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A Study on the Interaction of Structural System, Form, and Wind in High-Rise Buildings

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ABSTRACT
Advances in material science, the availability of high-strength materials, improved analytical tools, and a better understanding of structural design and behavior in high-rise buildings have produced lightweight and slender generations of high-rise buildings. The effect of wind loads on high-rise buildings' design and implementation processes is an essential issue for which architecture and engineering disciplines produce solutions together. This article examines the aerodynamic design strategies of high-rise buildings in the context of the structural system, form, wind interaction. In this study, the case study method was used to collect and analyze information about high-rise buildings, and a table was created with the criterion sampling method to understand the critical factors affecting the building performance for the field study, and the obtained data was analyzed. As a result of the examination, it was determined that it is essential to consider and evaluate the aerodynamic properties of high-rise buildings as a whole during and after the design phase within the scope of the structural system, as well as the form and wind precautions to be taken.
Keywords: Form, High-rise building, Structural system, Wind, Wind load.

1. INTRODUCTION
The world is experiencing the most significant wave of high-rise construction in history. With technological advances and design experience, considerable progress has been made in constructing high-rise buildings. Using high-strength materials, developing structural system designs, and lightweight flooring systems has reduced the building weight, damping values, and stiffness. Therefore, high-rise buildings are more susceptible to wind-induced excitations and wind loads (Mooneghi & Kargarmoakhar, 2016). Technological developments have increased the number and average height of high-rise buildings. This shows the efficiency of high-rise buildings in terms of architecture, structural design, and city. It also indicates that they will be important in urbanization shortly (Ilgın et al., 2021).

Advances in material science, the availability of high-strength materials, improved analytical tools, and a better understanding of structural design and behavior in high-rise buildings have produced lightweight and slender generations of high-rise buildings. Such buildings are exposed to time-varying loads such as earthquakes, winds, and gravity loads. Flexible high-rise buildings are susceptible to wind excitation, which affects the structural system and is an important design parameter (Amin & Ahuja, 2010; Davenport, 1988). Analyzing the effects of wind loads on buildings is one of the significant challenges in designing high-rise buildings. This condition is crucial for both human comfort and building durability. High-rise buildings' geometric form and structural components significantly affect wind forces and motion. Therefore, good design of structural components and the shape of the buildings minimizes wind excitation (Amin & Ahuja, 2010).

Regarding form, high-rise buildings are pretty complex, considering the numerous interdisciplinary interactions and design requirements. Only meeting the basic functional requirements in these high-rise buildings does not reveal the expression. In addition, architectural aesthetic vision, the structure's load-bearing system, aerodynamic form, and wind effects should also be considered. This article examines high-rise buildings in the context of the structural system, form, wind interaction. The number of structural system alternatives decreases as the building height increases. In other words, while structural system types are diverse in low-rise buildings, this situation becomes limited in high-rise buildings as the height increases (Ilgın & Karjalainen, 2023). Irregular building forms make this situation even more complicated, making the selection of the structural system type even more critical (Moon, 2011; Lacidogna et al., 2020).

Selecting a suitable structural system in building design is extremely important in providing resistance against wind forces. Wind, an unpredictable and dynamic force, can pressure high-rise buildings significantly. User comfort, general safety, and structural stability of the building are directly related to selecting the right structural system. A well-designed structural system design minimizes structural oscillation and vibration and effectively distributes wind loads. Different systems exhibit different performance behaviors under wind loads; therefore, choosing the optimum structural system is critical (Ali & Moon, 2007; Moon, 2014; Hasrat & Bhandari, 2025).

In the literature review, Ali and Moon (2007) researched technological advances and structural systems in developing high-rise buildings. Ali and Moon (2018) highlighted recent, emerging, and potentially emerging systems advances in high-rise buildings and provided a retrospective review of the significant structural systems. Xie (2014) summarized the aerodynamic approaches used in high-rise building design and examined the effectiveness and principles of these approaches. In their study, Li et al. (2025) found that aerodynamic effects in rectangular-shaped high-rise buildings have been studied extensively. However, this issue has received less attention in irregularly shaped high-rise buildings. For this reason, they designed different irregular forms, comprehensively analyzed aerodynamic effects, and discussed the results. Hui et al. (2023) studied the effects of wind on high-rise buildings with a design that meets both architectural and aerodynamic elements. The authors proposed a solution to reduce aerodynamic drag. Estrado et al. (2023) analyzed the wind effect on the structural behavior of a 3D building model. They developed a computational method to optimize the structural geometry to reduce wind effects at the design stage. Avini et al. (2019) investigated the wind loads on a prototype building with a rectangular cross-section of 80 m height. Hasrat and Bhandari (2025) conducted a performance-based wind analysis study to select optimal structural systems in reinforced concrete high-rise buildings. The study used different lateral load resistance systems, such as tube systems, X and V-type bracing, shear walls (at the center and corners of the building), and moment-resistant frame systems. Vibration performance against wind loads was investigated. As a result of the literature review, it is revealed that making interconnected decisions in the context of architectural and structural design in high-rise buildings is very important. In the study conducted by Takva et al. (2023), the design parameters and structural morphology of high-rise buildings were examined. As a result of the data they obtained, the authors designed two types of high-rise buildings. They investigated the effects of the building's structural system preferences on building performance and cost outputs.

Wind loads are one of the important parameters in the design of high-rise buildings. Buildings typically have sharp corners, which can cause wind flow separation, resulting in strong wind-structure interaction-induced loads. For a typical high-rise building, the aerodynamic forces are torsional moment, lift force, and drag force in the direction of the wind (Figure 1) (Mooneghi & Kargarmoakhar, 2016). Optimization of the building form is related to aerodynamic design parameters and reducing the effect of wind on the building surface.

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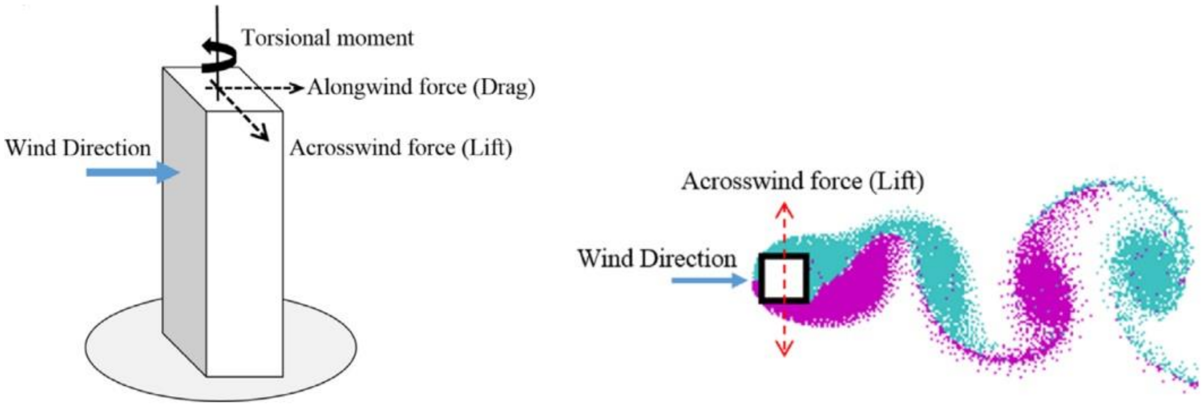

(a) (b)

Figure 1. (a) Aerodynamic forces on a high-rise building, (b) (plan view) Vortex shedding (Mooneghi & Kargarmoakhar, 2016).

The shape and formal structure of buildings decided during the design phase are essential for their performance against wind effects. Aerodynamic shapes, especially those with softened or rounded corners, can reduce the effects of wind forces (Figure 2) (Al-Najjar & Al-Azhari, 2021).

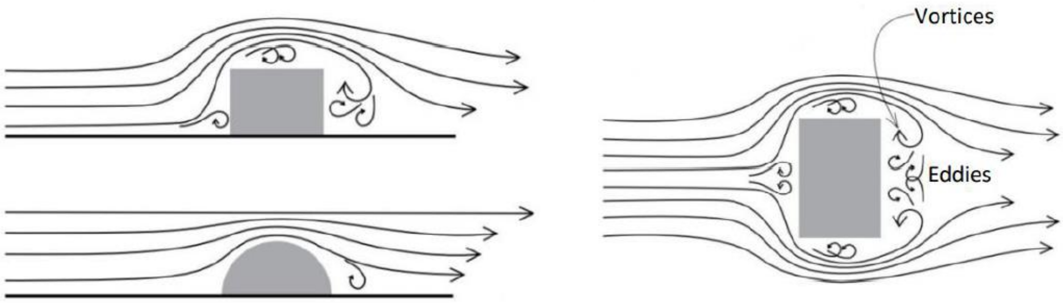

Figure 2. Wind forces, shape and form relationships (Ching et al., 2014).

This article examines the aerodynamic design strategies of high-rise buildings in the context of the structural system, form, wind interaction. In the field study conducted within the scope of the article, the eight tallest buildings constructed worldwide according to the Council on Tall Buildings and Urban Habitat (CTBUH) (URL-1) February 2025 data were compared in terms of form, plan scheme, aerodynamic design, Core location, Wind Load Adaptive Design Techniques, Structural system category, Aspect ratio features. The buildings examined were categorized using innovative technologies to reduce wind loads.

This study aims to contribute to the literature by determining the most effective strategies among different methods used within the scope of high-rise buildings' structural system, form, wind interaction. In addition, it reveals important results on how the cooperation between engineering and architecture disciplines can optimize structures in terms of aesthetics and durability. The study aims to bring innovative approaches within the structural system, form, wind interaction framework in high-rise building designs.

2. DESIGN TECHNIQUES TO REDUCE WIND LOADS IN HIGH-RISE BUILDINGS

2.1. Structural Systems in High-Rise Buildings

According to the studies conducted by Taranath, 1998; Ali and Moon, 2007; Gunel and Ilgın, 2007; Gunel and Ilgın, 2014; Ali and Moon 2018; Ilgın 2018, various structural systems and classifications are used in practice for lateral bracing of high-rise buildings. In

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light of the literature review, according to Ilgın et al., 2021 high-rise building structural system classifications are given in Figure 3.

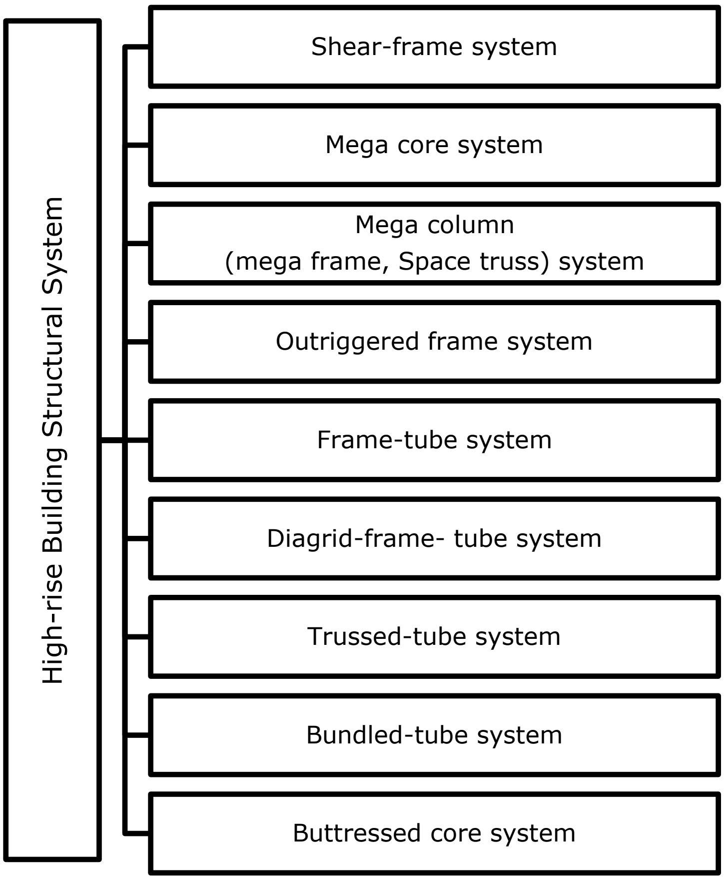
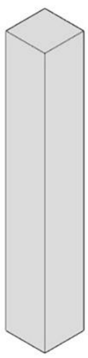
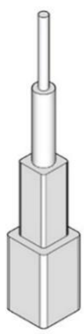
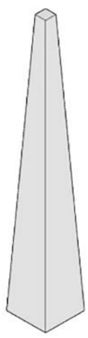
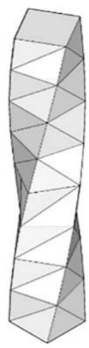
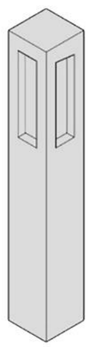
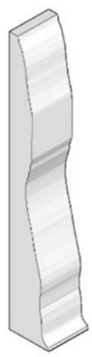


Figure 3. High-rise building structural system classifications (Ilgın et al., 2021).

2.2. Form in High-Rise Buildings

In high-rise buildings, building form is an important parameter in architectural design. The primary purpose is to minimize wind loads affecting the high-rise building. When the studies conducted by the authors Al-Kodmany and Ali, 2016; Ilgın, 2018; Ilgın et al., 2021, are examined, the classification given in Table 1 categorizes high-rise buildings according to their forms.

Table 1. Different form categories in high-rise buildings (Source: Authors).

Form	Prismatic	Setback	Tapered	Twisted	Porosity	Free
Schematic visual						

According to the study by Xie, 2014, some of the commonly used corner modifications in the plan diagram within the framework of the basic approach that can be applied to reduce wind loads are given in Figure 4. As a result of wind tunnel tests, a corner setback scheme

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was developed that reduced the overall design wind loads by approximately 25% compared to the original design (Xie, 2014; Irwin, 2010; Xie, 2012).

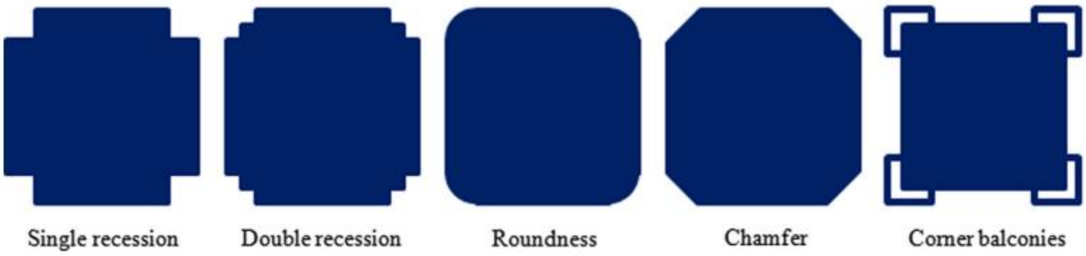

Figure 4. Corner modification examples (Xie, 2014).

Mooneghi and Kargarmoakhar (2016) emphasized that common building shapes are square or rectangular, and these shapes expose the building to relatively strong vortex-induced forces. Minor modifications can reduce these excitation forces in the shape of the building. As given in Figure 5, changes such as chamfered corners, slotted corners, corner recesses, rounding of corners, and changing the orientation of the building according to the most common strong wind direction are observed. Changing the corners towards the wind can reduce drag and fluctuating lift forces. The authors emphasized that these methods can reduce cross-wind and parallel-wind responses compared to rectangular buildings.

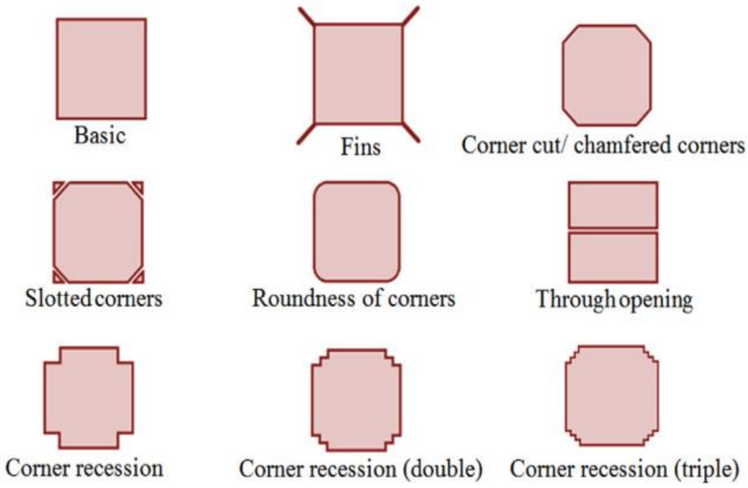

Figure 5. Minor aerodynamic modifications (Mooneghi & Kargarmoakhar, 2016).

2.2.1. Aspect (slenderness) ratio

As shown in Figure 6, The aspect ratio, defined as the ratio of the building height (H) to the narrow part of the building width (B), is the ratio of the structural system. Unlike dead and live loads, wind loads can change suddenly and rapidly. Buildings with an aspect ratio equal to or greater than six or more than 40 stories can be considered slender and flexible. For these buildings and those with unusual forms, it is necessary to consider the dynamic effect of wind. For this reason, wind tunnel tests are recommended for such buildings (Ilgın, 2018).

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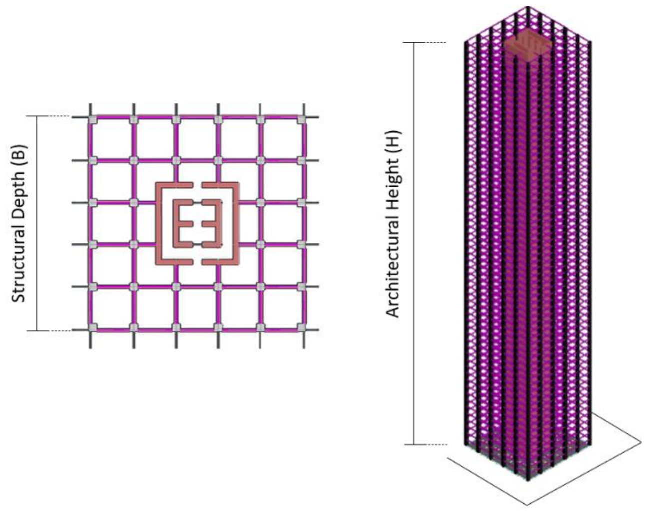

Figure 6. Aspect ratio (H/B) (Source: Authors).

3. MATERIAL AND METHOD

Within the scope of the study, the structural system, form, and wind relationship in high-rise buildings were examined. In this study, the case study method was used to collect and analyze information about super high-rise buildings, and a table was created with the criterion sampling method to understand the critical factors affecting the building performance for the field study, and the obtained data was analyzed. The designs of the examined buildings and the strategies used to reduce wind loads were evaluated.

By conducting a comprehensive literature review, studies on high-rise buildings were investigated, and the evaluation criteria for high-rise buildings were examined. In this context, the eight tallest buildings constructed worldwide were examined based on CTBUH February 2025 data (URL-1). In recent years, especially with the advancement in wind engineering, there has been a significant increase in the number of high-rise buildings. Today, high-rise buildings are encountered in many places. Figure 7 shows the eight tallest buildings examined within the scope of the study. Burj Khalifa stands out as the tallest building in the world, with a height of 828 m.

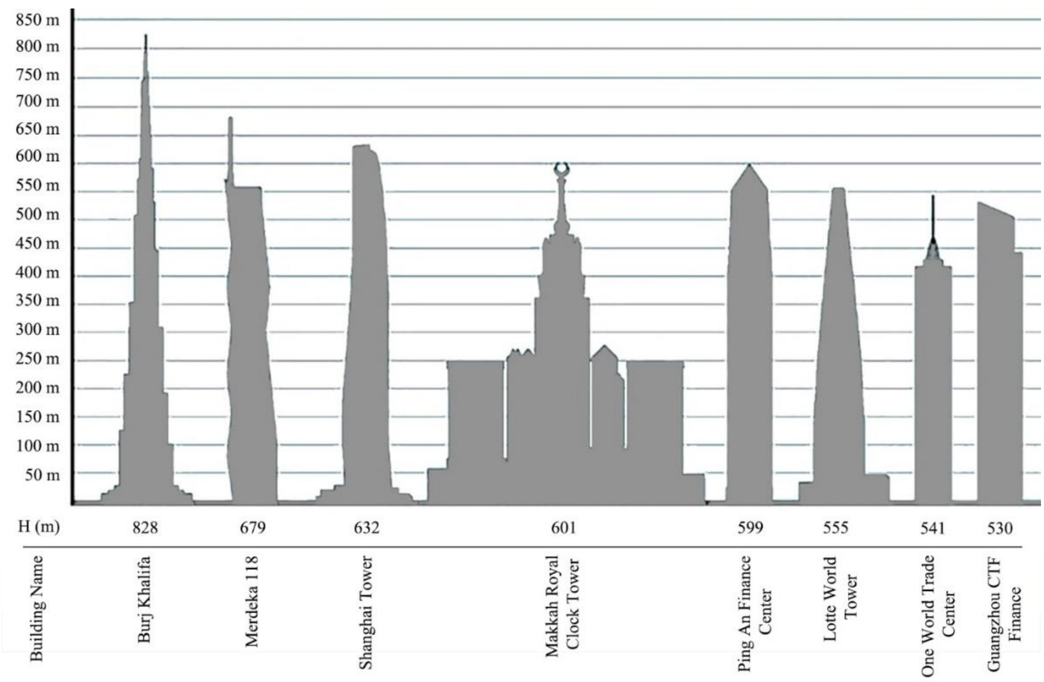

Figure 7. The tallest building in the world in February 2025 (Source: Authors).

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In order to ensure adequate representation of the eight tallest buildings constructed within the scope of the study, an examination table was created based on the criteria in Table 2. According to the data in Table 2, high-rise buildings are classified as multi-fiction or single-use in terms of functionality. Reinforced concrete and composite materials were preferred as structural materials.

Table 2. Representative of the eight tallest buildings examined (Source: Authors).

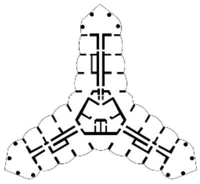
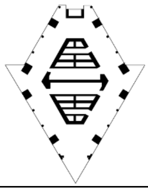
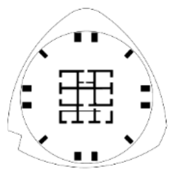
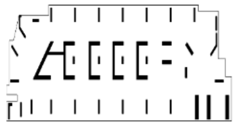
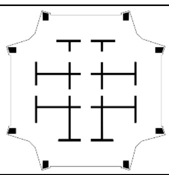
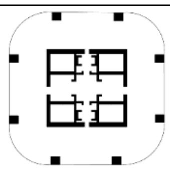
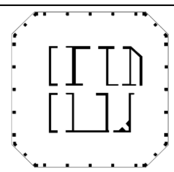
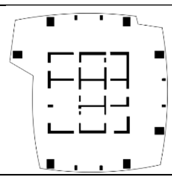
Name	Burj Khalifa	Merdeka 118	Shanghai Tower	Makkah Royal Clock Tower
Location	Dubai	Kuala Lumpur	Shanghai	Mecca
Completion	2010	2023	2015	2012
Floors/ Height (m)	163/828	118/679	128/632	120/601
Structural Material	Reinforced concrete	Composite	Composite	Reinforced concrete
Function	Multi-function	Multi-function	Multi-function	Hotel
Overview				
Name	**Ping An Finance Center**	**Lotte World Tower**	**One World Trade Center**	**Guangzhou CTF Finance Center**
Location	Shenzhen	Seoul	New York	Guangzhou
Completion	2017	2017	2014	2016
Floors/ Height (m)	115/599	123/555	94/541	111/530
Structural Material	Composite	Composite	Composite	Composite
Function	Office	Multi-function	Office	Multi-function
Overview				

*The source of the high-rise photographs in the table is taken from the CTBUH website (URL-2).

4. FINDINGS AND DISCUSSION

The number of high-rise buildings is increasing thanks to technological advances, increased strength in building materials, and advances in concrete pumping techniques. As a result of these developments, it is known that the number of high-rise buildings is constantly increasing worldwide. The parameters examined within the scope of the study are given in Table 3. Building form, plan scheme, core location, wind load adaptive design techniques, structural system category, and aspect ratio. The authors created these parameters as a result of the literature review to express the study's boundaries most comprehensively.

Table 3. Structural system, form, and wind analysis of high-rise buildings (Source: Authors).

Name	**Burj Khalifa**	**Merdeka 118**	**Shanghai Tower**	**Makkah Royal Clock Tower**
Building Form	Setback	Free	Twisted	Prismatic
Plan scheme				
Core location	Central core	Central core	Central core	Central core
Wind Load Adaptive Design Techniques	Aerodynamic form	Aerodynamic form	Aerodynamic form	Aerodynamic form
Structural system category	Buttressed core system-Outrigger frame system	Outrigger frame system	Outrigger frame system	Outrigger frame system
Aspect ratio	10.5	6.7	7.6	-
Name	**Ping An Finance Center**	**Lotte World Tower**	**One World Trade Center**	**Guangzhou CTF Finance Center**
Building Form	Tapered	Tapered	Tapered	Setback
Plan scheme				
Core location	Central core	Central core	Central core	Central core
Wind Load Adaptive Design Techniques	Aerodynamic form	Aerodynamic form	Aerodynamic form	Aerodynamic form
Structural system category	Outrigger frame system	Outrigger frame system	Outrigger frame system	Outrigger frame system
Aspect ratio	8.3	7.9	8.5	8.5

In examining h, high-rise buildings in the context of structural system, form, and wind, the eight tallest buildings constructed in the world according to CTBUH February 2025 data were considered, and evaluations were made within the framework of the determined parameters.

- When the building forms are examined, setback, free, twisted, prismatic, and tapered forms are preferred. Different form configurations are used throughout the building height to minimize wind loads' effects on the structure.

- When looking at the plan schemes, it can be said that different plan schemes are used. In wind interaction in high-rise buildings, minor aerodynamic modification methods are used in all plan schemes. In this way, the aim is to reduce cross and parallel wind effects.

- In all the buildings examined, it is seen that the core is at the plan center. The central core system was preferred in order to make maximum use of the facades. With this approach, where the center of gravity and the center of rigidity overlap, the stability and durability of the structure are ensured.

- When the design criteria against wind loads are examined, all of the buildings are based on aerodynamic form design, and wind engineering and analysis are important parameters in the design, considering wind loads.

- As a structural system, the use of an outrigger frame system was determined in the eight tallest buildings constructed in the world. In Burj Khalifa, an outrigger frame was used together with a buttressed core. In light of the data in Table 3, it can be said that the outrigger frame system is one of the most preferred structural systems in high-rise buildings.

- The aspect ratio and the structural system are related to each other. The aspect ratio is a parameter that significantly affects the structural behavior of high-rise buildings. When the high-rise buildings in Table 3 are examined, it is seen that the lowest value of this ratio is 6.7, and the highest value is 10.5. No clear information was obtained regarding the slenderness ratio for the Makkah Royal Clock Tower.

In light of the analyses, inferences, and evaluations were made in the context of high-rise buildings' structural system, form, and wind relationship, and discussions were presented. Wind loads in high-rise buildings and advanced techniques to reduce these loads were included. The study aimed to create awareness and consciousness among architects, engineers, and those interested in the subject.

5. CONCLUSION

When it comes to modern cities, one of the first symbolic expressions that comes to mind is high-rise buildings. High-rise buildings play an active role in the emergence of modern city silhouettes. Today, countries are racing to design and build the tallest building. This situation undoubtedly contributes to the development of high-rise buildings. The effect of wind loads on high-rise buildings' design and implementation processes is an important issue for which architecture and engineering disciplines produce solutions together. The aerodynamic forces caused by wind loads and the deformations caused by these forces come to the forefront as an important factor in terms of maintaining the durability and stability of the building.

The study examined designs compatible with wind load in high-rise buildings in the context of structural system, form, and wind relationship, and the effects and applications of aerodynamic design techniques were evaluated. It was determined that these techniques play a key role in creating a balance between aesthetics, stability, and durability in buildings. These innovative approaches have been developed to increase structural safety and improve user comfort. In the field study of the article, the eight tallest buildings constructed in the world were examined and tabulated in the context of structural system, form, and wind categories based on CTBUH February 2025 data. As a result of the examination, it was determined that it is essential to consider and evaluate the aerodynamic properties of high-rise buildings as a whole during and after the design phase within the scope of the structural system, form, and wind precautions to be taken. It is seen that these buildings are considered a good reference for high-rise buildings to be built in the future, and it is envisaged that these techniques will be further optimized and developed.

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