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Freeform Supertall Buildings

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Abstract To date, no research has been carried out in the literature that gives insight into the relationships between freeform and key design parameters in supertall towers (≥ 300 meters). This critical subject is investigated in this paper with data collected from 39 building cases, taking into account building function, load-bearing system, and structural material as design parameters. The key findings of the paper highlighted the following: (1) the only core typology was central core type; (2) mixed-use and office were the most favored functions; (3) the most favored system in freeform supertall tower projects was outriggered frame system; (4) composite construction was common among supertall towers and its closest follower was reinforced concrete; (5) building functions other than hotel exceeded 500 m in free form; (6) in the sample group, freeform buildings with outriggered frame and tubular systems exceeded half a kilometer as well; (7) both composite and reinforced concrete freeform towers pushed the limits of height considerably; and (8) as the number of some supertall tower buildings (such as hotel buildings) was not adequate, it did not seem possible to derive a scientific interrelation between the height of the building and the corresponding planning parameter. It is thought that revealing the current state of the free forms, which are among the most preferred skyscraper forms today, will shed light on the supertall building designs to be made in the future.

Keywords Supertall Building, Freeform, Structural System, Structural Material, Function, Building Height

1. Introduction

One of the important ways to cope with the dramatically growing human population with a population increase of 2.5 billion by 2050 is the skyscraper, that is, the vertical city paradigm [1]. Politicians, planners, and architects began to pay more and more attention to this paradigm [2]. Also, many cities around the world adopt tall buildings as their main building typology in the 21st century [3]. Since the 1950s, the architectural forms of high-rise buildings have undergone significant transformations, paving the way for iconic and unique forms in response to this increasing interest [4,5]. The 118-story and 644 m high Merdeka PNB118 with its crystalline form and the 118-story and 528 m high CITIC Tower with its vase-like form are among the prominent examples.

The selected building forms are particularly critical at the schematic design stage as they respond to different demands, such as the symbolic appearance of skyscrapers or building regulations. The skyscraper form paradigm shifts to create process generation based on performance design approaches. Combining analytic tools employed in the early design phases provides important prospects for the architectural form-finding process. This helps designers and architects move away from traditional methodologies.

Thanks to advances in design methodologies and digital technologies, especially architecture, today's supertall towers can be realized with extremely challenging forms rarely seen before [6]. The growing interest in 'iconic' skyscrapers in new urban settings, combined with the architect's passion for creating free forms, began to define today's building typology [7].

As the building height increases, the load-bearing system alternatives decrease [8]. In other words, while there is a wide range of load-bearing system choices in low-rise buildings, the options become limited in supertall buildings due to the challenges brought by the increase in building height [9]. Irregular building forms make this even more difficult, making the selection of appropriate structural systems even more critical for the successful implementation of projects [10,11]. In this sense, due to their complex geometry, accurately identifying and constructing any freeform tower is a very difficult task. The issue of integration of load-bearing systems and building forms comes to the fore. For example, triangular geometric units naturally defined by diagrid-frame-tube systems, such as the 98-story and 441 m high KK100, can more accurately identify any freeform tower without distortion [12].

In today's skyscraper design, aesthetic concerns are sometimes overemphasized, which can lead to negative consequences, especially due to the lack of interdisciplinary cooperation in structural design [6]. In this sense, it becomes even more important to know the relationship between the free form, which is one of the most frequently used building forms, and other design parameters.

Limited research has been done in the literature, taking into account the main design parameters of the tall building form. Among important studies, Elnimeiri and Almusharaf [13] examined the relationship between structural effectiveness and form to show that sustainable effectiveness is at the focal point of structural planning along with financial parameters. Poon and Joseph [14] studied the opportunities and challenges of tall building structural design over existing and planned projects. Alaghmandan et al. [15] researched the planning and structural design parameters of 70 skyscrapers to understand the potential tendency in form and structural systems. Szolomicki and Golasz-Szolomicka [16] took form, structural systems, damping systems, and sustainability as variables in tall buildings to study structural and architectural solutions. Golasz-Szolomicka and Szolomicki [17] explored the structural system and design aspects of the twisted towers to evaluate new material applications and construction techniques. Using 93 supertall towers, Ilgın et al. [18] examined important architectural and structural design concerns and contemporary developments in various associated relationships. Ilgın and Günel [19] explored aerodynamic design issues as current developments in skyscrapers. Ilgın [20] studied space efficiency in office buildings with critical design concerns on more than 40 supertall towers. Ilgın [21] analyzed space efficiency in residential skyscrapers over 27 supertall buildings. Ilgın [22] focused on the interrelationships between structural systems and basic design criteria in tall towers through 140 study cases. Ilgın [23] attempted to provide an understanding of tapered skyscrapers by using the main planning criteria for 41 supertall towers. Ilgın [24] scrutinized the interrelationships between the aspect ratio and the key planning parameters in 75 skyscrapers.

As a result, no study in the literature provides insight into the interrelationships between freeform and major planning parameters in supertall towers. This significant issue was explored in this article through 39 case study towers, taking into account their functions, structural systems, and structural materials. It is worth noting that the main determining factor in the selection of buildings in this study was the availability of data (i.e., core type, structural system, structural material) shown in the building list. Especially after the World Trade Center (USA) tragedy in 2001 during the September 11 attacks, data collection has been difficult due to the safety issues of skyscrapers. It is thought that this paper will contribute to the introductory guideline for planning and construction stakeholders e.g., architects, structural engineers, and developers.

2. Materials and Methods

As a research method in this article, literature survey including the Council on Tall Buildings and Urban Habitat database / CTBUH [25], scientific papers, doctoral theses, conference proceedings, architectural and structural publications, and other scientific references, was used as a research method.

In addition, a case study approach is used to collect data on selected towers to explore the interrelationships of freeform and major planning parameters. These buildings were 39 towers from various spots [22 in Asia (18 in China), 12 in the Middle East, 3 in Russia, 1 in the USA, and 1 in Australia]. In the 39 selected cases (Tables 1 and 2), highly detailed freeform supertall buildings without adequate knowledge of their interrelated design features were excluded from the Tables.

Table 1. Freeform supertall towers

#	Building name	Country / City	Height (m)	# of stories	Completion date	Function
1	Merdeka PNB118	Malaysia / Kuala Lumpur	644	118	UC	M (H/O)
2	CITIC Tower	China / Beijing	528	108	2018	O
3	Evergrande Hefei Center 1	China / Hefei	518	112	OH	M (H/R/O)
4	Pentominium Tower	UAE / Dubai	515	122	OH	R
5	Busan Lotte Town Tower	South Korea / Busan	510	107	NC	M (H/R/O)
6	TAIPEI 101	Taiwan / Taipei	508	101	2004	O
7	Zifeng Tower	China / Nanjing	450	66	2010	M (H/O)
8	KK 100	China / Shenzhen	441	98	2011	M (H/O)
9	Al Hamra Tower	Kuwait / Kuwait City	413	80	2011	O
10	Dynamic Tower	UAE / Dubai	388	80	NC	M (H/R)
11	PIF Tower	Saudi Arabia / Riyadh	385	72	2021	O
12	Shun Hing Square	China / Shenzhen	384	69	1996	O
13	Burj Mohammed Bin Rashid	UAE / Abu Dhabi	381	88	2014	R
14	1 Corporate Avenue	China / Wuhan	376	76	2021	O
15	Federation Tower	Russia / Moscow	373	93	2016	M (R/O)
16	Qingdao Hai Tian Center	China / Qingdao	369	73	2021	M (H/O)
17	St. Regis Chicago	USA / Chicago	362	101	2020	M (H/R)
18	Almas Tower	UAE / Dubai	360	68	2008	O
19	Greenland Group Suzhou Center	China / Suzhou	358	77	UC	M (H/O)
20	OKO - Residential Tower	Russia / Moscow	354	90	2015	M (H/R)
21	Guo Wei ZY Plaza	China / Zhuhai	350	62	UC	O
22	Spring City 66	China / Kunming	349	61	2019	O
23	Hengqin International Finance Center	China / Zhuhai	337	69	2020	M (R/O)
24	Shimao International Plaza	China / Shanghai	333	60	2006	M (H/O)
25	Azrieli Spiral Tower	Israel / Tel Aviv	323	91	UC	O
26	Burj Al Arab	UAE / Dubai	321	56	1999	H
27	Sinar Mas Center 1	China / Shanghai	320	65	2017	O
28	Australia 108	Australia / Melbourne	316	100	2020	R
29	MahaNakhon	China / Bangkok	314	79	2016	M (H/R)
30	Menara TM	Malaysia / Kuala Lumpur	310	55	2001	O
31	Pearl River Tower	China / Guangzhou	309	71	2013	O
32	Fortune Center	China / Guangzhou	309	68	2015	O
33	Jiangxi Nanchang Greenland Central Plaza, Parcel A	China / Nanchang	303	59	2015	O
34	Jiangxi Nanchang Greenland Central Plaza, Parcel B	China / Nanchang	303	59	2015	O
35	Kingdom Centre	Saudi Arabia / Riyadh	302	41	2002	M (H/R/O)
36	Capital City Moscow Tower	Russia / Moscow	301	76	2010	R
37	Al Wasl Tower	UAE / Dubai	300	64	UC	M (H/R/O)
38	Aspire Tower	Qatar / Doha	300	36	2007	M (H/O)
39	NBK Tower	Kuwait / Kuwait City	300	61	2019	O

Note on abbreviations: 'M' indicates mixed-use; 'H' indicates hotel use; 'R' indicates residential use; 'O' indicates office use; 'UAE' indicates the United Arab Emirates; 'UC' indicates under construction; 'NC' indicates never completed; 'OH' indicates on hold.

This study examined the following subjects that play a significant role in the planning of freeform skyscrapers: (1) function; (2) structural system; and (3) structural material (see Table 2).

Table 2. Freeform supertall towers by core type, structural system, and structural material

#	Building name	Core type	Structural system	Structural material
1	Merdeka PNB118	Central	Outriggered frame	Composite
2	CITIC Tower	Central	Trussed-tube	Composite
3	Evergrande Hefei Center 1	Central	Outriggered frame	Composite
4	Pentominium Tower	Central	Outriggered frame	RC
5	Busan Lotte Town Tower	Central	Outriggered frame	Composite
6	TAIPEI 101	Central	Outriggered frame	Composite
7	Zifeng Tower	Central	Outriggered frame	Composite
8	KK 100	Central	Diagrid-framed-tube	Composite
9	Al Hamra Tower	Central	Shear walled frame	Composite
10	Dynamic Tower	Central	Mega core	RC
11	PIF Tower	Central	Trussed-tube	Composite
12	Shun Hing Square	Central	Outriggered frame	Composite
13	Burj Mohammed Bin Rashid	Central	Outriggered frame	RC
14	1 Corporate Avenue	Central	Outriggered frame	Composite
15	Federation Tower	Central	Outriggered frame	Composite
16	Qingdao Hai Tian Center	Central	Outriggered frame	Composite
17	St. Regis Chicago	Central	Outriggered frame	RC
18	Almas Tower	Central	Outriggered frame	Composite
19	Greenland Group Suzhou Center	Central	Outriggered frame	Composite
20	OKO - Residential Tower	Central	Outriggered frame	RC
21	Guo Wei ZY Plaza	Central	Outriggered frame	Composite
22	Spring City 66	Central	Outriggered frame	Composite
23	Hengqin International Finance Center	Central	Outriggered frame	Composite
24	Shimao International Plaza	Central	Mega column	Composite
25	Azrieli Spiral Tower	Central	Shear walled frame	RC
26	Burj Al Arab	Central	Shear walled frame	Composite
27	Sinar Mas Center 1	Central	Outriggered frame	Composite
28	Australia 108	Central	Outriggered frame	RC
29	MahaNakhon	Central	Outriggered frame	RC
30	Menara TM	Central	Outriggered frame	RC
31	Pearl River Tower	Central	Outriggered frame	Composite
32	Fortune Center	Central	Outriggered frame	Composite
33	Jiangxi Nanchang Greenland Central Plaza, Parcel A	Central	Outriggered frame	Composite
34	Jiangxi Nanchang Greenland Central Plaza, Parcel B	Central	Outriggered frame	Composite
35	Kingdom Centre	Central	Shear walled frame	RC
36	Capital City Moscow Tower	Central	Outriggered frame	RC
37	Al Wasl Tower	Central	Outriggered frame	Composite
38	Aspire Tower	Central	Mega core	RC
39	NBK Tower	Central	Outriggered frame	Composite
Note on abbreviation: 'RC' indicates reinforced concrete				

In this paper, the following form classification was utilized [18]: (i) prismatic, (ii) setback, (iii) tapered, (iv) twisted, (v) leaning/tilted, and (vi) free forms (Figure 1). Here, free form is created by applying manipulations to a geometrically simple object (e.g., a line, a volume) when these manipulations and the sequences of the architectural designer's actions are not clear, or the form does not fit into no other categories [20]. Furthermore, the following core categorization of [26] was utilized: (a) central; (b) atrium, (c) external, and (d) peripheral. Hotel use, residential use, and office use were taken as the fundamental functions in skyscrapers, whereas their combinations were taken as mixed-use. In this article, the following load-bearing system categorization of Ilgın et al. [18, 27] was used: (1) shear-frame; (2) mega core; (3) mega column; (4) outriggered frame; (5) tube; and (6) buttressed core (Figure 2), whereas the following structural material categorization was utilized: steel, concrete, and composite. There is no universal definition of the number of stories or heights of supertall towers [28]. However, in this study, considering the CTBUH data bank [25], a supertall structure is considered equal to and greater than a 300m structure.

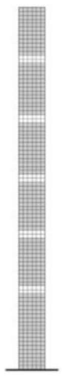
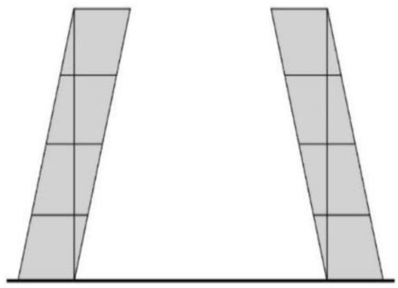
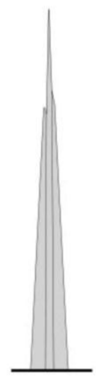
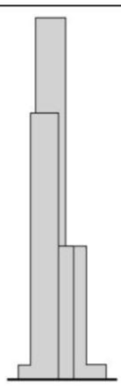
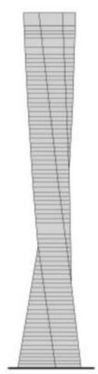
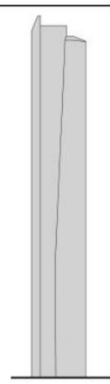
Prismatic	Leaning/tilted	Tapered
buildings whose two ends are similar, equal, and parallel in shape, with the same sides and exactly perpendicular axes	buildings with inclined form	buildings with a tapering effect by reduced floor plans and surface areas with a linear or non-linear profile along the height
		
Setback	**Twisted**	**Free***
buildings with recessed horizontal sections along the height	buildings with floors or facades that gradually rotate as they multiply upward along an axis, entering a twist angle	buildings not in the previously mentioned forms
		
* Free form is created by applying manipulations to a geometrically simple object (e.g. a line, a volume) when these manipulations and the sequences of the architect's actions are not clear, or the form does not fit into any before mentioned categories [20].		

Figure 1. Supertall building forms

Shear-frame system	**Mega core system**	**Mega column system**
consisting of shear wall/truss and frame with subsets of shear trussed frame and shear walled frame;	consisting of a mega core with much larger cross-sections than normal, running continuously along the height of the building as a main load-bearing element	consisting of mega columns or shear walls with much larger cross-sections than normal, running continuously along the height of the building as main load-bearing elements
		
Outriggered frame system	**Framed-tube system**	**Diagrid-framed-tube system**
consisting of at least one-story deep outriggers added to shear-frame system	consisting of closely spaced exterior columns with spandrel beams at the facade	a variation of the framed-tube system with diagonals instead of the columns
		
Trussed-tube system	**Bundled-tube system**	**Buttressed core system**
consisting of exterior columns with exterior multistory braces	consisting of a combination of more than one tube	an advanced "shear wall system," consisting of shear walls directly supporting the central core
		

Figure 2. Supertall structural systems (Photos' source: Wikipedia)

3. Results: Interrelations of Free form and Key Design Parameters

Interrelationships of free form and major planning issues connected with it, function, load-bearing system, and structural material were studied in this part. In addition to this, the interrelations of building height and function, structural system, and structural material were scrutinized. As the only core typology was central core type (Table 2) in our study, no analysis was performed on it.

3.1. Function

Figure 3 indicates that among 39 freeform skyscrapers, mixed-use and residential are the most preferred functions with 44%. The explanation for the high ratio of mixed-use might be justified by the fact that it facilitates a broad user portfolio with its full-day visitor possibility, hence maximizing rent payment [29].

3.2. Structural System

Figure 4 demonstrates that outriggered frame systems were largely utilized (>70%) in supertall cases, followed by shear walled frame with 10%. The high preference rate for outriggered frame system may be because it allows the placement of widely spaced exterior columns, thus minimizing the hurdle created by the closely spaced column layout. This gives architects more freedom in designing facades for free forms [30].

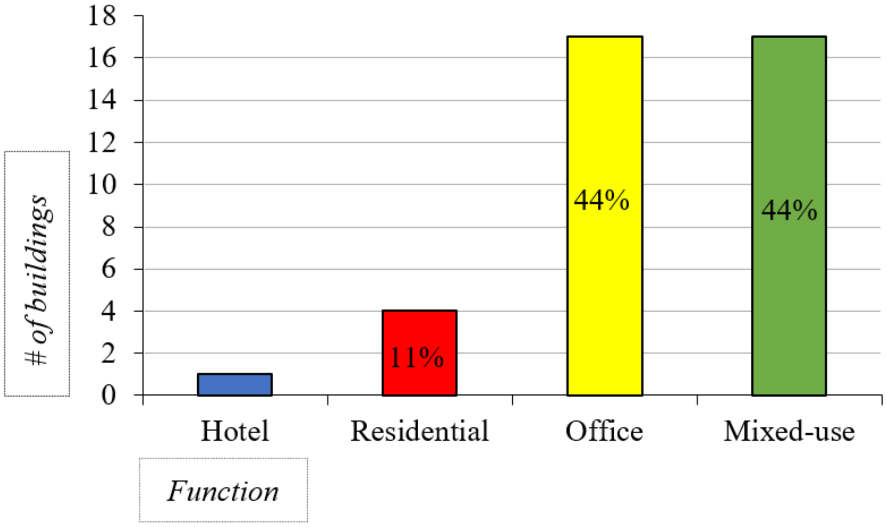


Figure 3. Freeform supertall buildings by function

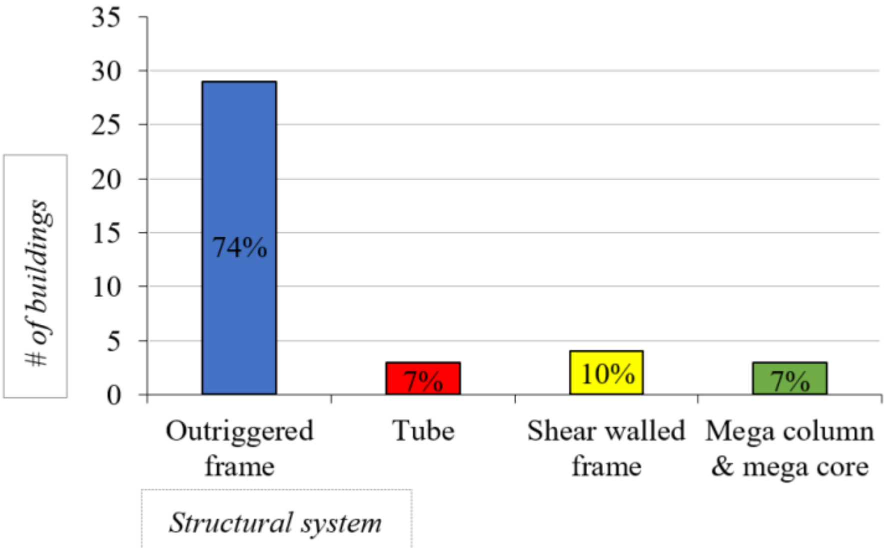


Figure 4. Freeform supertall buildings by structural system

Although the diagrid frame-tube system can more accurately identify any free-form tower without distortion thanks to its triangular units, unlike outriggered frame system, its diagonals can be obstructive on the facade. This may explain their absence in the sample group.

3.3. Structural Material

Figure 5 shows that among 39 freeform skyscrapers, composite buildings with 70%, followed by concrete utilization at 30%. The utilization of composite construction can be ascribed to the advantages of the two structural materials that compose it, namely the superiority of steel strength and concrete's fire endurance. Therefore, it was not surprising that 70% of supertall towers were constructed as composites.

3.4. Interrelations of Height and Function

In Figure 6, the bars show the total number of towers (right axis) by function, whereas dots correspond to the building height (left axis) with such a function. As indicated in Figure 6, the building functions other than hotel exceeded 500 m as in the cases of CITIC Tower and Merdeka PNB118. Additionally, due to the very small number of hotel buildings, only one, it would probably be inaccurate to develop a correlation between the function of these buildings.

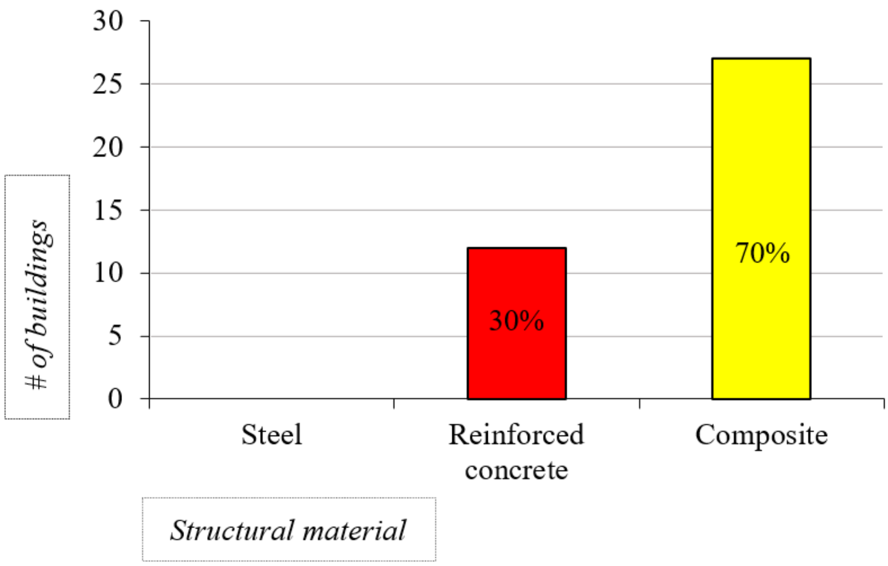


Figure 5. Freeform supertall buildings by structural material

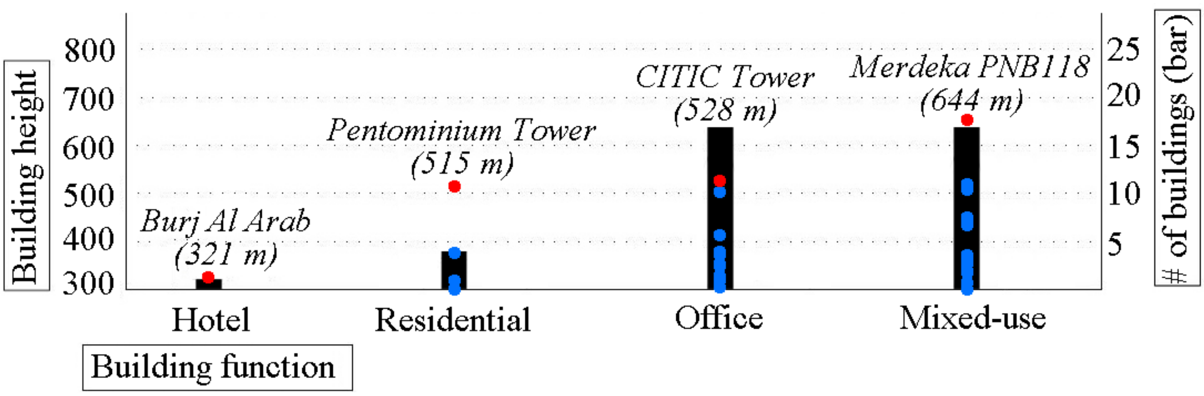


Figure 6. Interrelations of height and function

3.5. Interrelations of Height and Structural System

In Figure 7, the bars show the total number of towers (right axis) by the load-bearing system, while dots correspond to the building height (left axis) with such a system. As seen in Figure 7, the building with outriggered frame and tubular systems exceeded 500 m in the sample group. Moreover, because of the small number of towers with shear walled frame, mega column & mega core, and tube systems, it would probably not be accurate to obtain a relationship between the structural systems of these towers.

3.6. Interrelations of Height and Structural Material

In Figure 8, the bars show the total number of towers (right axis) by structural material, while dots correspond to the building height (left axis) with such a material. As shown in Figure 8, many composite towers were constructed above 400 m in height of the building as in Evergrande Hefei Center 1. Additionally, the 500 m limit was exceeded in both composite and reinforced concrete freeform structures, such as Pentominium Tower. Since there were no steel structures in the freeform sample group, a scientific judgment could not be reached from these structures.

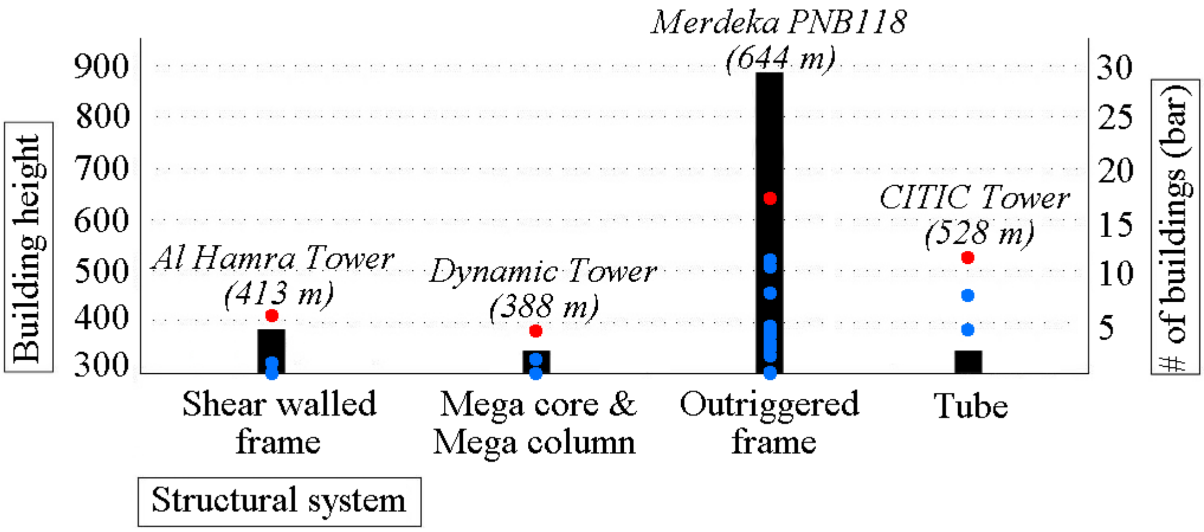


Figure 7. Interrelations of height and structural system

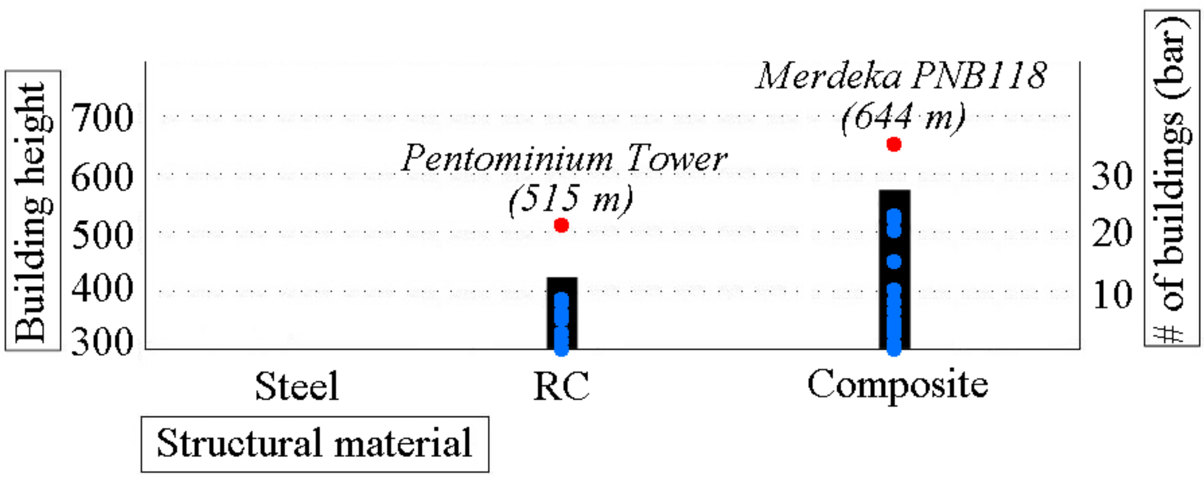


Figure 8. Interrelations of height and structural material

4. Discussion and Conclusions

Our findings show similarities and differences with other papers e.g., Ilgın et al. [20]. In 36 freeform towers, only the central core arrangement was preferred, which was similar to other studies [20,21]. Like tapered skyscrapers [23], freeform supertall towers were built mostly on the Asian continent. This finding was supported by Moon's paper [28], which highlighted Asia as a new hub for tall buildings. Asia, which forms the basis for today's skyscraper developments, is one of the regions where freeform design is at the forefront. Today, in the era of pluralism with various design approaches from local to international, Asian cities are trying to create international characteristics with large-scale high-rise structures with different forms [28]. The findings of office and mixed-use, which are the most preferred functions in this study, were also supported by the paper of Ilgın et al. [20]. Similarly, it was noted that the functions of the skyscrapers, which were designed as office buildings before, have changed and are now used as hotels, accommodations, and shopping centers [28]. The outriggered frame system and composite, which were the most common use among load-bearing systems and structural materials, respectively, came to the fore in other studies (e.g., [18]). In terms of interrelations of height and function, similar to the results in Ilgın's study [5], the building functions other than hotel exceeded 500 m in free form. In the sample group, freeform buildings with outriggered frame and tubular systems exceeded half a kilometer. Other building forms built with these structural systems were also challenged by height limits (e.g., [23]). The 500 m limit was exceeded in both composite and reinforced concrete freeform towers. Moreover, as the number of some supertall tower clusters (such as hotel buildings) was not adequate, it was hardly possible to establish a scientific correlation between planning considerations regarding building height.

In this research, using 39 supertall cases, interrelations between freefrom towers and major design parameters were examined. Consequently, it is thought that our findings will provide insight to key experts such as architectural and structural designers. In terms of skyscraper design, today's architects abandon the idea of a particular style and prefer to produce new structures in a highly pluralistic style, often featuring freeforms and iconic shapes. The reflection of this preference on structural design requires complex system solutions suitable for architectural design.

The experimental data presented in this article were limited to 39 case study towers. Yet, considering that the number of skyscrapers has grown substantially in the last decade, it can be anticipated that there will be an adequate number of building examples for consideration of small subcategories such as tubular supertall buildings.

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