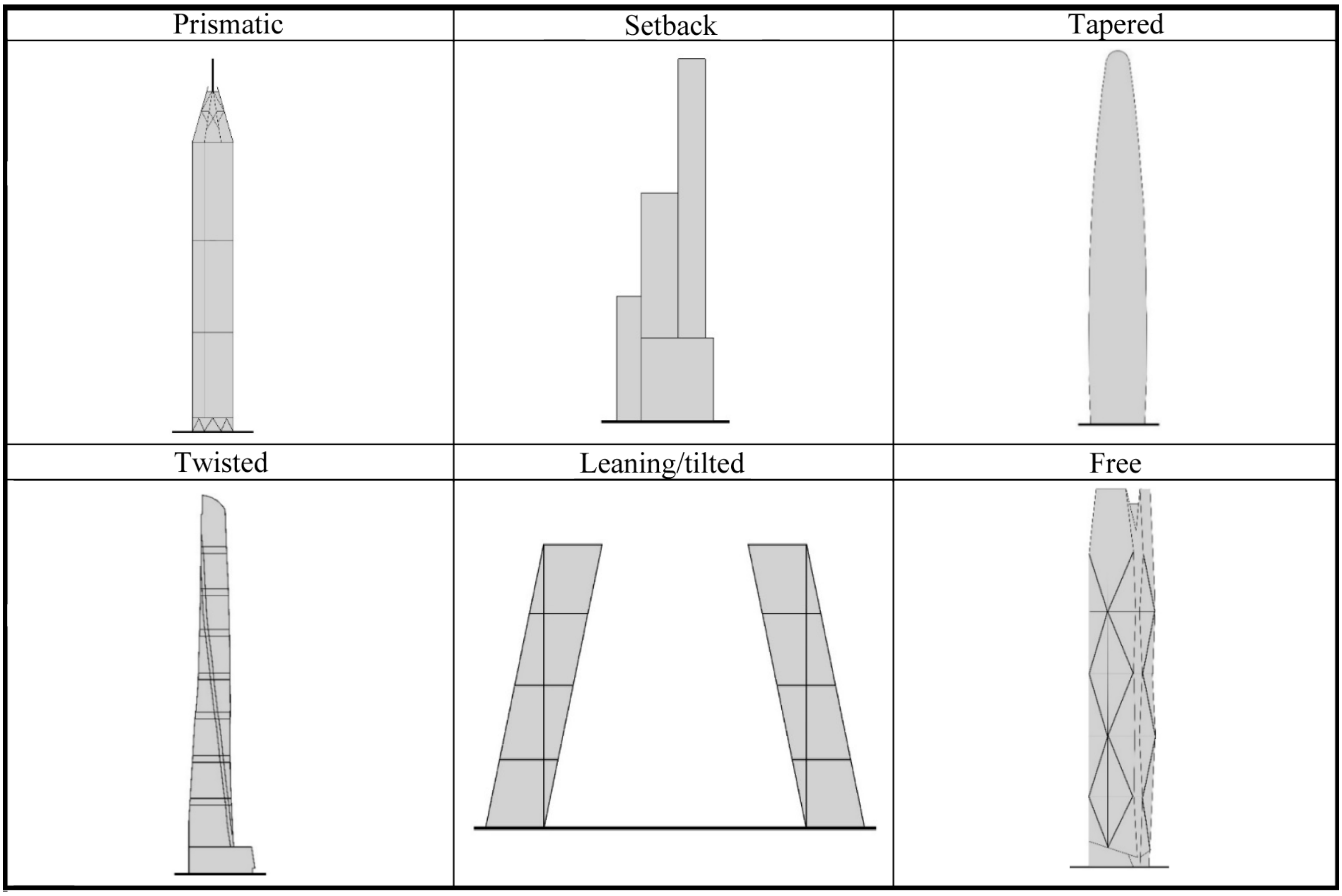


Figure 1. Super-tall building forms (figure by author).

The choice of a structural system holds significant importance for optimizing space efficiency in tapered super-tall developments, as it directly influences the arrangement and dimensions of structural components. Given its more comprehensive nature compared to existing categorizations of load-bearing systems (e.g., [36]), the categorization proposed by [37] for super-tall buildings was employed in this study. The schematic representation and definitions of the structural systems used in super-tall buildings can be found in Figure 2.

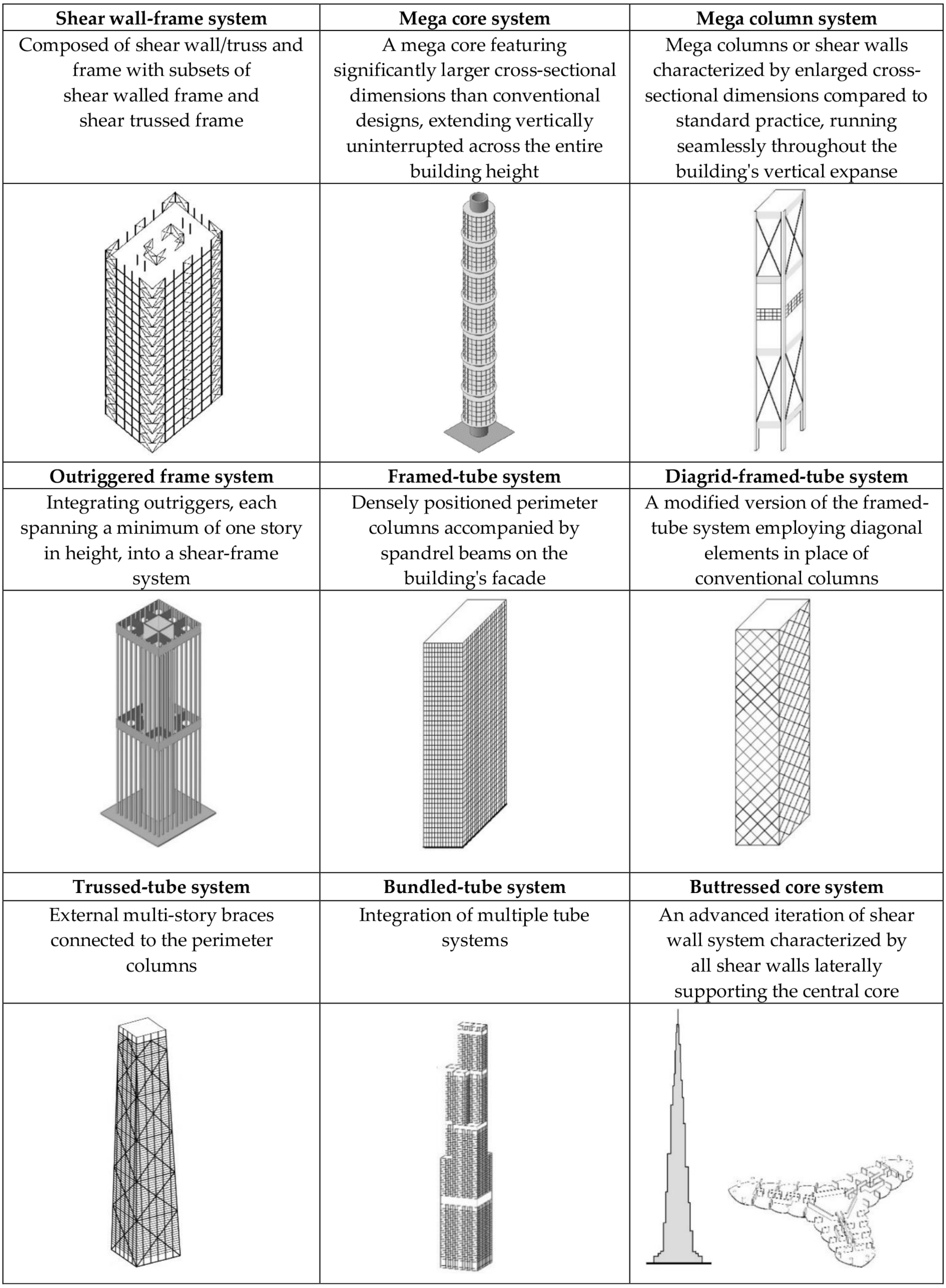


Figure 2. Super-tall building structural systems (figure by author).

It is important to highlight the potential to employ more eco-friendly structural options in tall buildings, such as constructions that blend reinforced concrete (RC) and masonry materials [38]. Here are some key aspects:

1. Sustainable Materials: Masonry, such as bricks or concrete blocks, is a sustainable building material with a low-carbon footprint. When combined with RC, which provides structural strength, you can create a building that relies on materials with a reduced environmental impact.
2. Energy Efficiency: Masonry provides good thermal mass, which can help regulate indoor temperatures. This reduces the need for extensive heating and cooling, resulting in lower energy consumption and costs over the building's lifespan.
3. Reduced Carbon Footprint: Mixing masonry with RC can lead to a reduction in the carbon emissions associated with the construction process. Masonry materials are often locally sourced and require less energy to produce compared to steel or other structural materials.
4. Aesthetic Versatility: Masonry offers various architectural possibilities, allowing for the creation of visually appealing buildings that can blend well with their surroundings. This is especially important in urban areas with a mix of historic and modern architecture.
5. Seismic Performance: RC-masonry mixed buildings can offer good seismic resistance. Masonry can dissipate energy during an earthquake, reducing the structural damage compared to more rigid materials.

As mentioned above, since structural materials exert influence on the dimensions of structural elements, they represent a vital factor impacting spatial efficiency. These materials can be categorized into three main groups: (i) steel, (ii) reinforced concrete, and (iii) composite. Considering the primary structural components to be columns, beams, shear trusses (braces), shear walls, and outriggers, and excluding floor slabs, this research employs the term 'composite' to describe buildings in which certain structural elements are constructed using reinforced concrete, while other structural elements are composed of steel (based on the type of structural member). Alternatively, it refers to structures where some structural elements consist of both structural steel and concrete concurrently (based on the cross-sectional composition), or a combination thereof.

The establishment of precise criterion for determining the specific number of stories or heights that characterize a structure as a super-tall tower remains a subject of discussion among the scientific community, as there is no universally accepted definition in this regard. However, in this research, the classification of a structure as a super-tall tower adheres to the criteria outlined by the CTBUH database, which designates a super-tall structure as one that measures 300 m or more in height [6].

Space efficiency pertains to the correlation between the net floor area (NFA) and GFA. It carries substantial significance, especially for investors, as it involves the optimization of usable space within floor plans to achieve maximum returns on investment. The level of space efficiency is chiefly influenced by a range of factors, including the selection of load-bearing systems and construction materials, the architectural form, and the layout of floor slabs. Furthermore, the concept of space efficiency plays a pivotal role in determining lease spans, which refer to the measurement of the distance between fixed internal elements like service core walls and external components such as windows. This factor directly impacts the efficient utilization of space within a given structure.

4. Findings

In this section, main architectural design considerations, such as function and core typology, main structural design considerations, encompassing the structural system and choice of structural materials, and space efficiency aspect, with its interconnected relationship to various design parameters, all within the context of tapered super-tall towers, are presented.

4.1. Main Architectural Design Considerations: Function and Core Typology

Concerning the intended functions of the skyscrapers, the examined set of case studies predominantly comprised mixed-use and office developments, encompassing over 90% of the total. Residential usage constituted roughly 7% of the overall occupancy, as illustrated in Figure 3. The significant presence of mixed-use towers can be attributed to the strategic adoption of vertical communities as a response to the challenges presented by population growth and urban expansion. The inclination towards mixed-use functionality has obtained even more prominence, especially during market fluctuations, as it facilitates improved rental profitability and broadens the customer base [39]. Furthermore, enhancing the design of multi-functional super-tall buildings by accommodating various functions with different lease spans could enhance the architectural appeal of tapered forms. For example, office spaces, which require larger spans compared to residential or hotel areas, can be situated on lower levels, taking advantage of the tapered structure to provide these larger spans. In contrast, the need for office towers can be ascribed to the concentration of commercial activity zones, driven by the continuing process of urbanization worldwide.

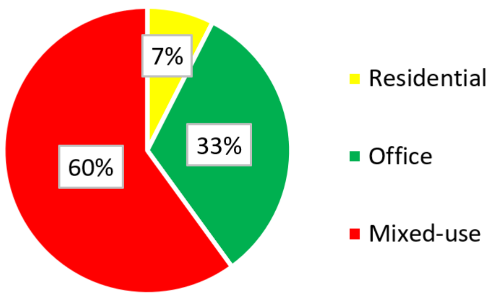


Figure 3. Tapered super-tall towers by function (figure by author).

Among the various design options explored for these buildings, central core strategy was the most employed selection in tapered super-tall towers. The widespread adoption of the central core method can be credited to its compact and effective structural design, which confers notable advantages in terms of bolstering overall structural robustness and facilitating streamlined fire escape scenarios, as detailed by [40]. Additionally, the central core's dual functions of providing stiffness and stability are integral to the overall earthquake resistance of super-tall buildings [41]. Its rigidity and ability to withstand lateral forces ensure that the building remains upright and maintains its structural integrity. Moreover, the core's capacity to evenly distribute forces throughout the building helps prevent localized damage and allows the entire structure to effectively endure seismic events. These critical attributes are essential for ensuring the safety of occupants and minimizing structural damage in earthquake-prone regions. On the other hand, the low occurrence of external and peripheral cores can be attributed to the increased length of circulation routes they create, resulting in longer fire evacuation paths [42].

4.2. Main Structural Design Considerations: Structural System and Structural Material

Upon examining the visual depiction depicted in Figure 4, it becomes evident that outriggered frame systems have garnered predominant favor, constituting the choice in 70% of cases. Tube systems make up a relatively smaller fraction, accounting for 20%. The overarching preference for outriggered frame systems can be ascribed to their intrinsic ability to provide a certain degree of flexibility in positioning the exterior columns. Consequently, architects benefit from greater design freedom when shaping the building envelope, especially in terms of creating unobstructed views to the outside. This expanded design latitude, in turn, fosters the exploration of increased height possibilities, rendering the outriggered frame system an appealing selection for constructing tapered skyscrapers.

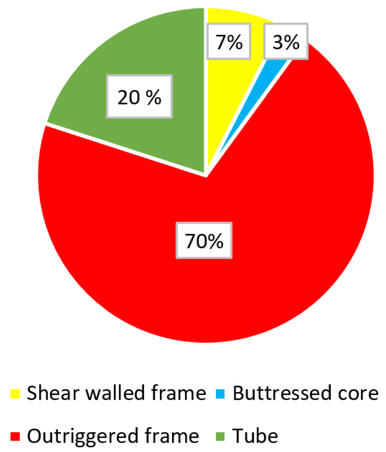


Figure 4. Tapered super-tall towers by structural system (figure by author).

As illustrated in Figure 5, most of the examined case studies predominantly employed composite construction, accounting for a dominant share of over 80%. Reinforced concrete (RC) construction followed, constituting approximately 10% of the total proportion. The widespread use of composite construction in tapered super-tall towers can be rationalized by considering the favorable amalgamation of steel's high tensile strength and concrete's compressive strength, in addition to the fire resistance and damping properties inherent in concrete [43]. These combined factors collectively contribute to the popularity of composite construction as a viable option for meeting the structural demands of tapered super-tall towers.

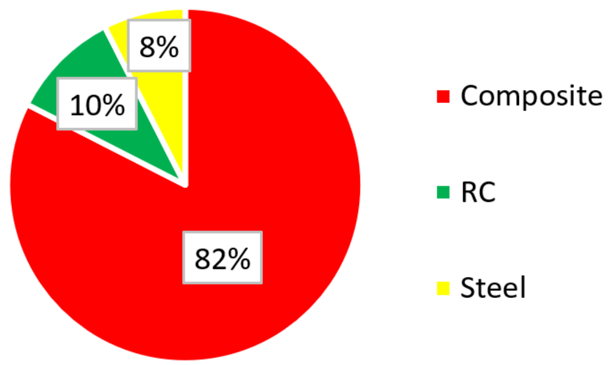


Figure 5. Tapered super-tall towers by structural material (figure by author).

4.3. Space Efficiency in Tapered Super-Tall Towers

The suggested space efficiency threshold for tall towers, as advocated by Yeang [44], could be set at 75%. In Ilgın's research [21], concerning tall office buildings, it was established that the mean space efficiency and core-to-gross floor area ratio were 71% and 26%, respectively. The range of values spanned from a minimum of 63% and 15% to a maximum of 82% and 36%, respectively.

Likewise, in Ilgın's investigation of residential towers [22], it was determined that the mean space efficiency and core-to-gross floor area ratio were 76% and 19%, respectively. The range of values encompassed a minimum of 56% and 11% to a maximum of 84% and 36%, respectively. In Ilgın's article [23] concentrating on mixed-use super-tall buildings, it was determined that the mean space efficiency and core-to-gross floor area ratio were 71% and 26%, respectively. The range of values extended from a minimum of 55% and 16% to a maximum of 84% and 38%, respectively.

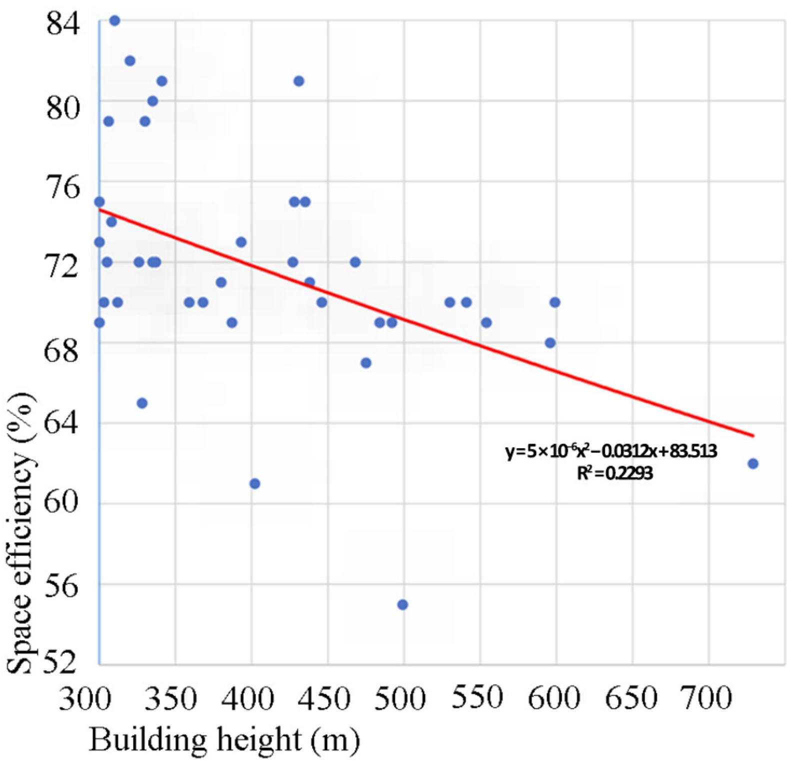
In this paper, through the examination of 40 tapered super-tall towers, the mean space efficiency and core-to-gross floor area ratio were computed at about 72% and 26%, respectively. The range of values spanned from a minimum of 55% and 11% to a maximum of 84% and 38%, respectively, as depicted in Appendix C.

4.3.1. Interrelation of Space Efficiency and Building Height

In the pursuit of creating sustainable and efficient urban environments, the design and construction of skyscrapers have become a focal point of architectural and engineering innovation. Among the myriad factors influencing the form and function of these towering structures, the interplay between space efficiency and building height stands as a crucial determinant.

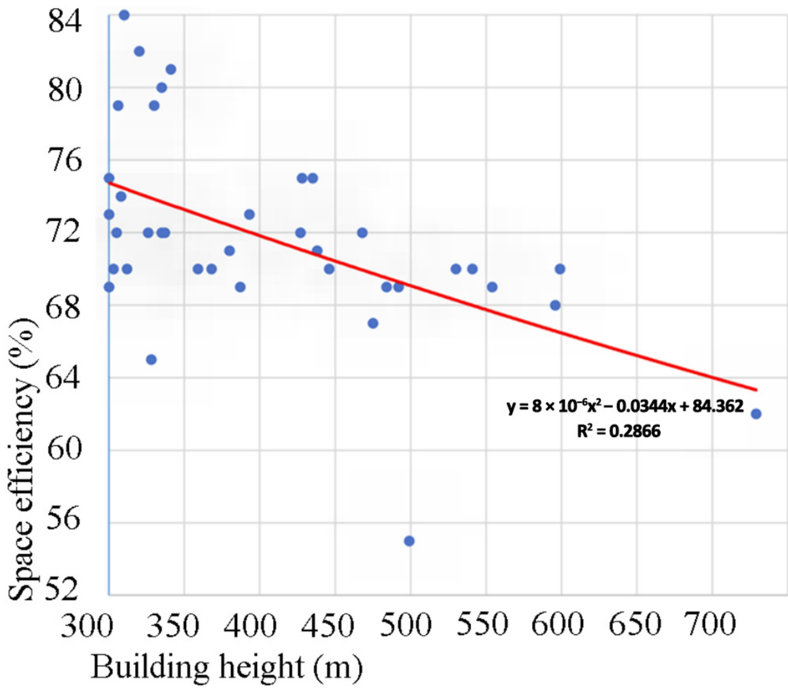
Within this context, Figure 6a,b illustrate the relationship between space efficiency and the height of tapered skyscrapers. The data points in these figures represent the tapered skyscrapers investigated in the case study. In order to analyse the correlations within the dataset, a polynomial regression methodology was employed. This choice was made based on its capacity to provide a more accurate R-square correlation coefficient compared to linear or exponential regression approaches. The observation that the Guangxi China Resources Tower and Chongqing Tall Tower cases were remarkable outliers was noteworthy, exhibiting space efficiency at 61% and 81%, and a core to GFA ratio at 38% and 17%, respectively.

The influence of these outliers on the regression line can be visualized in Figure 6b. As depicted by the trendline in Figure 6a, there is a tendency for space efficiency to decrease as building height increases. Furthermore, when we remove the outliers, the declining trend becomes more pronounced, as illustrated in Figure 6b. This decline can be attributed to the phenomenon where as skyscrapers increase in height, the dimensions of the central core and load-bearing elements expand, making it more challenging to achieve higher space efficiency ratios.



(**a**)

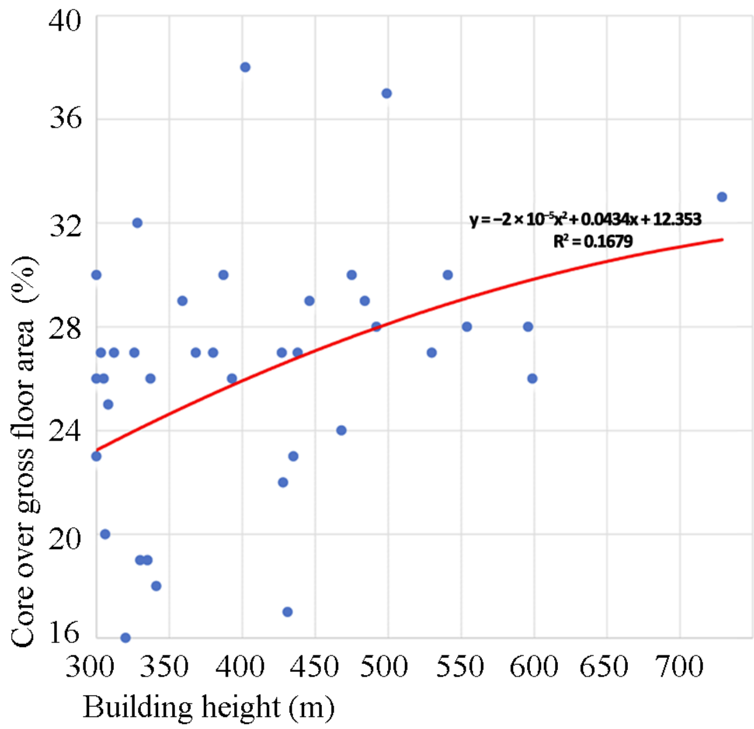
Figure 6. *Cont.*



(**b**)

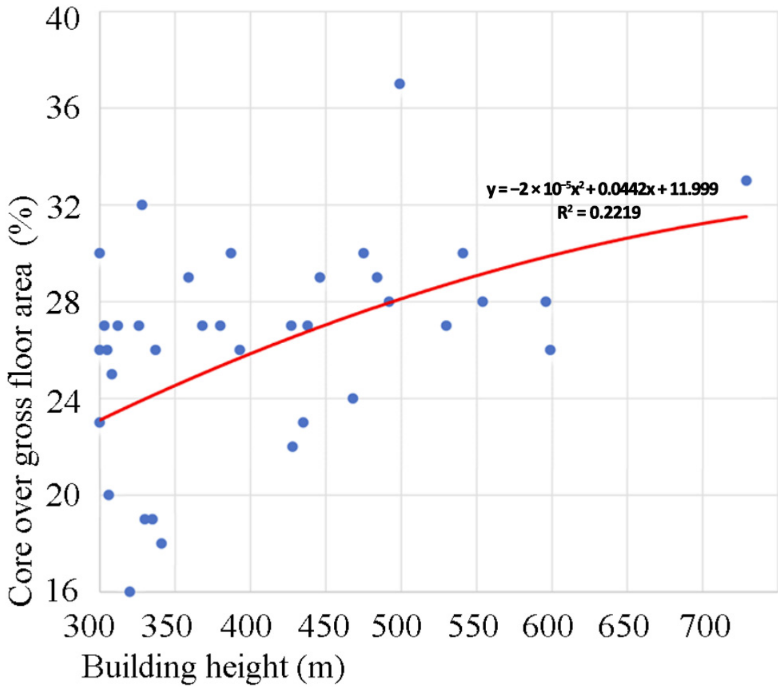
Figure 6. The interrelationship between space efficiency and height: (**a**) including outliers, (**b**) excluding outliers (figure by author).

Figure 7a,b provide further insight into the relationship between the core-to-GFA ratio and the height of the tower. This reinforces the earlier observation that there is an increasing need for larger service cores as the tower's height increases. Similar to the scenario in Figure 6b, the removal of outliers accentuates a more pronounced upward trend, as demonstrated in Figure 7b.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. The interrelationship between core over GFA and height: (**a**) including outliers, (**b**) excluding outliers (figure by author).

4.3.2. Interrelation of Space Efficiency and Function

Figure 8 presents a visual summary of data concerning tapered skyscrapers, particularly emphasizing their various functions. The graph displays bars on the right-hand side, which depict the cumulative quantity of these buildings. These bars are categorized according to their functional types. Additionally, the chart incorporates blue dots to represent the space efficiency of these skyscrapers for each specific function. In contrast, red dots are employed to emphasize the tapered skyscraper with the highest level of space efficiency in each respective function category. Moreover, the black bar in the graph serves as a graphical representation of the count of super-tall buildings within the sample set that shares the same function. This data not only provides insights into the prevalence of tapered skyscrapers, but also elucidates how different functions influence their space efficiency, with a particular focus on the most efficient instances.

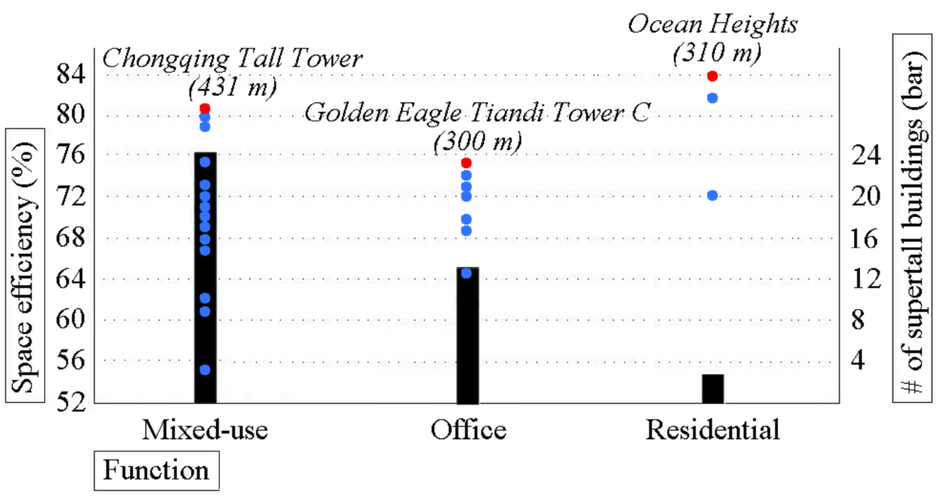


Figure 8. The interrelationship between space efficiency and function (figure by author).

In the context of functions employed in tapered skyscrapers, mixed-use has emerged as the dominant choice, with 24 cases falling into this category. These towers demonstrated space efficiency ranging from 55% to 81%, with an average of approximately 72%. Meanwhile, skyscrapers designated for office functions, a total of 13, displayed space efficiency spanning from 65% to 75%, with an average of about 72%. In contrast, residential use was significantly less prevalent, being employed in only three towers, with an average space efficiency of 75%.

The average space efficiency does not exhibit any variation between mixed-use and office development. Considering the infrequent use of residential functions in tapered skyscrapers, it appears improbable to establish a statistically significant correlation between the spatial efficiency of these towers and their accommodated functions.

4.3.3. Interrelation of Space Efficiency and Structural System

Figure 9 provides a visual summary of data related to tapered skyscrapers, focusing on their structural systems. The graph shows bars on the right side, which represent the cumulative number of these buildings. These bars are categorized based on the types of load-bearing systems including outriggered frame, tube, shear walled frame and buttressed core systems. The chart also includes blue dots that signify the space efficiency of these skyscrapers for each specific load-bearing system. In contrast, red dots are used to highlight the tapered skyscraper with the highest level of space efficiency achieved within each corresponding structural system. Furthermore, the black bar in the graph is a visual representation of the count of super-tall buildings within the sample set that utilizes the same structural system. This information helps us understand not only the prevalence of tapered skyscrapers, but also how different load-bearing systems impact their space efficiency, with a focus on the most efficient examples.

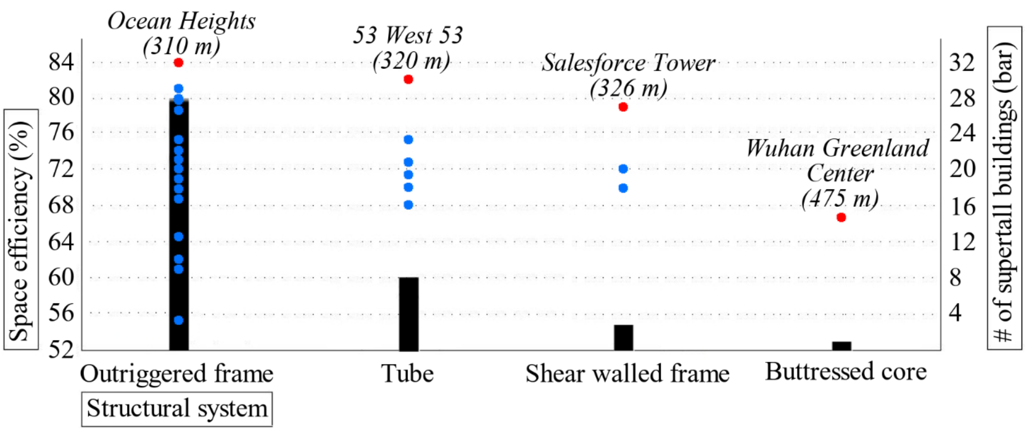


Figure 9. The interrelationship between space efficiency and structural system (figure by author).

Within the domain of load-bearing systems employed in tapered skyscrapers, outriggered frame systems emerged as the prevailing selection with 28 towers. These towers demonstrated space efficiency ranging from 55% to 84%, with an average of approximately 71%. Conversely, shear walled frame and buttressed core systems were notably less common, being utilized in only four towers. Skyscrapers constructed with tube systems, totalling eight in number, exhibited space efficiency ranging from 68% to 82%, with an average of around 72%.

The subtle variations in space efficiency that manifest across diverse load-bearing systems within tapered skyscrapers can be attributed to the exceptional performance of outriggered frame and tube systems. These two structural systems have earned widespread acclaim within the industry due to their well-documented effectiveness in handling the structural loads placed upon skyscrapers. Their adoption and recognition have been driven by their demonstrated ability to efficiently distribute and manage the forces and stresses encountered by such tall and complex structures, ensuring stability and safety in high-rise buildings.

The infrequent utilization of shear walled frame and buttressed core systems further complicates the task of establishing a robust and scientifically significant correlation. Therefore, while it is reasonable to infer that structural systems do influence space efficiency to some extent, the lack of the number of case studies and consistent implementation of alternative systems makes it challenging to draw definitive conclusions about their impact.

4.3.4. Interrelation of Space Efficiency and Structural Material

Figure 10 provides a visual summary of data related to tapered skyscrapers, focusing on their structural materials. The graph features bars on the right side, which represent the cumulative number of these buildings. These bars are categorized based on the specific structural materials they are constructed with. Within this graphical representation, one can also observe the presence of blue dots, serving as indicators of the spatial efficiency of these skyscrapers in relation to their specific structural materials. These blue dots help illustrate how different materials influence the space efficiency of these buildings. In contrast, red dots are used to highlight the most space-efficient tapered skyscraper achieved within each corresponding structural material category. Additionally, the black bar in the graph visually shows the count of super-tall buildings in the sample set that use the same structural material. This information provides insight into the prevalence of various structural materials in tapered skyscrapers and their impact on space efficiency, with a specific focus on the most efficient examples within each material category.

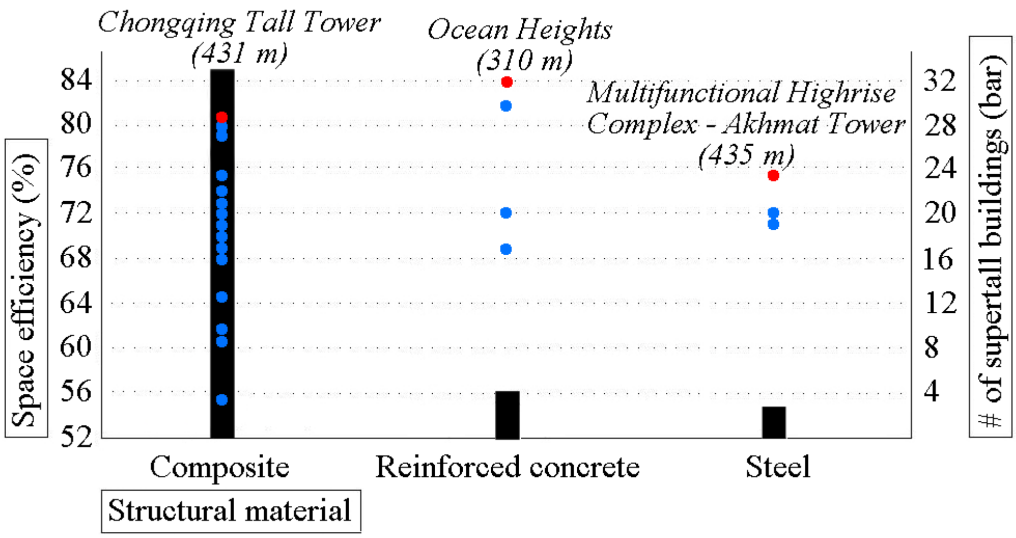


Figure 10. The interrelationship between space efficiency and structural material (figure by author).

In the context of materials used in tapered skyscrapers, composite construction has become the primary choice, with 33 towers embracing this approach. These towers have shown a space efficiency ranging from 61% to 81%, averaging at about 72%. On the other hand, reinforced concrete and steel construction were less popular, with only four and three towers employing these methods, respectively. Skyscrapers constructed with reinforced concrete achieved a space efficiency ranging from 69% to 84%, with an average of around 74%.

Given the relatively rare utilization of reinforced concrete and steel in the construction of tapered towers, it seems unlikely that one can establish a statistically substantial correlation between the spatial efficiency of these towers and the materials employed in their structural configurations.

5. Discussion

This paper centered its attention on scrutinizing space efficiency in tapered skyscrapers, involving an evaluation of 40 case study towers. The primary aim was to delve into the principal design parameters linked to both architectural and structural facets, which exert an influence on space efficiency. The results presented in this paper demonstrated both similarities and differences in comparison to previous studies, such as the research undertaken by [23,45]. The principal findings derived from this inquiry can be summarized as follows:

1. Average space utilization among the scrutinized towers stood at 72%, with variations spanning from 55% to 84% among various instances;
2. Average ratio of core area to GFA was 26%, displaying fluctuations in the range of 11% to 38% across different scenarios;
3. In the majority of examined instances involving tapered structures, a central core architectural typology was consistently employed, primarily engineered to facilitate a diverse range of mixed-use functions; and;
4. Outriggered frame system emerged as the prevailing structural system, and composite materials were the most frequently employed structural material in the analyzed instances;
5. Significant differences in the influence of function and load-bearing systems on the space efficiency of tapered towers were not observed.

In line with the findings of Yeang's research [44], which establishes a 75% space efficiency benchmark for tall towers, it is evident that tapered skyscrapers fall short of this benchmark, exhibiting an average space efficiency rating of 72%. Similarly, investigations conducted by Ilgın [21,23] into office and mixed-use skyscrapers have revealed mean space efficiencies of 71%, further indicating that these structures do not meet Yeang's established threshold for space efficiency. The challenges surrounding space efficiency that persistently emerge in the context of both tapered skyscrapers and office/mixed-use skyscrapers can be predominantly attributed to two foundational factors; namely, the dimensions of the service core area and the particular structural components that are meticulously incorporated into the planning and construction of these towering edifices. These two key elements are inextricably linked, working in concert to impose significant limitations on the overall effectiveness in optimizing space utilization within these monumental structures. As a natural consequence of these limitations, they inevitably contribute to a discernible shortfall in space efficiency when benchmarked against the rigorous standards established by Yeang's extensive research in the domain [44].

In alignment with the studies carried out by [23,45], the central core approach emerged as the preferred choice among the examined structures. The primary aim of tapered skyscrapers was predominantly focused on mixed-use functionalities, a conclusion supported by the research results of [33].

Concerning load-bearing systems and structural materials, the widespread adoption of outriggered frame systems and composite constructions emerged as prevalent approaches within the case studies, aligning with the findings reported in the research conducted by Ilgın [21,23].

As observed in the research conducted by [24,29], the connection between building height and space efficiency exhibited an inverse relationship due to the increased allocation of core space and the utilization of larger structural system elements at greater heights. The findings regarding the associations between space efficiency and structural systems mirrored the conclusions drawn from the papers authored by Ilgın [21,23]. These studies indicated no significant divergence in the impact of load-bearing systems on space efficiency.

Subsequent research initiatives might concentrate on investigating other common tall building configurations, such as freeform designs. Through comparative analyses, valuable revelations regarding the connection between building form and space efficiency could be uncovered. There is also a need to delve deeper into the environmental sustainability aspects of tapered skyscrapers, including their energy efficiency, renewable energy integration, and overall environmental impact. Furthermore, a longitudinal study tracking the performance and adaptability of these structures over time, especially in the face of changing urban and climatic conditions, would be invaluable.

The author acknowledges the limitations of this paper. The data analysis was limited to a set of 40 tapered super-tall towers, which may not entirely represent the wide array of skyscrapers in the region. To bolster the reliability of the results, future inquiries could contemplate enlarging the dataset to encompass more extensive case study buildings, thus affording a more thorough and compelling analysis. Moreover, to extend the relevance of the research, forthcoming studies may also encompass skyscrapers below the 300 m threshold, allowing for the establishment of numerous subgroups for more intricate examination and interpretation.

6. Conclusions

Present-day tapered skyscrapers predominantly manifest as mixed-use complexes characterized by central core designs and incorporate outriggered frame systems constructed using composite materials. The endeavor to enhance spatial efficiency in tapered super-tall towers is a multifaceted one, markedly impacted by the skyscraper's overall height. Within this framework, the dimensions of components related to the service core, including circulation elements, and the load-bearing system elements, assume paramount importance. Nevertheless, with scrupulous selection, the structural system and construction materials can wield a beneficial influence on spatial efficiency. In this context, architects entrusted with skyscraper design must adeptly strike a harmonious balance among considerations related to aesthetics, functionality, and sustainability. Achieving this equilibrium enables the creation of distinctive and environmentally conscious tapered edifices that embody the tenets of contemporary design and ecological responsibility.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A. Tapered Super-Tall Buildings

#	Building Name	Country	City	Height (m)	# of Stories	Completion Date	Function
1	Suzhou Zhongnan Center	China	Suzhou	729	137	NC	M
2	Ping An Finance Center	China	Shenzhen	599	115	2017	O
3	Goldin Finance 117	China	Tianjin	596	128	OH	M
4	Lotte World Tower	Republic of Korea	Seoul	554	123	2017	M
5	One World Trade Center	USA	New York	541	94	2014	O
6	Tianjin CTF Finance Centre	China	Tianjin	530	97	2019	M
7	Greenland Jinmao International Financial Center	China	Nanjing	499	102	UC	M
8	Shanghai World Financial Center	China	Shanghai	492	101	2008	M
9	International Commerce Centre	China	Hong Kong	484	108	2010	M
10	Wuhan Greenland Center	China	Wuhan	475	97	UC	M
11	Chengdu Greenland Tower	China	Chengdu	468	101	OH	M
12	The Exchange 106	Malaysia	Kuala Lumpur	446	95	2019	O

#	Building Name	Country	City	Height (m)	# of Stories	Completion Date	Function
13	Guangzhou International Finance Center	China	Guangzhou	438	103	2010	M
14	Multifunctional Highrise Complex—Akhmat Tower	Russia	Grozny	435	102	OH	M
15	Chongqing Tall Tower	China	Chongqing	431	101	OH	M
16	Haikou Tower 1	China	Haikou	428	94	UC	M
17	One Vanderbilt	USA	New York	427	58	2020	O
18	Guangxi China Resources Tower	China	Nanning	402	86	2020	M
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	OH	M
22	Golden Eagle Tiandi Tower A	China	Nanjing	368	77	2019	M
23	Hanking Center Tower	China	Shenzhen	359	65	2018	O
24	One Shenzhen Bay Tower 7	China	Shenzhen	341	78	2018	M
25	Tianjin World Financial Center	China	Tianjin	337	75	2011	O
26	Wilshire Grand Center	USA	Los Angeles	335	62	2017	M
27	DAMAC Heights	United Arab Emirates	Dubai	335	88	2018	R
28	China World Tower	China	Beijing	330	74	2010	M
29	Golden Eagle Tiandi Tower B	China	Nanjing	328	68	2019	O
30	Salesforce Tower	USA	San Francisco	326	61	2018	O
31	53 West 53	USA	New York	320	77	2019	R
32	CITIC Financial Center Tower 1	China	Shenzhen	312	-	UC	M
33	Ocean Heights	United Arab Emirates	Dubai	310	83	2010	R
34	Guangfa Securities Headquarters	China	Guangzhou	308	60	2018	O
35	The Shard	UK	London	306	73	2013	M
36	Northeast Asia Trade Tower	Republic of Korea	Incheon	305	68	2011	M
37	One Manhattan West	USA	New York	303	67	2019	O
38	Torre Costanera	Chile	Santiago	300	62	2014	M
39	Shimao Riverside Block D2b	China	Wuhan	300	53	UC	M
40	Golden Eagle Tiandi Tower C	China	Nanjing	300	60	2019	O

Buildings are listed from highest to lowest. Note on abbreviations: 'M' indicates mixed-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.

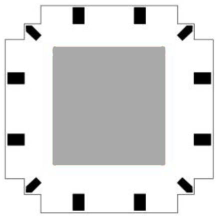
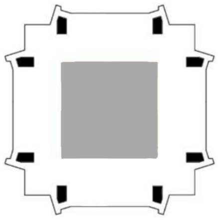
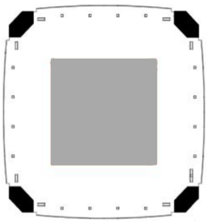
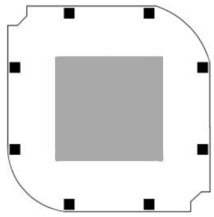
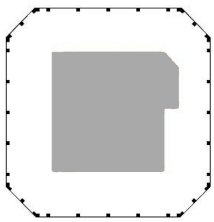
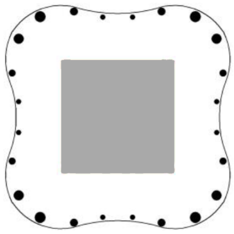
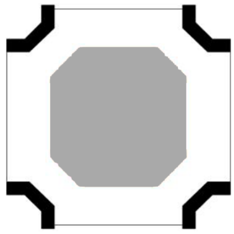
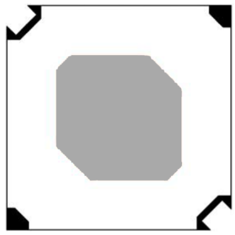
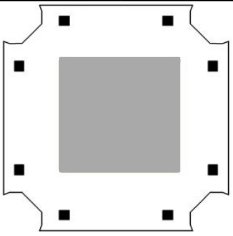
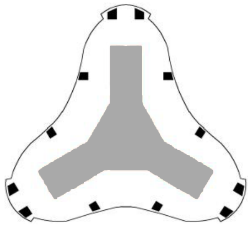
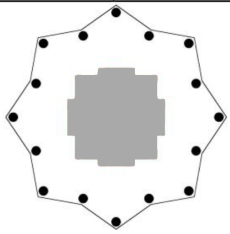
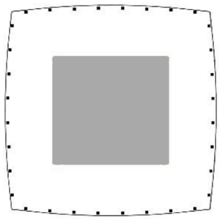
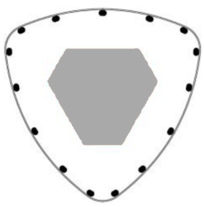
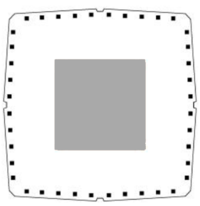
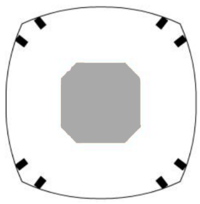
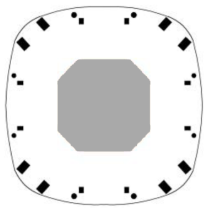
Appendix B. Tapered Super-Tall Buildings by Core Type, Structural System, and Structural Material

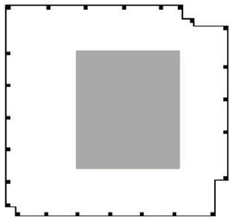
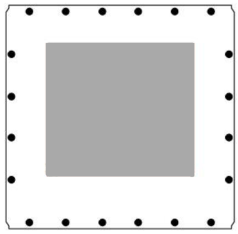
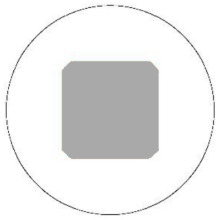
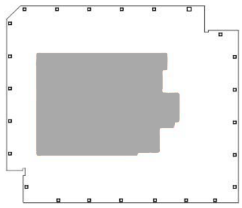
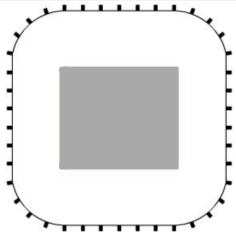
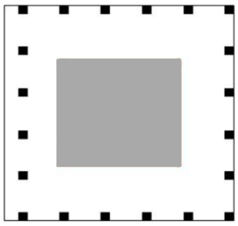
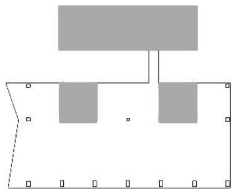
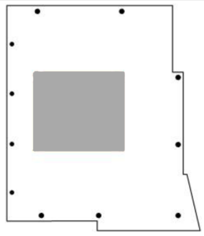
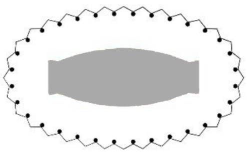
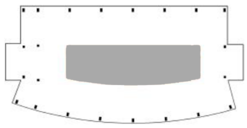
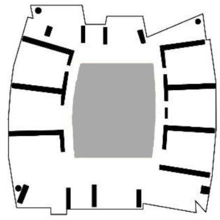
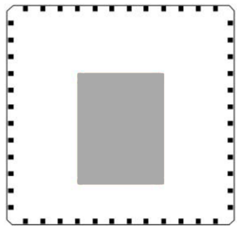
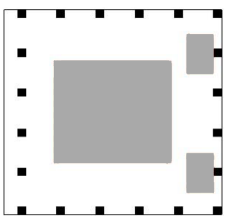
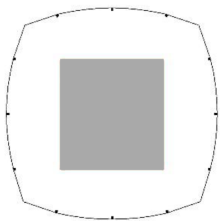
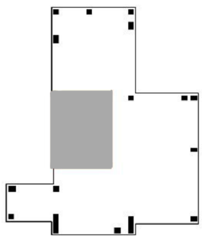
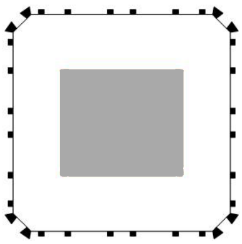
#	Building Name	Core Type	Structural System	Structural Material
1	Suzhou Zhongnan Center	Central	Outriggered Frame	Composite
2	Ping An Finance Center	Central	Outriggered frame	Composite

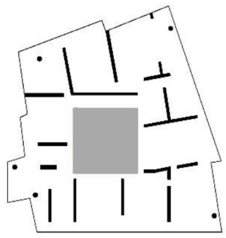
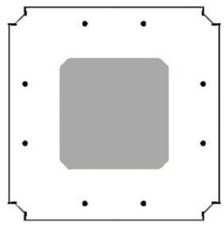
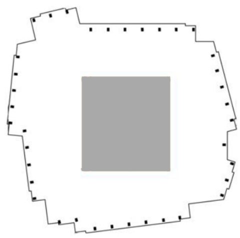
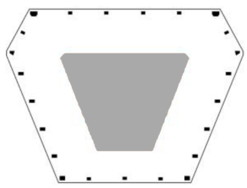
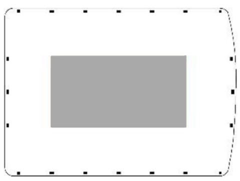
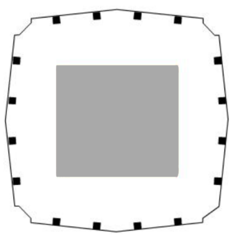
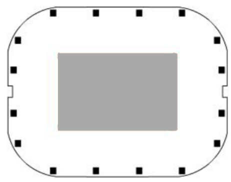
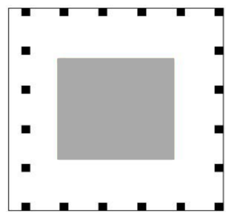
#	Building Name	Core Type	Structural System	Structural Material
3	Goldin Finance 117	Central	Trussed-tube	Composite
4	Lotte World Tower	Central	Outriggered Frame	Composite
5	One World Trade Center	Central	Outriggered frame	Composite
6	Tianjin CTF Finance Centre	Central	Framed-tube	Composite
7	Greenland Jinmao International Financial Center	Central	Outriggered Frame	Composite
8	Shanghai World Financial Center	Central	Outriggered Frame	Composite
9	International Commerce Centre	Central	Outriggered Frame	Composite
10	Wuhan Greenland Center	Central	Buttressed Core	Composite
11	Chengdu Greenland Tower	Central	Outriggered Frame	Composite
12	The Exchange 106	Central	Outriggered frame	Composite
13	Guangzhou International Finance Center	Central	Outriggered Frame	Composite
14	Multifunctional Highrise Complex—Akhmat Tower	Central	Framed-tube	Steel
15	Chongqing Tall Tower	Central	Outriggered Frame	Composite
16	Haikou Tower 1	Central	Outriggered Frame	Composite
17	One Vanderbilt	Central	Outriggered frame	Composite
18	Guangxi China Resources Tower	Central	Outriggered Frame	Composite
19	China Resources Tower	Central	Diagrid-framed-tube	Composite
20	30 Hudson Yards	Central	Outriggered frame	Steel
21	Guiyang World Trade Center Landmark Tower	Central	Framed-tube	Composite
22	Golden Eagle Tiandi Tower A	Central	Outriggered Frame	Composite
23	Hanking Center Tower	External	Trussed-tube	Steel
24	One Shenzhen Bay Tower 7	Central	Outriggered Frame	Composite
25	Tianjin World Financial Center	Central	Outriggered frame	Composite
26	Wilshire Grand Center	Central	Outriggered Frame	Composite
27	DAMAC Heights	Central	Outriggered frame	RC
28	China World Tower	Central	Outriggered Frame	Composite
29	Golden Eagle Tiandi Tower B	Central	Outriggered frame	Composite
30	Salesforce Tower	Central	Shear walled frame	Composite
31	53 West 53	Peripheral	Diagrid-framed-tube	RC
32	CITIC Financial Center Tower 1	Central	Diagrid-framed-tube	Composite
33	Ocean Heights	Central	Outriggered frame	RC
34	Guangfa Securities Headquarters	Central	Outriggered frame	Composite
35	The Shard	Central	Shear walled Frame	Composite
36	Northeast Asia Trade Tower	Central	Outriggered Frame	Composite
37	One Manhattan West	Central	Shear walled frame	Composite
38	Torre Costanera	Central	Outriggered Frame	RC
39	Shimao Riverside Block D2b	Central	Outriggered Frame	Composite
40	Golden Eagle Tiandi Tower C	Central	Outriggered frame	Composite

Buildings are listed from highest to lowest. Note on abbreviation: 'RC' indicates reinforced concrete.

Appendix C. Tapered Super-Tall Buildings by Floor Plan with Space Efficiency and Core/GFA

Building name							
Space efficiency*				Core/GFA**			
Suzhou Zhongnan Center		**Ping An Finance Center**		**Goldin Finance 117**		**Lotte World Tower**	
62%	33%	70%	26%	68%	28%	69%	28%
							
Low-rise floor		Low-rise floor		Ground floor		Low-rise floor	
One World Trade Center		**Tianjin CTF Finance Centre**		**Greenland Jinmao International Financial Center**		**Shanghai World Financial Center**	
70%	30%	70%	27%	55%	37%	69%	28%
							
Low-rise floor		Low-rise floor		Ground floor		Low-rise floor	
International Commerce Centre		**Wuhan Greenland Center**		**Chengdu Greenland Tower**		**The Exchange 106**	
69%	29%	67%	30%	72%	24%	70%	29%
							
Low-rise floor		Low-rise floor		Ground floor		Ground floor	
Guangzhou International Finance Center		**Multifunctional Highrise Complex - Akhmat Tower**		**Chongqing Tall Tower**		**Haikou Tower 1**	
71%	27%	75%	23%	81%	17%	75%	22%
							
Low-rise floor		Low-rise floor		Low-rise floor		Low-rise floor	

One Vanderbilt	**Guangxi China Resources Tower**	**China Resources Tower**	**30 Hudson Yards**
72% 27%	61% 38%	73% 26%	69% 30%
			
Ground floor	Low-rise floor	Low-rise floor	Low-rise floor
Guiyang World Trade Center Landmark Tower	**Golden Eagle Tiandi Tower A**	**Hanking Center Tower**	**One Shenzhen Bay Tower 7**
71% 27%	70% 27%	70% 29%	81% 18%
			
Low-rise floor	Low-rise floor	Low-rise floor	Low-rise floor
Tianjin World Financial Center	**Wilshire Grand Center**	**DAMAC Heights**	**China World Tower**
72% 26%	80% 19%	72% 19%	79% 19%
			
Low-rise floor	Low-rise floor	Low-rise floor	Low-rise floor
Golden Eagle Tiandi Tower B	**Salesforce Tower**	**53 West 53**	**CITIC Financial Center Tower 1**
65% 32%	72% 27%	82% 16%	70% 27%
			
Low-rise floor	Low-rise floor	Low-rise floor	Low-rise floor

Ocean Heights		Guangfa Securities Headquarters		The Shard		Northeast Asia Trade Tower	
84%	11%	74%	25%	79%	20%	72%	26%
							
Low-rise floor		Low-rise floor		Low-rise floor		Low-rise floor	
One Manhattan West		**Torre Costanera**		**Shimao Riverside Block D2b**		**Golden Eagle Tiandi Tower C**	
70%	29%	69%	30%	73%	26%	75%	23%
							
Low-rise floor		Low-rise floor		Ground floor		Low-rise floor	

In the floor plans, the gray areas correspond to the service core, while black areas signify structural elements.
Space efficiency*: calculated as the ratio of the net floor area [obtained by subtracting the service core (the gray area on the floor plan) and structural elements from GFA] to GFA.
Core/GFA**: calculated as the ratio of the service core (the gray area on the floor plan) to GFA.

References

1. Leslie, T. *Chicago Skyscrapers, 1934-1986: How Technology, Politics, Finance, and Race Reshaped the City*; University of Illinois Press: Champaign, IL, USA, 2023.
2. Al, S. *Supertall: How the World's Tallest Buildings Are Reshaping Our Cities and Our Lives*; WW Norton & Company: New York, NY, USA, 2022.
3. Sengupta, D.; Choi, Y.R.; Tian, B.; Brown, S.; Meadows, M.; Hackney, C.R.; Banerjee, A.; Li, Y.; Chen, R.; Zhou, Y. Mapping 21st century global coastal land reclamation. *Earth's Future* **2023**, *11*, e2022EF002927. [CrossRef]
4. Qu, J.; Wang, Z.; Du, P. Comparative Study on the Development Trends of High-rise Buildings Above 200 Meters in China, the USA and the UAE. *Int. J. High-Rise Build.* **2021**, *10*, 63–71.
5. Li, Q.; Wang, L. Is the Chinese skyscraper boom excessive? *J. Urban Aff.* **2022**, *44*, 1117–1135. [CrossRef]
6. CTBUH Council on Tall Buildings and Urban Habitat. Illinois Institute of Technology, S.R. Crown Hall, 3360 South State Street, Chicago, Illinois, USA. Available online: www.ctbuh.org (accessed on 25 October 2023).
7. Alkoud, A. Investigating the Impact of Tall Building Ordinances (TBOs) on the Evolution of Ultra-Tall Buildings Typology: Case Studies in Chicago and Dubai. Ph.D. Thesis, Illinois Institute of Technology, Chicago, IL, USA, 2023.
8. Al-Kodmany, K.; Ali, M.M. An overview of structural and aesthetic developments in tall buildings using exterior bracing and diagrid systems. *Int. J. High-Rise Build.* **2016**, *5*, 271–291. [CrossRef]
9. Meena, R.K.; Raj, R.; Anbukumar, S. Effect of wind load on irregular shape tall buildings having different corner configuration. *Sādhanā* **2022**, *47*, 126. [CrossRef]
10. Zhang, X.; Weerasuriya, A.U.; Lu, B.; Tse, K.T.; Liu, C.H.; Tamura, Y. Pedestrian-level wind environment near a super-tall building with unconventional configurations in a regular urban area. *Build. Simul.* **2020**, *13*, 439–456. [CrossRef]
11. Goncikowski, M. Research by design-determining the form of the initial architectural concept of a skyscraper building in Warsaw. *Archit. Eng. Des. Manag.* **2023**, 1–31. [CrossRef]
12. Kushal, M. Comparison of aerodynamic coefficients of tall tapered triangular building modified with golden spiral in plan. *Mater. Today Proc.* **2023**, *72*, 3121–3132. [CrossRef]
13. Al-Kodmany, K. High-Rise Developments: A Critical Review of the Nature and Extent of Their Sustainability. In *Pragmatic Engineering and Lifestyle: Responsible Engineering for a Sustainable Future*; Emerald Publishing Limited: Bingley, UK, 2023; pp. 1–20.
14. Tuure, A.; Ilgın, H.E. Space Efficiency in Finnish Mid-Rise Timber Apartment Buildings. *Buildings* **2023**, *13*, 2094. [CrossRef]
15. Okbaz, F.T.; Sev, A. A model for determining the space efficiency in non-orthogonal high rise office buildings. *J. Fac. Eng. Archit. Gazi Univ.* **2023**, *38*, 113–125.
16. Goessler, T.; Kaluarachchi, Y. Smart Adaptive Homes and Their Potential to Improve Space Efficiency and Personalisation. *Buildings* **2023**, *13*, 1132. [CrossRef]

17. Ibrahimy, R.; Mohmmand, M.A.; Elham, F.A. An Evaluation of Space Use Efficiency in Residential Houses, Kabul City. *J. Res. Appl. Sci. Biotechnol.* **2023**, *2*, 1–6. [CrossRef]
18. Hamid, G.M.; Elsawi, M.; Yusra, O. The Impacts of Spatial Parameters on Space Efficiency in Hybrid Villa-Apartments in Greater Khartoum, Sudan. *J. Archit. Plan.* **2022**, *34*, 425–440.
19. Suga, R. Space Efficiency in Hotel Development. Master's Thesis, Business Administration with a Specialization in Real Estate Management and Development, MODUL University Vienna, Vienna, Austria, 2021.
20. Ilgın, H.E. Core Design and Space Efficiency in Contemporary Supertall Office Buildings. In *Sustainable High-Rise Buildings: Design, Technology, and Innovation*; Al-Kodmany, K., Du, P., Ali, M.M., Eds.; The Institution of Engineering and Technology: London, UK, 2022. [CrossRef]
21. Ilgın, H.E. Space efficiency in contemporary supertall office buildings. *J. Archit. Eng.* **2021**, *27*, 4021024. [CrossRef]
22. Ilgın, H.E. Space efficiency in contemporary supertall residential buildings. *Architecture* **2021**, *1*, 25–37. [CrossRef]
23. Ilgın, H.E. A study on space efficiency in contemporary supertall mixed-use buildings. *J. Build. Eng.* **2023**, *69*, 106223. [CrossRef]
24. Arslan Kılınç, G. Improving a Model for Determining Space Efficiency of Tall Office Buildings. Ph.D. Thesis, Department of Architecture, Mimar Sinan Fine Art University, Istanbul, Turkey, 2019. (In Turkish).
25. Von Both, P. A stakeholder-and function-based planning method for space-efficient buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012040. [CrossRef]
26. Höjer, M.; Mjörnell, K. Measures and steps for more efficient use of buildings. *Sustainability* **2018**, *10*, 1949. [CrossRef]
27. Zhang, L.; Zhang, L.; Wang, Y. Shape optimization of free-form buildings based on solar radiation gain and space efficiency using a multi-objective genetic algorithm in the severe cold zones of China. *Sol. Energy* **2016**, *132*, 38–50. [CrossRef]
28. Nam, H.J.; Shim, J.H. An analysis of the change in space efficiency based on various tall building corner shapes and lease spans. *J. Archit. Inst. Korea Plan. Des.* **2016**, *32*, 13–20.
29. Sev, A.; Özgen, A. Space efficiency in high-rise office buildings. *METU J. Fac. Archit.* **2009**, *26*, 69–89. [CrossRef]
30. Saari, A.; Tissari, T.; Valkama, E.; Seppänen, O. The effect of a Redesigned Floor Plan, Occupant Density and the Quality of Indoor Climate on the Cost of Space, Productivity and Sick Leave in an Office Building—A Case Study. *Build. Environ.* **2006**, *41*, 1961–1972. [CrossRef]
31. Kim, H.; Elnimeiri, M. Space efficiency in multi-use tall building. In Proceedings of the Tall Buildings in Historical Cities-Culture and Technology for Sustainable Cities, Seoul, Republic of Korea, 10–13 October 2004.
32. Carapellucci, F.; Conti, V.; Lelli, M.; Liberto, C.; Orchi, S.; Valenti, G.; Valentini, M.P. Tools and Methodologies for the Analysis of Home-to-Work Shuttle Service Impacts: The ENEA "Casaccia" Case Study. *Future Transp.* **2023**, *3*, 901–917. [CrossRef]
33. AutoCAD. Available online: https://www.autodesk.com/ (accessed on 25 October 2023).
34. Ilgın, H.E.; Karjalainen, M.; Pelsmakers, S. Contemporary tall residential timber buildings: What are the main architectural and structural design considerations? *Int. J. Build. Pathol. Adapt.* **2023**, *41*, 26–46. [CrossRef]
35. Ilgın, H.E. Use of aerodynamically favorable tapered form in contemporary supertall buildings. *J. Des. Resil. Archit. Plan.* **2022**, *3*, 183–196. [CrossRef]
36. Ali, M.M.; Al-Kodmany, K. Structural systems for tall buildings. *Encyclopedia* **2022**, *2*, 1260–1286. [CrossRef]
37. Ilgın, H.E. A study on interrelations of structural systems and main planning considerations in contemporary supertall buildings. *Int. J. Build. Pathol. Adapt.* **2023**, *41*, 1–25. [CrossRef]
38. Almssad, A.; Almusaed, A.; Homod, R.Z. Masonry in the Context of Sustainable Buildings: A Review of the Brick Role in Architecture. *Sustainability* **2022**, *14*, 14734. [CrossRef]
39. Ali, M.M.; Al-Kodmany, K. Tall Buildings and Urban Habitat of the 21st Century: A Global Perspective. *Buildings* **2012**, *2*, 384–423. [CrossRef]
40. Özşahin, B. An Assessment of the Relation between Architectural and Structural Systems in the Design of Tall Buildings in Turkey. *Buildings* **2022**, *12*, 1649. [CrossRef]
41. Kawade, M.P.; Bangde, V.S.; Sawai, G.H. Seismic analysis of tall building with central core as tube structure. *Int. Res. J. Mod. Eng. Technol. Sci.* **2020**, *2*, 300–310.
42. Ilgın, H.E. Potentials and Limitations of Supertall Building Structural Systems: Guiding for Architects. Ph.D. Thesis, Department of Architecture, Middle East Technical University, Ankara, Turkey, 2018.
43. Abed, J.; Rayburg, S.; Rodwell, J.; Neave, M. A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability* **2022**, *14*, 5570. [CrossRef]
44. Yeang, K. *Service Cores: Detail in Building*; Wiley-Academy: London, UK, 2000.
45. Oldfield, P.; Doherty, B. Offset cores: Trends, drivers and frequency in tall buildings. *CTBUH J.* **2019**, 40–45.