EVALUATION AND COMPARISON OF CONSTRUCTION TECHNOLOGIES FOR HIGH-RISE BUILDINGS *

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Keywords

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Structural Systems
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Abstract

The development of human societies in different countries around the world is increasing dramatically. High-rise buildings are being constructed as a response to the challenges of limited and expensive urban land, and they are crucial for urbanization. Today, besides serving as structures for economic growth in cities, high-rise buildings remain symbolic of prestige and power for countries and companies. These buildings entail immense architectural and engineering complexity, necessitating a comprehensive planning approach for their design and construction. With the availability of numerous alternative solutions for various aspects of building design and construction systems, there is a need for an evaluation framework that is comprehensive, transparent in decision-making, and reliable and practical in its application. The aim of the article is to create a framework for the evaluation of construction systems, building materials, construction technologies, and methods of high-rise buildings. The scope of the article is the 30 tallest buildings listed in CTBUH (Council on Tall Buildings and Urban Habitat). After evaluating the effects caused by the elevation of buildings and the application options for these effects, examining the scope according to these application options and as a result creating matrices for each building constitutes the method of the study.

YÜKSEK KATLI BİNALAR İÇİN YAPIM TEKNOLOJİLERİNİN DEĞERLENDİRİLMESİ VE KARŞILAŞTIRILMASI *

Anahtar Kelimeler

Yüksek Binalar
Strüktür Sistemleri
Yapım Teknolojileri
Yapım Yöntemleri
Yenilikçi Yaklaşımlar

Öz

Dünya genelinde farklı ülkelerde insan toplumlarının gelişimi dramatik bir şekilde artmaktadır. Sınırlı ve pahalı kentsel arazinin zorluklarına cevap olarak inşa edilen yüksek binalar kentselleşme için hayati öneme sahiptir. Yüksek binalar, şehirlerde ekonomik büyümeye hizmet etmenin yanı sıra, ülkeler ve şirketler için prestij ve gücün simgesi de olmaktadır. Bu binalar, kapsamlı bir planlama yaklaşımını gerektiren geniş bir mimari ve mühendislik karmaşıklığı içermektedir. Bina tasarımı ve inşaat sistemlerinin çeşitli yönleri için birçok alternatif çözüm bulunmasıyla birlikte, kapsamlı, karar vermede şeffaf ve uygulanması güvenilir ve pratik olan bir değerlendirme çerçevesine ihtiyaç vardır. Bu makalenin amacı, yüksek binaların yapım sistemleri, yapı malzemeleri, inşaat teknoloji ve yöntemlerinin değerlendirilmesine yönelik bir çerçeve oluşturmaktır. Makalenin kapsamı, CTBUH'da (Council on Tall Buildings and Urban Habitat) listelenen en yüksek 30 binadır. Binaların yükselmesi ile oluşan etkilerin ve bu etkilere yönelik uygulama seçeneklerinin değerlendirilmesinin ardından kapsamın bu uygulama seçeneklerine göre irdelenmesi ve sonuç olarak her bina için matrisler oluşturulması, çalışmanın yöntemini oluşturmaktadır.

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Introduction

High-rise buildings stand out as the symbolic structures of all modern cities because of the prestige they represent and the strong emotional reactions they evoke. Although high-rise buildings have been built for religious purposes since ancient times, technologically, high-rise buildings are an invention of the late 19th century. With the developing technology after the Industrial Revolution, these and similar structures found the opportunity to develop vertically. "The first true tall building was the Home Insurance Building of 1885, the brainchild of architect William LeBaron Jenney who came up with the idea of using an internal steel skeleton to carry the structural loads of the building," (Noderer, 1952). This 11-story building has been recognized as the world's first skyscraper by the CTBUH (CTBUH-1, 2023) and some other sources (Domosh, 1987; Leslie, 2010; Preservation Chicago, 2006).

The practicability of high-rise buildings has been possible with a series of technological developments. The first of these is the progress in structural systems and building materials. In the economic conditions before the 1st World War, the use of stone, the traditional structural system, became widespread, and this, of course, was associated with problems. "As buildings rose higher, the thickness of stone walls at the base soon became untenable, a situation exemplified by Chicago's Monadnock Building of 1893, designed by Daniel Burnham and John Root" (Nagelberg, 1967). Another example is the Dakota Apartments, a residential complex built in New York's Upper West Side in 1884. While the thickness of the masonry perimeter walls on the ground floor of the nine-story building is 7.1 m, this thickness decreases to 4.1 m from the sixth floor (Landau and Condit, 1996). This has led to a significant reduction in the building's salable and leasable effective areas. With the Industrial Revolution and the two world wars that followed, the steel industry developed, and the use of steel and concrete as building materials opened the way for the construction of high-rise buildings.

However, the structural steel developments were insufficient for the development and feasibility of high-rise buildings. The period between 1885-1930 was the invention of elevator systems that accelerated the development of high-rise buildings. The elevator system was also another innovation in Home Insurance Building (Valente, 2012). Afterward, developments in hydrophore, fire safety, heating, ventilation, and air conditioning systems were also important factors, as well as the elevator. In the 1910s, higher buildings such as the Woolworth building (the highest building before World War I), which consisted of 55 stories of a reinforced concrete (RC) structure, symbolized the Gothic style with a height of 241 meters, and 18 years later the Empire State Building with 102 stories, height 381 meters were built. In the early 1930s European Modernists became interested in the typology can change it forever. "Le Corbusier's Cartesian Skyscraper and Mies Van Der Rohe's glass skyscraper foreshadowed a movement in architecture that would last to this day" (Abel, 2003).

Definition of the Problem

As the height rises with each new high-rise building, the effects of vertical loads (such as live loads and dead loads) and lateral loads (such as wind and earthquake) on the structure have increased at the same rate. Thus, innovative applications became necessary, both in the establishment of the ground-building relationship and in the design of the structure. These problems are significantly solved with innovative structural systems, and formwork systems which are used to construct tall buildings. determining how the world's highest buildings use these innovative applications and systems has formed the research motivation of the paper.

Aim, Scope, and Method

This article aims to examine the relationships between building height and the use of innovative applications that respond to this need for elevation. Furthermore, the study has focused on the analysis of the structural systems, materials, and formwork methods employed in the world's 30 tallest buildings listed by CTBUH. The reasons for using the database in question, CTBUH;

- gives titles such as "World's Tallest Building" and refereeing building heights;
- organizes annual conferences and global awards programs on the subject;
- establishes academic collaborations for funded research projects;
- recognized as a global authority with extensive online resources and physical outputs (CTBUH-2, 2023).

After evaluating the effects caused by the elevation of buildings and the application options for these effects, examining the scope according to these application options and as a result creating matrices for each building constitutes the method of the study.

1. Definition of High-Rise Buildings

Looking at the history of American urban architecture at the turn of the twentieth century, it is seen that high-rise buildings emerged as a response to the rapidly increasing urban population (Brown, 2011). Today, many reasons, including the attempt to produce a concept of the skyline, a national credit or pride, and cultural identity, have made high-rise buildings an inevitable feature of urban development, (Al-Kodmany, 2013).

Since the emergence of high-rise buildings, many definitions have been made in different parts of the world, depending on different social, environmental, cultural, and urban conditions, that can be taken into account in the designation of high-rise buildings. For example, the height and proportion of the building in comparison to the urban built environment around it are factors that can be taken into account in the determination of high-rise buildings (Figure 1). A building that is not particularly tall can be classified as a tall building if it has sufficient slenderness. Another consideration that can be taken into account in the determination is whether typical technical solutions for 'tall buildings' are used. (Partovi and Svard, 2016).

On the other hand, high-rise buildings are referred to as 'tower buildings' and 'skyscrapers' (Hasol, 2003). They are defined as "the building with a very high height compared to the floor area" (Hasol, 1993) and "the building whose height is at least 60.50 m at the lowest elevation visible from any of its facades according to the Zoning Regulation" (Hasol, 2017).

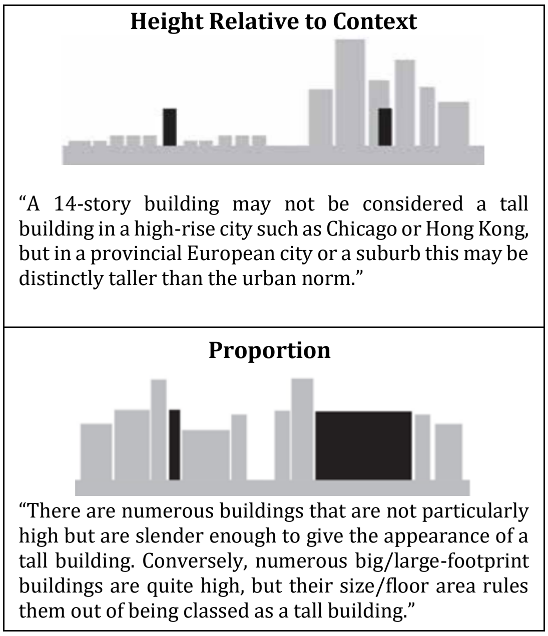
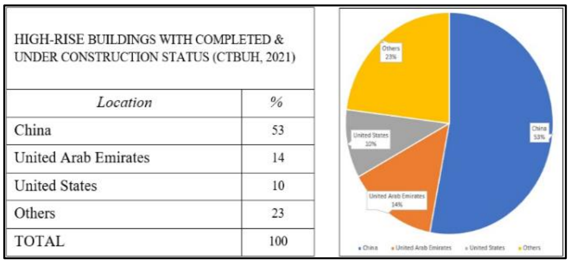


Figure 1: CTBUH Height Criteria for Measuring & Defining Tall Buildings (CTBUH-3), Source: CTBUH-3, 2023

According to (CTBUH-2021) a supertall building is defined as a building over 300 m, and a mega-tall building is defined as a building over 600 m. Another definition states that high-rise buildings are "buildings having many stories; sufficiently tall so that the use of an elevator is essential" (Harris, 2000:472). As can be seen, different sources provide varying definitions of high-rise buildings based on criteria such as proportion, quantitative height, and/or number of floors.

From a global perspective, in terms of the countries with the highest number of high-rise buildings, as shown in Figure 2, three countries hold the record for the most high-rise constructions, accounting for approximately 77% of all high-rise buildings completed and under construction worldwide since 1980. China has the highest number of high-rise buildings in the world, accounting for 53%. Dubai, with iconic high-rise buildings like Burj Khalifa and Marina 101, ranks as the country with the second-highest number of skyscrapers, accounting for 14%. The United States is the third leading country, with 10% of the world's highest buildings (CTBUH-4, 2021).



HIGH-RISE BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (CTBUH, 2021)

Location	%
China	53
United Arab Emirates	14
United States	10
Others	23
TOTAL	100

Figure 2: The rate of "the high-rise buildings with completed and under construction status" regarding location. Source: CTBUH-4, 2021

As shown in Figure 3 the average height of a high-rise building varies from year to year. According to the (CTBUH-5, 2021) the average height of the 20 highest buildings declined to 351 meters, down from 377 meters in 2019 (the highest figure recorded in 20 years). The average height of all buildings 200 meters and higher to complete in 2020 was 254 meters.

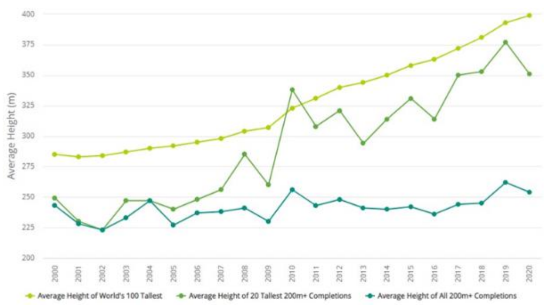


Figure 3: World's 100 Highest Average Building Height. Source: CTBUH-5, 2021

As a result, as the high-rise building race in the world continues, it is seen buildings that need more innovative solutions are designed and built with both increasing height and different aesthetic concerns. Considering that the evolution of structural systems is a process that follows the rise of structures step by step, it is clear that there will be more elegant solutions in the future.

2. Structural Systems in High-Rise Buildings

The structural systems of high-rise buildings are determined based on the vertical and lateral loads they experience. As the height of a building increases, various factors contribute to the overall weight, including the building's structural components, architectural elements such as walls, finishing works, technical equipment, exterior systems, and more. These factors collectively contribute to the vertical loads, commonly referred to as dead loads. Additionally, as the building's usage area expands, there will be an increase in the number of occupants and movable items such as furniture, which are considered live loads.

Furthermore, high-rise buildings are subjected to lateral loads such as earthquakes and wind forces, which also escalate with the building's height. Designing high-rise structures typically involves intricate calculations and computer simulations to ensure that the building can safely withstand all anticipated vertical and horizontal loads. These analyses are essential to guarantee the structural integrity and safety of the building under various loading conditions.

2.1. Vertical Loads on the Structure of High-Rise Buildings

It is evident that a high-rise building is subjected to a wide range of different loads, both external and internal, which can be static or dynamic in nature. In this simple classification, the direction of the loads is taken into account, as previously mentioned.

"The weight of the building itself, along with the weight of the occupant, furniture, and equipment inside the building," are typically distributed through the columns and beams of the structure, and ultimately transferred to the foundation (Garrison, 2005). Beams are designed to withstand bending stress. Columns are designed to withstand the compressive forces resulting from the building's weight and also shear forces resulting from the lateral loads such as earthquake and wind effects, while the foundation is constructed to safely distribute these forces into the ground.

The distribution of vertical loads through the columns and beams of a high-rise building is accomplished through a specifically designed structural system. This system typically comprises a network of columns, beams, and slabs that collaborate to support the building's weight and distribute it to the foundation.

The columns, which transfer the load from the beams to the foundation, are vertical elements typically made of RC or steel. They are utilized to resist compressive forces (Nakipoğlu et al, 2022). The size and spacing of the columns are determined by various factors, including the building's height, the structure's weight, and the expected loads.

Horizontal elements are known as beams span between the columns and provide support for the slabs. Similar to columns, beams are also constructed from RC or steel and designed to resist bending and shear forces. The size and spacing of the beams depend on factors such as the distance between columns and the anticipated loadings they will carry (Nakipoğlu et al, 2022).

Slabs, on the other hand, are the horizontal elements constituting the building's floors. Typically made of RC, slabs are supported by beams. The size and thickness of the slabs are determined by factors including the span between beams and the anticipated loadings they will bear (Abdulwahid et al, 2013). Through the collective efforts of columns, beams, and slabs, a high-rise building forms a load-bearing system capable of supporting the structure's weight and distributing it to the foundation. This meticulously designed system ensures the long-term safety and stability of the structure.

2.2. Lateral Loads on the Structure of High-Rise Buildings

A high-rise building is threatened by lateral loads specifically due to its height. These lateral forces are the load-bearing forces caused by elements such as wind, earthquakes, live loads on the building or the equipment carried by the building, and ground movements due to various geological effects.

Wind load is the most intense and unpredictable lateral load that has a great impact on high-rise buildings. As the height of the building increases, the wind load also increases. Wind load can be divided into both static and dynamic loading depending on the period. "Static wind effect primarily causes elastic bending and twisting of structure. Dynamic wind effect for a high, long span and slender structures requires a 'dynamic analysis' of the structure" (Mendis et al., 2007).

A building is a barrier against the wind. When a building is exposed to wind gusts, wind currents run parallel to the center on either side of the building, which is called a vortex shedding, this is especially true in high-rise buildings (Figure 4). The reason for this effect is that the high-velocity wind spreads to both sides simultaneously. Vortex shedding, causes alternating whirling air folds to form at a certain frequency (Krishnappa et al, 2022). This stimulates the structure and creates periodic lateral forces that cause vibration.

These vibrations can be harmful if they coincide with the natural frequency of the building and eventually cause the building to get tired.

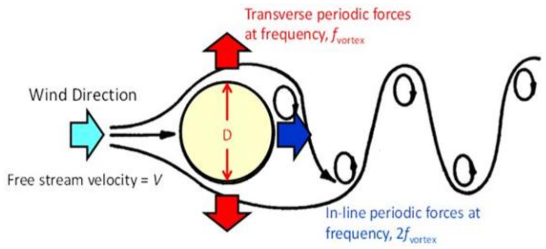


Figure 4: Vortex Shedding Phenomenon on High-rise Buildings. Source: MECA, 2023

Earthquakes, another lateral force, are also one of the most dangerous and unexpected loads that cause a lot of damage to structures in various ways. The ground plates are constantly moving, the pressure increases as these plates continue to move. When the pressure reaches a critical threshold, it releases energy in the form of seismic waves, and an earthquake occurs. The duration of ground movements is usually a few seconds or even minutes for large earthquakes. Earthquakes are measured in terms of acceleration in both directions.

3. Precautions Against Lateral Loads

Recently, new ideas and designs have been proposed to design earthquake reinforcement to improve structural behavior during ground motion and replace traditional designs. One suitable method is to use various techniques to control structural vibrations (Chikmath et al, 2022). Energy attenuating systems, different types of dampers as well as base isolation devices can be used for such purposes to prevent buildings from possible damage by reducing the structural response during earthquakes (Naderpour, et al., 2019). Apart from these, there are ground improvements, deep foundation systems, structural monitoring of lateral movements in buildings, innovative arrangements in building elements such as core and columns, and innovations in building materials. Within the scope of the study, building materials, structure systems and formwork technologies used in the creation of these structural systems will be discussed.

3.1. Materials Used in High-Rise Buildings

High-rise buildings can utilize different materials in their structural systems, including reinforced concrete (RC), steel, and composite materials that combine the two. However, there are limitations to using wood as a material for tall buildings due to factors such as cost, structural strength, and especially fire safety. Examples of wooden high structures include Mjøstårnet in Brumunddal, Norway, Limberlost Place in Toronto, Canada, 503 on Tenth in Portland, USA, and Treet buildings, but their heights are relatively limited.

Several designs for taller buildings, such as the W350 Tower in Tokyo, Japan with 70 floors and 350 m height, Oakwood Tower in London, England with 80 floors and 300 m height, and River Beach Tower in Chicago, USA with 80 floors and 228 m height, have remained at the concept stage.

In the 1960-1970s, steel was commonly used in high-rise buildings, but since the 1970s, the use of RC has increased due to its high strength and performance compared to steel. In recent years, composite structures have gained popularity due to their combination of the axial loads of concrete and the high resistance of steel against horizontal loads. According to the CTBUH database, 7 of the world's 100 tallest buildings have all-steel structures, with the newest being 30 Hudson Yards in New York, USA, completed in 2019. This indicates that steel is not widely preferred in high-rise buildings beyond a certain threshold due to structural and economic considerations.

Concrete, although it has high compressive strength, has low tensile stress capacity. To address this weakness, steel reinforcements are added to concrete, resulting in the emergence of RC as a building material. In the CTBUH database, 27 out of the world's 100 tallest buildings are constructed entirely with concrete, with the newest being the Central Park Tower, a 98-floor building with a height of 472.4 m, completed in 2020. This building is currently the tallest all-concrete building globally, ranked 13th among the top 100. Most of the other all-concrete buildings (excluding the Central Plaza in Hong Kong built in 1992) were constructed after 2008.

Composite structures have gained popularity as innovative structural systems because RC consumes less usable floor area compared to steel. The combination of concrete's axial load capacity and steel's resistance to horizontal loads has led to the increased use of composite elements in buildings. The prevalence of composite structures has been observed in North America, Japan, and Europe since the late 19th century. In the CTBUH database, 63 out of the world's 100 tallest buildings and 12 of the highest buildings have composite structures, indicating that composite solutions are a more suitable option for the growing trend of tall buildings.

3.2. Structural System Types of High-Rise Buildings

In the early 20th century, the primary focus of structural systems in buildings was on withstanding vertical loads. However, in the 1960s, significant changes were made to the structural systems of high-rise buildings, leading to the adoption of more suitable systems beyond the widely used "rigid frame system" for large steel or concrete buildings. Advancements in materials research, aiming to discover materials with high strength and low density, have made it possible to increase the height of buildings while reducing their weight. However, as mentioned earlier, horizontal loads caused by wind and earthquakes pose significant challenges. Therefore, particularly in high-rise buildings, new structural systems are designed to account for not only vertical loads (such as fixed loads and live loads) but also lateral loads resulting from wind forces and seismic waves. Starting from the 1960s, research on classifying height-based load-bearing systems began, and as a result, the load-bearing systems of high-rise buildings were categorized into two groups: exterior and interior structures. This classification was established by Falconer in 1981;

3.2.1. Interior Structures

The systems in the interior structure group are;

- rigid frame system,
- braced hinged frame,
- shear wall hinged frame,
- staggered truss,
- shear wall (shear truss) - frame interaction,
- core outrigger,
- buttressed core.

The 'rigid frame system', also known as the 'moment-bearing frame system', is a structural system used in steel or RC-constructed high-rise buildings consisting of linear elements such as beams and columns, connected to each other by nodal points based on moments.

The 'braced hinged frame', usually works by combining two structural systems, one main and one subsidiary. The goal is for buildings to show the lowest slope among other domains against lateral loads. This system consists of 'steel shear trusses' in addition to 'steel hinged frames' that are constructed in a single diagonal, cross bracing, k bracing, and v bracing.

The 'shear wall hinged frame', is used in RC buildings and is an interconnected shear wall. The interconnections of the elements of this system provide stiffness beyond the overall strength of the shear walls. This system is used for buildings within 10 -80 stories or even higher buildings. The remarkable point of this system is the location of the shear wall to carry the horizontal load and limit the horizontal displacement. Therefore, the location of the shear wall in the design is very important to choose correctly.

The 'staggered truss' system, is a type of structural steel frame used in high-rise buildings. The system consists of a series of high trusses arranged in steps on adjacent column lines, covering the overall width between two rows of outer columns, and can be built up to 40 stories.

The 'shear wall (shear truss) - frame interaction', consists of two groups (braced rigid frame) and (shear wall rigid frame). this system can provide the necessary lateral strength in terms of bending mode, and a more efficient console, and the internal core can be designed for gravity loads. Shear walls and truss structures can provide stiffness of up to 40 stories and allow for larger openings.

The 'core outrigger' system, consists of a central core with outriggers, connecting the core to the outer columns. The central core contains either braced frames or shear walls. The outrigger system considering the advent of mega-columns for exceptionally high-rise buildings in the perimeter structure can be built up to 150 stories.

The 'buttressed core' system, has a different plan (applied with a Y-shaped or triangular plan with three wings with a central core), the design of which uses conventional materials and structural techniques with a significant increase in height. It is a system with an inherently stable form in which each wing is supported by two other wings that together create shear strength and increased moment of inertia. The core also provides the torsional strength of the building. This system can provide a height of over 1000 meters (200 stories).

3.2.2. Exterior Structures

External structure subsets are;

- framed tube,
- braced tube,
- bundled tube,
- tube-in-tube,
- diagrid,
- space truss,
- superframe.

The 'framed tube', is an economical solution for high-rise buildings. In this system, the peripheral parts of the building are allocated for the installation of columns at very close distances, which are connected to each other by thick beams. This system consists of rigid frames, but the difference between this system and rigid frames is due to the following features: The columns are very close to each other and contain rigid vertical elements (beam + slab), which work exactly like a tube and appropriate for buildings having 40-100 stories.

The 'braced tube' system, is designed to increase the user capacity in high-rise buildings and to locate a large distance between columns. Therefore, the number of columns is reduced, which is economically desirable. The braced tube system is obtained by adding diagonal elements that often intersect at the corner columns of the tube structure. With this reinforced system, higher buildings with 100-170 stories can be built (Ali and Moon, 2018).

New construction systems are constantly being developed to achieve a higher level and minimize the "slip delay" phenomenon. One of the systems is the 'bundled tube' system. The stated structural system is created by grouping two or more independent interconnected tubes to obtain a single multicellular tube. A bundled tube system is built to effectively resist any external force, whether from the braced tube or frame tube in general, and is appropriate for buildings within about 110 stories. One of the most famous examples of buildings using this system is the Willis Tower (formerly Sears Tower) (Figure 5).

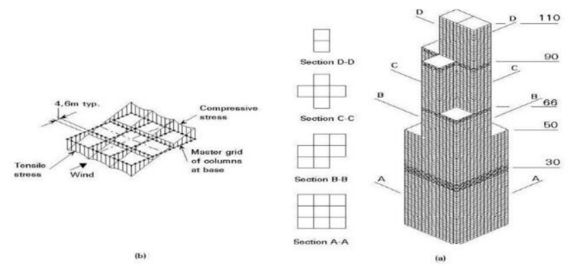


Figure 5: Willis Tower. (a) Shear Leg Behaviour. (b) Modular Floor Configuration. Source: Marabi, 2016.

The 'tube-in-tube' system, also known as "hull and core", consists of a core tube inside the structure which holds services such as utilities and lifts, as well as the usual tube system on the exterior which takes the majority of the gravity and lateral loads. The inner and outer tubes interact horizontally as the shear and flexural components of a wall-frame structure" (Sreevalli, et al., 2017). This system can be constructed 90–150 per different tube.

One of the structures that has recently emerged as a new solution for high-rise buildings that combines structural strength, decorative features, and morphological adaptability is called 'diagrid structures'. This system can be built in these two groups; (1) 'uniform-angle diagrid' (steel, concrete, and composite types are used) can be constructed up to 80-110 stories; (2) 'varying-angle diagrid' (steel or composite) can be used up to 130 stories.

The 'space truss', emerged in search of light, fast, and industrial solutions in high-rise building technologies. This system ensures that large openings in buildings are executed with a column-free and lightweight structure, making the structures more flexible and efficient in terms of performance. Up to 150 stories are mostly constructed with composite.

The 'super frame', also known as 'mega frame', is categorized into the stand-alone super frame and super framed conjoined tower structure which is a conceptual expansion and modification of the stand-alone superframe. Conjoined supertall towers are a relatively new architectural phenomenon. With this system, height can be increased very efficiently up to about 250 stories.

3.3. Innovative formwork systems used in the construction of tall buildings

In order to have a precise perception of how tall structures are constructed it is needed to look at the processes and techniques. Modern formwork systems are widely used in the construction of tall buildings which offer unique advantages and characteristics. Here are some of the commonly used formwork systems briefly introduced: slip form construction, jump form construction, climbing formwork construction, table form/ flying form construction, column system formwork construction, and tunnel form construction.

In recent years, 'slip form construction' has been very popular, especially for high-rise buildings with more than 10 stories. However, for low-rise buildings, this method is not economically viable. "Basically, this method involves the continuous placing of concrete in a shallow mold having the same plan as the building to be constructed. This rigid mold, or 'slip form' as it is called, forms the working deck which is jacked slowly upwards at a controlled rate until the required elevation is reached" (Tiwary, 2017). Sliding form construction is used in three forms; vertical slip form, horizontal slip form, and tapered slip forming.

'Jump form construction' is one of the methods of structure cores (elevators, stairs, etc.) for high-rise buildings. The structure of the formwork is cast in a set of vertical sections called 'lifts'. Typically, this type of formwork is built of steel members and concrete form panels are attached to this frame. After sufficient strength of the concrete, the formwork is moved back and then jumped to a higher level. The jump form is generally used in three forms; normal jump/climbing form, guided-climbing jump form, and self-climbing jump form.

'Climbing form' construction is a formwork system used in the construction of vertically RC elements that allow construction to proceed without interruption. This formwork can be anchored to the structure at the desired height and move vertically and horizontally for each concreting unit. The size of the mold should be equal to the height of the floor, otherwise, it will not be economical and practical. Types of climbing form are as follows; climbing formwork (crane-climbing), climbing formwork (self-climbing), and gliding formwork.

"A table form/flying form is a large preassembled formwork and falsework unit, often forming a complete bay of suspended floor slab. It offers mobility and quick installation for construction projects with regular plan layouts or long repetitive structures" (Rupasinghe, et al., 2007). This system is designed for high-rise structures and heavy loads. The system includes the main frame, diagonal members, jacks, and accessories that connect them. The mainframes, which are the basic elements of the system, can be manufactured in different sizes.

The 'Column system formwork' system has a modular nature. An important criterion for the cost-effectiveness of the column system formwork system is the quick and easy adjustment of the cross-section and height with the least effort and the least possible number of system components. In addition, columns with the same cross-section are often constructed in series and large numbers so that the systems can be quickly moved to the next use without any assembly effort.

The 'Tunnel form' system is used as a modern innovation to create repetitive cellular structures. This is a steel formwork that is used during the placing of the concrete to form the floor and the wall at the same time. They can be in different shapes, sizes, and modules. The formwork system is supported by hot air blowers which accelerate the setting of the concrete. This system becomes more economical for symmetric construction like mass housing projects and contains a huge quantum of symmetrical work.

4. Results and Findings

The analysis of the structural evolution of high-rise buildings worldwide was conducted using the synthesis method. For this analysis, a selection was made of the 30 highest buildings constructed within the last 15 years. These buildings were thoroughly examined, taking into account factors such as the structural materials employed, the type of structural system implemented, and the formwork technologies utilized in their construction. To ensure a comprehensive evaluation, each of the 30 high-rise buildings in the sample underwent a detailed analysis. The data obtained from this analysis were meticulously collected and organized into evaluation tables specific to each building. These evaluation tables served as valuable references for studying and comparing the structural characteristics and advancements exhibited by each high-rise building within the sample.

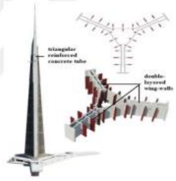
1. Jeddah Tower		
Building Information	Location: Jeddah, Saudi Arabia Height: 1.007 metres (3.281 ft) Floors: 168 Architect: Adrian D. Smith, Adrian S + Gordon Gill Architecture Completed date: unknown Function: Residential/Serviced apartments Material: Concrete	
Structural System	➢ Reinforced concrete tube ➢ Double-layered wing-walls	
Construction Techniques	➢ Climbing formwork	

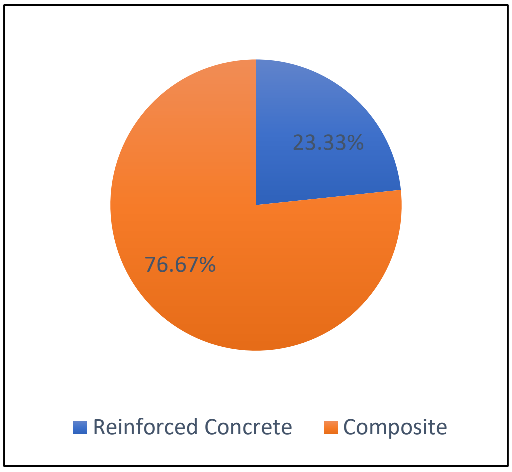
Figure 6: One example of the tables for each of the 30 tall structures.

Figure 6 provides an example of the evaluation tables used for analyzing the structural materials, systems, and construction techniques of the selected high-rise buildings. These tables are organized according to separate categories such as function, location, construction date, formwork systems (which play a crucial role in high-rise construction), structural systems, and building materials. Through this comprehensive examination, a comparative analysis was conducted to assess the similarities and differences among the high-rise buildings. Table 1, presents the final matrix that summarizes the results of the evaluation tables. This matrix encompasses materials inspection, structural inspection, and formwork technology inspection. The table, Specifically, highlights the usage of reinforced concrete (RC) in 7 out of 30 surveyed buildings, accounting for 23.33% of the sample. (Figure 7) The primary reasons for this choice include the ease of procurement, minimal need for specialized detailing, and lower cost associated with RC. On the other hand, composite materials, such as steel over concrete and concrete-steel composite, were observed in 23 buildings

(76.67%) within the sample. It is worth noting that none of the 30 highest buildings constructed in the last 15 years exclusively employed steel as the primary structural material.

Table 1: Comparative analysis matrix of the sample high-rise buildings.

				Struct. mtrl.		STRUCTURAL SYSTEM									FORMWORK TYPE					
						Interior				Exterior				CORE TYPE						
No.	Name	h. (m)	Floor count	Reinforced Concrete	Composite	Outriggered frame	Buttressed core	Core + dynamic form	Shear walled frame	Trussed tube	Bundled frame tube	Mega frame tube	Diagrid frame tube		Climbing formwork	Slip form	Self-climbing	Jump lift self-climbing	Jump form sliding f.w.	Not obtained
1	Jeddah Tower	1000	167	■		■								Central	■					
2	Burj Khalifa	828	163	■			■							Central		■				
3	PNB118 Merdeka	644	118		■	■								Central	■					
4	Wuhan Greenland Center	636	126		■	■								Central	■					
5	Shangai Tower	632	128		■	■								Central			■			
6	Chicago Spire Tower	610	150		■	■								Central						■
7	Ping An Finance Center	599	119		■	■								Central	■					
8	Goldin Finance 117	597	128		■					■				Central			■			
9	Lotte World Tower	555	123		■	■								Central	■					
10	One W.T.C.	541	91		■	■								Central			■			
11	CITIC Tower	528	108		■					■				Central				■		
12	Shangai World F.C.	492	101		■	■								Central	■					
13	Lakhta Tower	462	86		■	■								Central	■					
14	Vincom Landmark 81	461	81		■						■			Central					■	
15	Zifeng Tower	450	66		■	■								Central	■					
16	Exchange 106	446	95		■	■								Central	■					
17	Nanning China Resorces Tower	445	94		■							■		Central	■					
18	One Vandervilt	427	67		■	■								Central	■					
19	Dynamic Tower	420	80	■				■						Central						■
20	Al Hamra Tower	414	83	■					■					Central	■					
21	China Resources Tower	393	68		■								■	Central						■
22	PIF Tower	385	72		■	■								Central	■					
23	Federation Tower	374	93	■		■								Central	■					
24	Raffles City Chongqing T4N	355	74		■						■			Central	■					
25	Comcast Technology Center	342	60		■				■					Central	■					
26	Shard Tower	309	95		■	■								Central				■		
27	Northeast Asia Trade Tower	305	68		■	■								Central						■
28	Hangzhou Wangchao Center	280	52		■								■	Central						■
29	56 Leonard Street	250	60	■					■					Central	■					
30	One Thousand Museum	215	62	■					■					Central	■					



Reinforced Concrete	7
Composite	23

Figure 7: The rate of construction materials of the 30 sample buildings.

The analysis of the selected high-rise buildings revealed that the average height of buildings constructed with reinforced concrete (RC) structures is 500.14 m, while buildings with composite structures have an average height of 473.65 m. These findings indicate that there is no significant difference in the average height between buildings constructed with these two building materials, as shown in Table 1.

Out of the 30 buildings in the sample, 23 were built with interior structures, while 7 were constructed with exterior structures. The prevalence of interior structures is attributed to their ease and cost-effectiveness compared to exterior structures, despite the aesthetic and similar benefits offered by the latter, as illustrated in Figure 8.

Regarding the structural systems used in the buildings, Figure 8 demonstrates that the outrigger system was employed in 17 buildings (56.67%), the shear wall frame system in 4 buildings (13.33%), the bundled frame tube system in 2 buildings (2.7%), the diagrid system in 2 other buildings (6.67%), the trussed tube system in 2 buildings (2.7%), the buttressed core system in 1 building (1.3%), and the mega form tube system in 1 building (1.3%). It is noteworthy that all of the sample buildings incorporate a core system.

Furthermore, as part of the study, another assessment focused on building materials has been conducted. The evaluation revealed a consistent preference for reinforced concrete (RC) structures across all 7 buildings. Notably, the analysis of Table 1 highlights the utilization of various interior structure types in these buildings (Figure 9).

Interior Structure	Outriggered frame	17	23
	Buttressed core	1	
	Core + dynamic form	1	
	Shear walled frame	4	
Exterior Structure	Trussed tube	2	7
	Bundled frame tube	2	
	Mega frame tube	1	
	Diagrid frame tube	2	

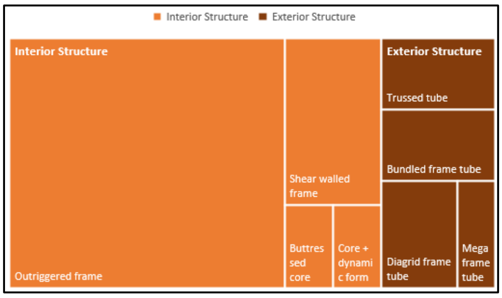
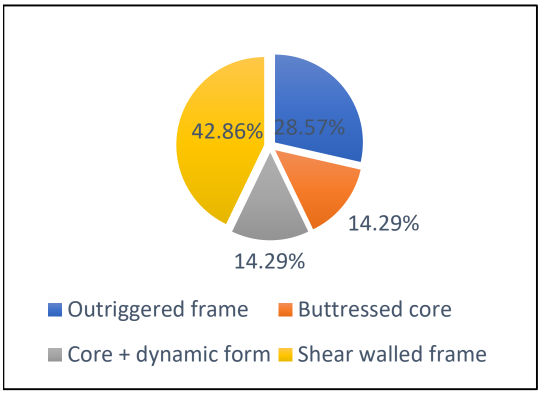


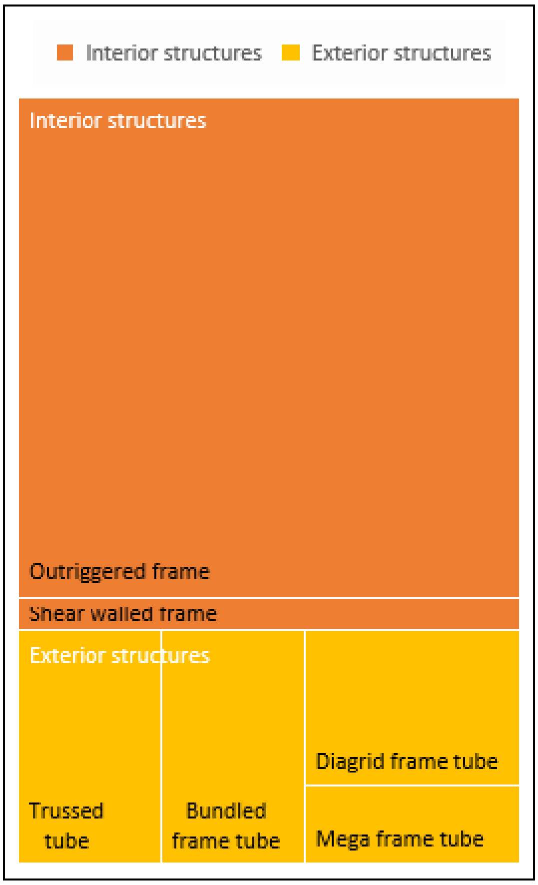
Figure 8: The rate of “the high-rise buildings with completed and under construction status” regarding structural systems of the 30 sample buildings.



Outriggered frame	2
Buttressed core	1
Core + dynamic form	1
Shear walled frame	3

Figure 9: Types of interior structures used in RC buildings.

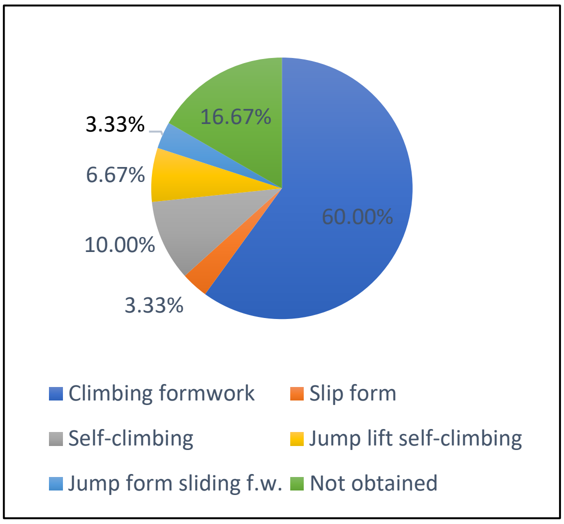
Based on the analysis, among the 23 buildings constructed with composite structures, 16 were designed as interior structures while 7 were designated as exterior structures. This indicates a prevalent use of composite structures for interior configurations. Additionally, it was noted that all exterior structures in the sampled buildings were constructed using composite materials, as illustrated in Table 1 and (Figure 10).



Interior structures	Outriggered frame	15
	Shear walled frame	1
Exterior structures	Trussed tube	2
	Bundled frame tube	2
	Mega frame tube	1
	Diagrid frame tube	2

Figure 10: Types of interior and exterior structures used in composite buildings.

In accordance with the findings of this study (as illustrated in Figure 11), it was determined that among the examined examples, climbing formwork was employed in the construction of 18 buildings, accounting for 60.00% of the total. Moreover, the slip form technique was utilized in one building (3.33%), self-climbing formwork was employed in three buildings (10.00%), jump lift self-climbing formwork was used in two buildings (6.67%), and jump form sliding formwork technique was utilized in one building (3.33%). Unfortunately, the specific formwork types used in the remaining 5 buildings could not be obtained for this study.

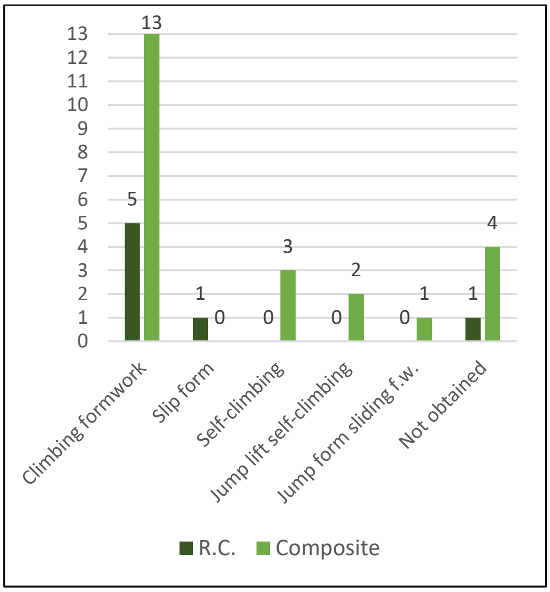


Climbing formwork	18
Slip form	1
Self-climbing	3
Jump lift self-climbing	2
Jump form sliding f.w.	1
Not obtained	5

Figure 11: The rate of formwork type of the 30 sample buildings.

The assessment of formwork technologies utilized in the examined examples unveiled the application of five distinct methods, as outlined in Table 1. Among these methods, climbing formwork emerged as the most prevalent, employed in 18 buildings (60.00%) (Figure 11). The widespread use of climbing formwork can be attributed to the numerous advantages it offers, including heightened productivity, time and cost efficiency, enhanced safety measures, versatility, improved concrete quality, flexibility, adaptability, and improved construction planning.

Self-climbing formwork was employed in 3 buildings (10.00%). This formwork technology, although relatively newer compared to climbing formwork, is gaining popularity due to its capacity to minimize labor needs, enhance safety, and accelerate construction timelines. Alongside these two technologies, jump lift self-climbing formwork was utilized in 2 buildings (6.67%), while slip form and jump form sliding formwork were each used in 2 buildings (Figure 11).



	Interior structure	Exterior structure	Total
Climbing formwork	16	2	18
Slip form	1	0	1
Self-climbing	2	1	3
Jump lift self-climbing	1	1	2
Jump form sliding f.w.	0	1	1
Not obtained	3	2	5
Total	23	7	30

Figure 12: Comparison of building material and formwork type

During the analysis of the correlation between structural materials and formwork technologies, it was noted that climbing formwork was extensively utilized in both reinforced concrete (RC) and composite structure buildings. Out of the 7 buildings with RC structures, climbing formwork was employed in 5 buildings (71.42%), while slip-form technology was utilized in one building. Unfortunately, data regarding the formwork technology of one RC building could not be obtained (Figure 12).

Regarding the composite structure buildings, climbing formwork was employed in 13 buildings (56.52%) out of the 23 analyzed. In addition, self-climbing technology was used in 3 buildings (13.04%), jump lift self-climbing in 2 buildings (8.69%), and jump from sliding formwork in 1 building (4.35%). Information on the formwork technology of 4 composite buildings could not be obtained (Figure 12).

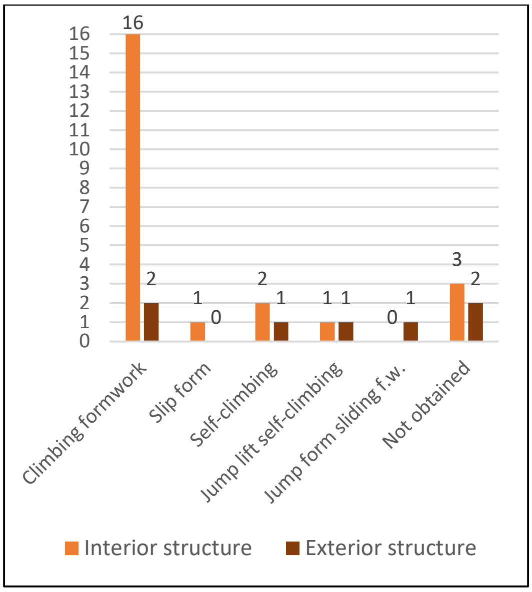
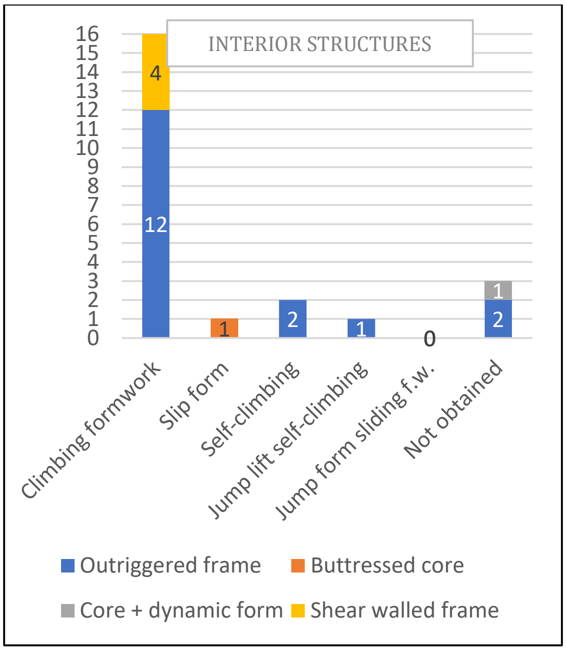


Figure 13: Comparison of structure type and formwork type

In the analysis of formwork technologies used in interior and exterior structures, it was found that climbing formwork was predominantly employed in both types of structures. Among the 23 interior structure buildings in the sample, climbing formwork was used in 16 buildings (69.56%). This indicates that factors such as easy manufacturing and the cost-effectiveness of climbing formwork play a significant role in its selection. Furthermore, self-climbing technology was used in 2 interior structure buildings, slip-form technology was used in 1 building, and jump lift self-climbing technology was used in 1 building. Data on the formwork technology of 3 buildings with interior structures could not be obtained (Figure 13). In buildings with exterior structures, climbing formwork was also the most frequently used method, with 2 buildings (28.57%) employing this technology. Additionally, self-climbing technology was used in 1 building, jump lift self-climbing technology in 1 building, and slip form technology in 1 building. Information on the formwork technology used in 2 buildings with exterior structures could not be obtained (Figure 13).

	Outriggered frame	Buttressed core	Core + dynamic form	Shear walled frame	Interior Total	Trussed tube	Bundled frame tube	Mega frame tube	Diagrid frame tube	Exterior Total	TOTAL
Climbing formwork	12	0	0	4	16	0	1	1	0	2	18
Slip form	0	1	0	0	1	0	0	0	0	0	1
Self-climbing	2	0	0	0	2	1	0	0	0	1	3
Jump lift self-climbing	1	0	0	0	1	1	0	0	0	1	2
Jump form sliding f.w.	0	0	0	0	0	0	1	0	0	1	1
Not obtained	2	0	1	0	3	0	0	0	2	2	5
TOTAL	17	1	1	4	23	2	2	1	2	7	30



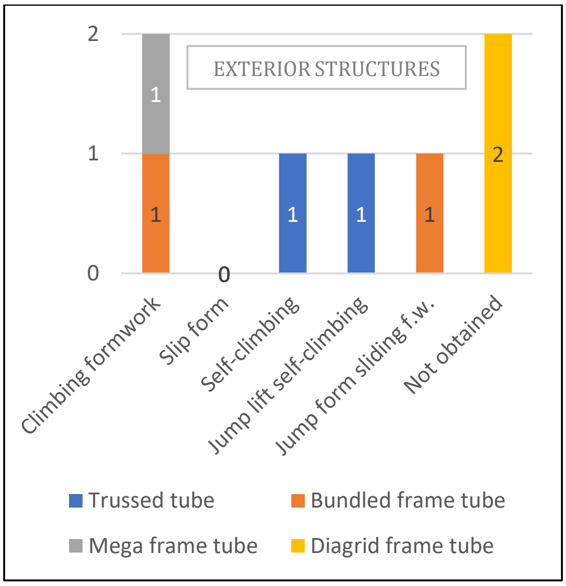


Figure 14: Comparison of structure types and formwork type

In the analysis of formwork types employed in different structure types, it was observed that climbing formwork is predominantly utilized in buildings with internal structures. Among the internal structure types, climbing formwork was employed in 12 outriggered frame buildings and 4 shear-walled frame buildings (refer to Figure 14). Notably, outriggered frame buildings exhibited a greater diversity of formwork technology types compared to other interior structure types. Out of the 5 formwork types used in the sample, 3 were implemented in outriggered frame buildings, while the remaining 3 structure types each preferred a single formwork technology (Figure 14).

In contrast, there was no significant concentration of formwork types observed in the subtypes of external structures. Climbing formwork was used once in bundled frame tube and mega frame tube structures. Trussed tube buildings, on the other hand, showed a preference for 1 self-climbing technology and 1 jump lift self-climbing technology (Figure 14). Although the number of exterior structure buildings is smaller than that of interior structures, the dispersed use of formwork types in the exterior structure category suggests that more specialized solutions are employed to address the unique nature of these structures.

5. Evaluation and Conclusion

As the population in cities grows, so does the demand for high-rise buildings. Looking at the continuous process of high-rise construction globally, it is evident that large cities compete on the world stage to claim the title of having the tallest building, symbolizing their power, prestige, and global standing in the growing economy.

The primary challenge in designing structural systems for high-rise buildings is addressing the displacement caused by lateral loads. As the height of the building increases, lateral displacements also increase proportionally. Consequently, the options for choosing structural systems decrease with increasing altitude. However, advancements in materials and technology have made it possible to increase building height by reducing the weight of the structure.

A new approach involves employing a hybrid structural system, which combines two or more systems that mutually reinforce each other. This enhances the rigidity of the new structural system while minimizing issues such as deformation due to lateral displacement, which can lead to damage, structural errors, and uncomfortable conditions for occupants.

Upon evaluating the 30 tallest buildings selected as a sample from the CTBUH database, which were constructed over the last 15-year period, the following findings were obtained regarding their structural materials, structure types, core types, and formwork technologies:

- Despite the increase in building height, the use of interior structure is predominant.
- However, the need for elevation is met by the increased use of composite, a relatively new structural material.
- In the context of being a combination of these two factors, outrigger frame buildings are mostly preferred.
- Among the reviewed buildings, the use of a central core is the only option in terms of stiffness.
- Although there are newer technologies, climbing formwork technology is still mostly preferred in high-rise buildings.

Innovative approaches extracted from technology have led to the development of building systems and structural processes. These rapidly changing systems directly affect the design and construction process and have led to optimizations in the construction industry.

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