A STUDY ON THE PRELIMINARY DESIGN OF TALL BUILDINGS: INVESTIGATING STRUCTURAL COMPONENTS

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A STUDY ON THE PRELIMINARY DESIGN OF TALL BUILDINGS: INVESTIGATING STRUCTURAL COMPONENTS

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ABSTRACT

A STUDY ON THE PRELIMINARY DESIGN OF TALL BUILDINGS: INVESTIGATING STRUCTURAL COMPONENTS

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Tall buildings are built to respond to limited and high-cost urban land problem, and they became essential for urbanization which changes the sights of the cities. These buildings are huge investments, and keeping Net Floor Area (NFA) within acceptable limits while satisfying stiffness and strength requirements of the building is important; therefore, different structural systems are improved in order to overcome huge lateral load demands. Since simple design approaches and rule-of-thumb dimensioning methods based on conventional structures and loads cannot be adapted to tall buildings, tall buildings, particularly supertall buildings which are more than 300m in height requires a long and repetitive planning phase before structural and architectural design. The aim of this study is to provide the approximate dimensions of the structural components, particularly core and columns, of tall buildings for preliminary design phase by investigating existing buildings. For this purpose, a database of tall buildings which is obtained from existing buildings is created and corresponding statistical analysis results are presented.

At the first stage of the study, a literature survey has been conducted in order to determine the structural design considerations of tall buildings. According to these considerations, identity parameters, architectural parameters and structural parameters are specified and collected for as much existing buildings as possible. Important parameters such as aspect ratio, core area and column area have been calculated, and special features such as dampers and wind openings have been detected. Structural system details of outriggered frame buildings such as outrigger height and number of outriggers have been investigated. Regarding the collected information, statistics on preliminary design variables of tall building's structural systems have been presented.

According to the analyses, core area and column area ranges of tall buildings are given for outriggered frame, tube and shear frame structural systems and for specific regions. The results showed that, shear frame system is the least efficient structural system whereas outriggered frame system is as favored as tube system in terms of net floor area. The results showed that, for preliminary design of a tall building regardless of its structural system, location, structural material or height, 27% and 3% can be taken as conservative central values of core and column area ratio, respectively.

Minimum, maximum and average values of ratios of core area to floor area and total column area to floor area are provided with respect to alternative structural system of tall buildings. The results of this study can be easily used by architects and engineers in the preliminary design stage of tall buildings.

Keywords: Tall Building, Tall Building Structural Systems, Net Floor Area, Statistical Analysis of Tall Buildings, Structural Components

ÖZ

YÜKSEK YAPILARIN ÖN TASARIMI ÜZERİNE BİR ÇALIŞMA: TAŞIYICI SİSTEM ELEMANLARININ İNCELENMESİ

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Yüksek yapılar kalabalık kent merkezlerinde az sayıda ve yüksek maliyetli arsalardan kaynaklanan yerleşim problemine karşı geliştirilmiş çözümlerdir. Bu yapılar büyük yatırım projeleri olup, tasarımların kiralanabilir alanı yeterli düzeyde tutarken, taşıyıcı sistem gerekliliklerini de karşılaması beklenmektedir. Geleneksel yaklaşımlar, çok büyük yanal yük taleplerine maruz kalan bu binalara uyarlanamadığından, yüksek yapılar için özel taşıyıcı sistemler ve planlama yöntemleri geliştirilmiştir. Bu sebeple yüksek yapıların ön tasarım boyutlandırması, özellikle süper yüksek yapılarda (300 metreden yüksek binalar) hem mimarlar hem de mühendisler için uzun hazırlık aşamaları gerektirmektedir. Bu çalışmanın amacı var olan binaların istatiski analizleri ile yüksek binaların ön tasarımında kullanılacak taşıyıcı sistem eleman boyutlarını belirlemektir. Bu amaçla, ilk olarak literatür taraması yapılmış ve taşıyıcı sistem ile ilişkili önemli parametreler belirlenmiş ve bu parametreler olabildiğince çok sayıda bina için toplanmıştır. Toplanan verilere göre binaların çekirdek alanları ve kolon alanları hesaplanmış ve analiz edilmiştir. Toplanan binalarda varsa rüzgâr açıklıkları ve sönümleyiciler gibi özel uygulamalar belirlenmiş, yatay perdeli çerçeve sistemlerin yatay perdelerinin yükseklikleri ve sayıları incelenmiştir. Çalışma sonucunda, belirli bölgeler için perdeli çerçeve sistemler, dirsek perdeli çerçeve sistemler ve tüp sistemlerde kullanılmak üzere kolon alanı ve çekirdek alanı oranları verilmiştir.

Perdeli çerçeve sistemlerin taşıyıcı sistem verimliliğinin süper yüksek binalarda düşük olduğu ve net kiralanabilir alana göre dirsek perdeli çerçeve sistemlerin tüp sistemler kadar avantajlı olduğu görülmüştür. Çalışma sonucuna göre, yüksek bina tasarımında, tercih edilen taşıyıcı sistemden, taşıyıcı sistem malzemesi, yükseklik ve bölgeden bağımsız olarak, 27% çekirdek alanı ve 3% kolon alanı güvenli alt limit olarak kullanılabilir. Bu çalışmada, farklı taşıyıcı sistemlere göre minimum, maksimum ve ortalama çekirdek alanı ve kolon alanı oranları hesaplanmış olup; bu veriler yüksek bina tasarımının hazırlık aşamalarında mimarlar ve mühendisler tarafından kullanılabilir.Anahtar Kelimeler: Yüksek Yapılar, Yüksek Yapılarda Taşıyıcı Sistem, Kiralanabilir Net Alan, Yüksek Yapıların Taşıyıcı Elemanları

To my parents…

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LIST OF ABBREVIATIONS

AR: Aspect Ratio

ATO: Architecturally Topped Out

C: Composite

CTBUH: Council of Tall Buildings and Urban Habitat

E: Education

H: Hotel

MEP: Mechanical Electrical Plumbing

MRF: Moment Resisting Frame

NFA: Net Floor Area

O: Office

R: Residential

RC: Reinforced Concrete

S: Steel

SG1: Sample Group 1

SG2: Sample Group 2

SG3: Sample Group 3

STO: Structurally Topped Out

TMD: Tuned Mass Dampers

TSD: Tuned Sloshing Dampers

UC: Under Construction

CHAPTER 1

INTRODUCTION

1.1. Motivation Statement

From the early ages of mankind, people tend to rise; therefore, they built high graves, temples and monuments in order to show their respects to the leaders or gods. Nowadays, tall buildings are accepted as not only the symbol of the power and prestige but also a necessity, since they respond to requirements of the crowded cities.

Tall buildings are large in scale, complex in nature and more expensive in construction; hence, its economic planning is particularly important (Ho, 2007). There are lots of calculations and preparation behind those investments; however, any miscalculation may result in cancelation of the project even if construction has already started. Since tall buildings are more sophisticated than conventional buildings, conventional planning methods and cost estimations cannot be adapted to them. Although each structural system developed for tall buildings have different requirements and behaviors, it is possible to provide basic estimations about size and number of structural components. For this reason, this study aims to specify the dimensions of the structural components of tall buildings for preliminary design phase by investigating existing buildings.

Having data on core ratio (total core area divided by floor plate area) and column ratio (total column area divided by floor plate area) for a given structural system, material, building function, location and building height can provide preliminary information to designers. From profitability point of view, net floor area (NFA) is important for the realization of the projects, and it is seen that total average core and column area in floor plans can help to estimate net leasable area and thus initial planning tasks.

NFA can be described as the area without service core and structural components such as shear walls and columns and can be compared for different structural systems by obtained data from core and column ratio. For these reasons, tall buildings with different structural systems are investigated, and statistical analyses about their structural system properties are provided in the scope of the study. According to sample groups, the most common structural systems are specified and analyzed.

According to analyses, the ratio of the structural components (core and column) in a single floor plate area is specified for different structural systems and regions. The results of the analyses also show that, the efficiency of the structural systems is different and shear frame system is the least efficient structural system compared to outriggered and tube systems. On the other hand, outriggered frame can be preferred for higher buildings than tube systems although external structural systems require less core area compared to internal structural systems.

According to NFA analyses, function of the building is the primary factor that affects the net leasable area and leasable span. Following the function, structural system decision and the location of the building are other factors that are determinant on NFA.

1.2. Aim and Objectives

Tall buildings, particularly supertall (+300m) or megatall (+600m) buildings, require extraordinary construction techniques and advanced structural systems which should withstand huge lateral loads. Although there are many features of a tall building, this study particularly focuses on fundamental architectural and structural design considerations such as location, building form, building height, aspect ratio, core ratio, column ratio and leasable span.

The aim of this research is to provide a statistical analysis on quantitative parameters of structural system of tall buildings, and compare these results for different structural systems. For this purpose, core and column ratio of existing tall buildings have been investigated with respect to their location, building function, structural system and structural material.

While achieving this aim, following research objectives have been identified;

- Providing a database about tall buildings and the properties of their structural system,
- Investigating the selection of the structural systems with respect to different height ranges,
- Investigating the correlation between core and column ratio and other design variables such as building height, aspect ratio (AR), location etc.,
- Providing data on distribution of different parameters such as structural system, aspect ratio, building function, building height and structural material.

1.3. Methodology

A comprehensive literature review on structural system parameters of tall buildings is conducted as the first step. It is decided to collect data on properties of tall building structural systems by investigating existing buildings. Required parameters which have an effect on the size of the structural components for tall buildings have been specified, and 141 existing buildings are analyzed in order to generate a database as mentioned before. The number of the samples cannot be further increased; due to the limitations on reaching data.

According to sample groups, the most common structural systems are specified as shear walled frame system, outriggered frame system and tube system. These systems are compared with respect to building height, location and structural material.

Structural systems are investigated in terms of core area ratio and column area ratio, since there are effective parameters on the net floor area of the building. The size of these components is determined according to literature survey and floor plans of existing buildings. Floor plans of the buildings are gathered from different sources such as books, journal articles and conference proceedings. In addition, NFA is compared for different structural systems as well.

Samples are divided into similar groups, and these sample groups are modified with respect to results of the first analyses. According to results, outcomes of this study are specified.

1.4. Disposition

This study contains 5 chapters.

First chapter introduces the statement of the motivation of this research, aim and objectives with a brief recognition of methodology and disposition.

Second chapter presents literature review about structural system parameters of tall buildings and previous studies in this field.

Third chapter includes a detailed description of material and method of the study.

Fourth chapter comprises the results of the statistical analyses.

Fifth chapter discusses the results and concludes the study. There are suggestions for further researches in this chapter as well.

CHAPTER 2

LITERATURE REVIEW

Since the precursor buildings have been constructed in there, tall buildings have been identified with the United States of America in the late 19th century. These buildings had been called "American Building Type" in the very beginning, and 99% of the world's 100 tallest buildings had been in North America in 1930 (Ali & Moon, 2007; Gunel & Ilgın, 2014). Through the developments of global economy, improvements in structural systems, material possibilities and construction technologies, the idea of tall building spread around the world. As of April 2019, 13% of the 100 tallest completed buildings in the world are in North America whereas 50% of them are in China according to Council of Tall Buildings and Urban Habitat (CTBUH) database.

Home Insurance Building (Chicago, 1885) is considered as the first skyscraper in the world (Figure 2.1.), since it was the first building built with a steel structural frame system (Gunel & Ilgın, 2014).

Figure 2.1. (Left) Home Insurance Building (1885) Source: The Skyscraper Center, (Right) Shanghai WFC (2008), Jin Mao Tower (1999), Shanghai Tower (2015) Source: Gensler

Numerous things have changed since first skyscraper, such as material preference, structural system types, building form. Thus, this study aims to scrutinize the design characteristics of structural system members by examining tall buildings with the status of completed and under construction.

Watts (2016) claims that it is possible to increase space efficiency by designing the tall buildings within proper combination of height, building shape, core and column spacing. Floor plate, building proportion, location, degree of architectural expression, site conditions, life safety enhancements and function of the building are the other parameters that should be considered during construction stages.

Other factors such as market conditions, global economy, local labor and material sources, working hour limitations for construction, national codes/regulations, environmental strategy, construction site, safety and health precautions *etc.* are implicitly taken into consideration in this study by examining the tall buildings which are in completed or under construction status.

Although there are more factors that must be considered for a tall building during its design and construction periods, this study primarily investigates the factors which have direct impacts on structural system. These parameters are explained in the next section in detail.

2.1. Characteristics of Structural System Layout

Due to high number of storeys, large floor plans and long construction periods, tall buildings are huge investments, and structural cost has a big concern in the budget. Zhou *et al.* (2014) claims that the structural cost is a quarter of the total cost, whereas Wang *et al.* (2012) points that structural cost ratio of a tall building is about 30-35%.

There are numerous considerations for structural system of a tall building such as substructure, superstructure and parameters like lateral and gravity loads, building shape, height of the building, structural material, building function, *etc.* In this study, these considerations are separated based on the strength of their relations with structural system as primary and secondary considerations. Primary design considerations directly affect the structural system decisions and behavior. Although secondary considerations generally have less impact, they are still determinant on structural systems. Mechanical Electrical Plumbing (MEP), elevators, façade are accepted as indirect considerations for tall buildings since they affect the structural system circuitously, and they cannot be determinant on structural design. Primary, secondary and indirect considerations are determined based on the previous studies from Wang *et al.* (2012), Ho (2007), Baker (2013), Kim and Elnimeiri (2004), Sakisian (2012), Ali and Moon (2007), Ali and Al-Kodmany (2012), Zhou *et al.* (2014), Scott *et al.* (2007), Kaihai and Yayong (2012) and Choi (2009).

2.1.1. Design Considerations

Baker (2013) claims that wind loads, properties of materials, behavior of structural systems, slenderness ratio, harmony between wind and building shape, distance between core and perimeters, hierarchy among the structural components should being concerned during design and construction process of tall buildings. Besides while considering all these parameters, economics of the building should also be taken into account. Tall buildings should be easy and quick to be built, since they contain thousands of structural components, and these buildings must respond to not only forces of nature, but also the requirements of the building.

Structural design of tall buildings has been studied before by considering many different aspects. Wang *et al.* (2012) define the building shape, lateral resistance system and structural material as structural considerations. Zhao *et al.* (2014) claim that floor systems have a great impact on structural systems. Scott *et al.* (2007) point that complex building shape affects the structural systems. Zhou *et al.* (2014) investigate the influence of floor plane layouts, elevation of buildings and outriggers on different structural systems with respect to structural efficiency. In Zhou *et al.*

(2014), structural system selection, building function, building height, aspect ratio, building shape and wind modifications, floor plan configurations and floor type are specified as determinant for structural efficiency.

According to previous studies, the considerations which affect the structural efficiency are specified. These considerations which affect the structural performance directly or indirectly, are classified as structural system, structural material, building function, building height, aspect ratio, building shape and wind modifications, floor type, location and leasable span.

2.1.1.1. Structural System

Improvements in computational tools, mechanical technologies and developments in structural materials allow to higher buildings compared to conventional materials and methods. Stiffness generally becomes more critical than strength in tall buildings' structural systems due to height of buildings (Khan, 1969 as cited in Ali & Moon, 2007).

A stiff shear structural system which is strong enough to overcome shear forces and stiff enough to withstand the shear lag effect is necessary for entire building which works as a giant cantilever rather than a combination of individual elements. Although a stiff shear system can reduce shear deformations, it is not practical to do the same for the flexural deformations. Increasing the cross-sectional area of structural members, especially vertical members, can reduce the bending deflections (Baker, 2013).

Although compression forces require attention in tall buildings, it is harder and expensive to withstand the tension forces. Gravity can be useful in order to resist the tension forces in a cost-friendly way. Since maximum gravity and wind load are unlikely to occur at the same time, improving a proper combination between gravity resisting and wind resisting system accomplishes the most cost-effective solution for structural systems. Using the excess capacity of one structural system in order to resist the forces of the other is an efficient and cost friendly approach. If the elements resisting these tension forces are pre-compressed with the mass of the building, the structural design becomes easier and costs less, since high rise buildings are in pre-compression position by its nature (Baker, 2013).

The structural system of tall buildings should withstand all lateral loads, even unpredicted forces due to sudden wind changes and high gravity loads. Since traditional load bearing systems are not capable of resisting to these loads, more sophisticated structural systems have been developed.

Fazlur Khan has invented tubular structural systems in 60's and classified them according to their structural efficiency (Mufti & Bakht, 2002). Since then, so many classifications have been done by numerous engineers and researchers.

Ali and Moon (2007) have divided structural systems into two broad categories as interior structures and exterior structures based on the distribution of the components of primary lateral load bearing system in the building. When the major part of the lateral load bearing system is located inner part of the building, that system can be described as 'interior structure'. Similarly, when the major part of the structural system is located at the perimeter of the building, that system can be described as 'exterior structure'. Therefore, moment-resisting frames (MRF) and shear trusses/shear walls are considered as interior structures, while tube systems are considered as exterior structures (Table 2.1.). Authors state that exterior structural systems are technically more efficient than interior structures from structural point of view. Similarly, Moon (2012) claims that the structural efficiency can be increased by locating the primary structural members over the building's perimeter.

Table 2.1. *Interior and exterior structures (Source: Ali & Moon, 2007)*

INTERIOR STRUCTURES	Efficient Number of Storey Limit	EXTERIOR STRUCTURES	Efficient Number of Storey Limit
Rigid Frames	20-30	Tube	60-150
Braced Hinged Rigid Frames	10	Diagrid	60-100
Shear Wall/Hinged Frames	35	Space Truss Structures	150
Shear Wall/Truss Interaction System	40-70	Super frames	100-160
Outrigger Structures	150	Exo-skeleton	100

Another classification is proposed by Günel and Ilgın (2014) for tall buildings according to structural behavior of the systems under lateral loads (Figure 2.2.). In addition to the systems listed in Figure 2.2., authors mentioned rigid frame systems, flat plate/slab systems, core systems and shear wall systems and declared these systems as feasible for buildings less than 40 storeys.

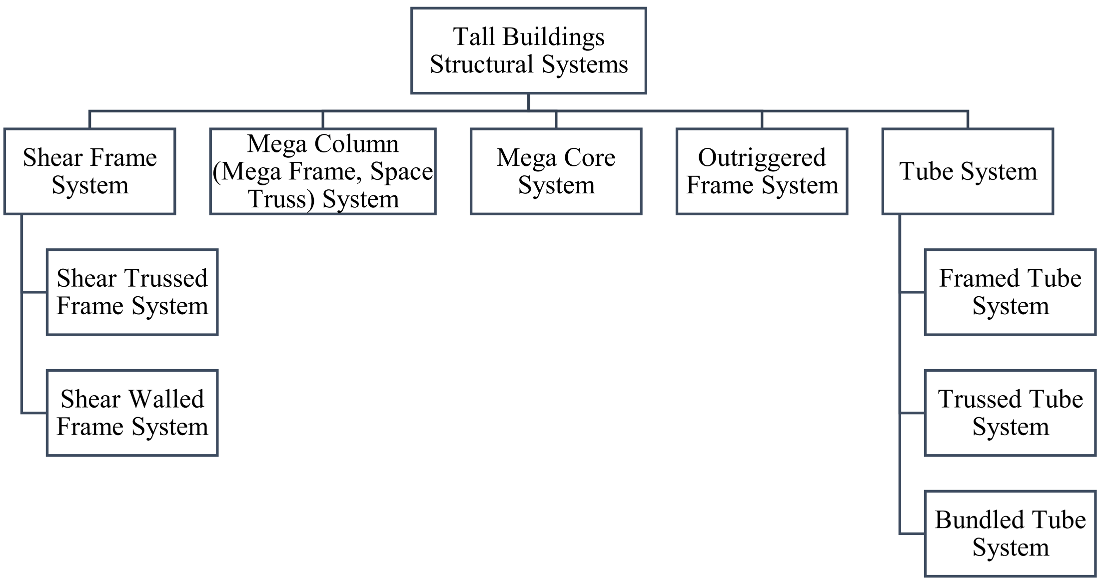


Figure 2.2. Structural system classification (Source: Günel & Ilgın, 2014)

The efficiency of these structural systems is examined and compared with each other since they have been developed. Moon (2010, 2014, 2015) investigated each structural system's efficiency separately by making some modifications in the shape such as twisting, tilting, tapering angle or different angle for bracing/diagrid implementation. Ali and Moon (2007) compared the exterior and interior structural system groups with each other while Zhou *et al*. (2014) compared some exterior structural systems such as, mega bracing tube, frame tube, diagonal grid tube and entity tube. These studies are explained in detail in the following paragraphs.

Moon (2015) studied on comparison of different structural systems by computer simulations. A conventional box with 36 m x 36 m plan dimension and 18 m x 18 m core dimension has been designed as a building with 60, 80 and 100 storeys which correspond to an aspect ratio of 6.5, 8.7 and 10.9, respectively. All these models are designed as braced tube, diagrid and outriggered frame system, and the results showed that diagrid structures are generally the most efficient system up to 100 storey against lateral loads compared to the other systems investigated in Moon (2015).

Zhou *et al*. (2014) simulated 3D models with 54 m x 54 m plan area (27 m x 27 m core dimensions) with 405 m height and 90 storey with moment frame, mega frame, frame tube, diagonal grid tube and entity tube structural system, and compared them to each other (Figure 2.3.). According to the results, the proportion of the lateral deformation caused by bending moment has been found as maximum for tube systems whereas it is minimum for moment frame systems. Then, outriggers were implemented into the moment frame and mega frame structural systems as three levels, at each 30 storey It is seen that outriggers have improved the structural efficiency about 40%.

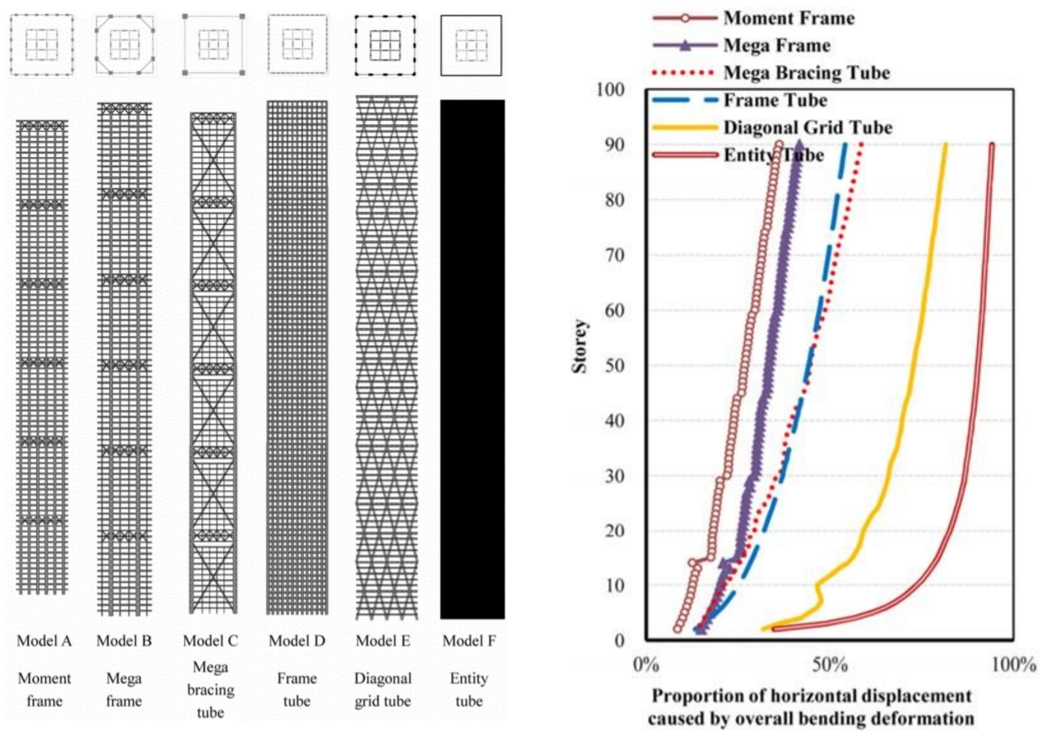


Figure 2.3. Comparison of different structural systems (Source: Zhou *et al.*, 2014)

In another study, the structural efficiency of diagrid and braced tube systems are compared by changing the angle of the braces, column spacing and type of the braces such as X Brace and Chevron Brace (Moon, 2012). According to the results, combination of different angles of diagrids maximize the structural efficiency. Moon (2012) states that, "As the column spacing becomes denser toward the building's corners, the web columns' contribution to the system's bending stiffness increases, and vice versa in braced tube structural system."

Diagrid structures transfer the loads from top of the building to the ground efficiently because of its highly redundant structure (Scott *et al.*, 2007). Moreover, exterior bracing and diagrid systems reduce building material consumption while enhancing structural performance (Al-Kodmany & Ali, 2016).

2.1.1.2. Structural Material

Concrete is strong in compression and very weak in tension while steel has a great tensile strength. According to Günel and Ilgın (2014), in 1930, 96% of the world's tallest 100 buildings were steel, while 4% was reinforced concrete and composite. Since the combination of steel and concrete provide advantages of both materials at the same time and result in higher efficiency in the buildings, the number of composite buildings increased (Figure 2.4.) within decades.

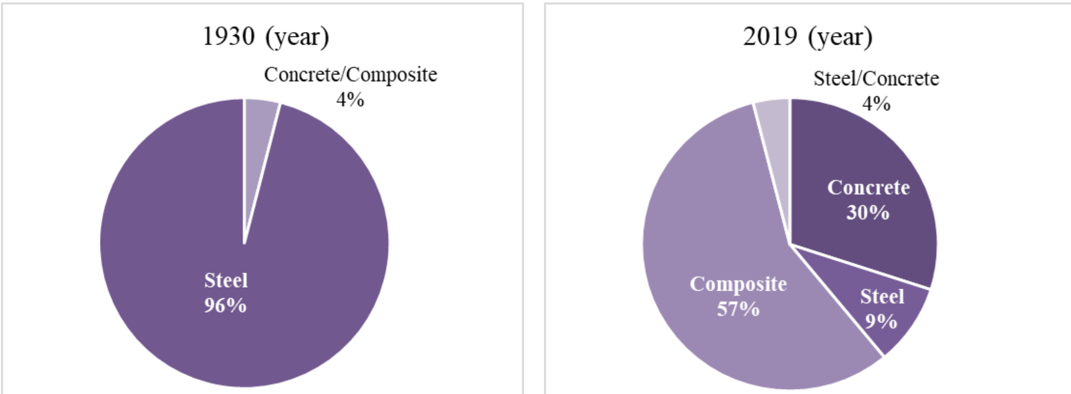


Figure 2.4. Structural material distribution according to years (Source: CTBUH database, retrieved in 20 April 2019)

On the other hand, improvements in high strength concrete and pumping technology, reinforced concrete has become widely used in tall buildings. The structural material of two highest building in the world, 828m tall Burj Khalifa (completed) and 1000m tall Jeddah Tower (under construction) are made of reinforced concrete. Furthermore, steel requires supplementary fireproofing precautions while concrete is more durable against fire by its nature. According to Ho (2007), both steel and reinforced concrete can be used for tall buildings; however, high-strength concrete is more common due to its lower cost compared to steel.

Concrete became more comparable to steel in terms of construction time due to new technologies. The construction of a tall building's core typically lies on the critical path of the program and has an enormous impact on the schedule. By using slip-form or jump-form techniques, a 3 to 4-day cycle is achievable for core wall construction, and this construction speed is similar to steel construction. In other words, concrete construction is not slower than the steel construction anymore. (Ho, 2007; Baker, 2013)

Another development in material field is the enhancements of the physical properties of the materials. High strength materials can make the structural members more slender and lighter for a given axial capacity of vertical members. The core thickness can be reduced by using high strength materials as well, and less core thickness not only reduces the vertical load on the foundation, but also increases the leasable area.

Using less amount of materials in the structures reduces the dead load on the foundation and indirect cost drivers such as labor and transportation. According to Wang *et al.* (2012), a hybrid structure takes full advantage of both steel and concrete, and steel frame or steel elements can be used as formwork system for reinforced concrete which leads to a great reduction of the formwork and scaffolding cost. Additionally, reducing amount of material can reduce carbon emissions, which helps to make the construction sustainable and less harmful to the universe.

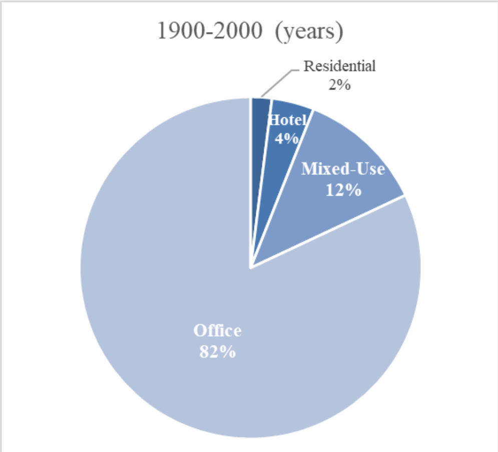
The location of the construction site is also a critical point to determine the type of structural material. Local material sources, labor cost and transportation expenses must be considered while deciding the structural material. For example, steel buildings are very common in USA, whereas concrete is widely used in Middle East.

Structural material also depends on the aim of the building. Baker (2013) claims that, since office floors generally require large span i.e., column-free area with bigger mechanical equipment, steel floor framing can be selected in order to reduce slab thickness and increase the strength. The author also compares steel and reinforced concrete with respect to their structural efficiency and specified the pros and cons of both materials. Although concrete requires higher section of vertical elements, concrete frames have more mass and inherent damping properties compared to steel. On the other hand, steel structures generally provide more opportunity for complex and non-linear geometries. Steel is also dimensionally more stable due to creep and shrinkage effects, whereas concrete elements keep deforming over time, and this may lead to the redistribution of forces. From a seismic point of view, steel has less mass and its greater ductility generally has an advantage against seismic force. The most proper solution often lies in the combination of both materials, with steel framing and concrete vertical elements.

Lastly, structural materials may require thermal design, especially in case of a combination of exposed and interior steel structures. For instance, in New York Times Building, variations in temperature was determinant on the structural design. It was foreseen in the early design phase that a temperature change about 21°C causes 9 cm elongation in 200 m long steel column which supports the top office, while a span about 9 m can accept only 3 cm differential motion. Therefore, wind-resisting outrigger trusses are supplemented with 'thermal trusses' which provide a link between exposed and interior columns. These trusses cut maximum elongation of exposed columns in half and reduce the difference between columns by a factor of three by pushing down on exterior column and pulling up the adjacent interior column at the same time (Scarangello, 2008).

2.1.1.3. Building Function

Building function is determinant on the structural system, since each function has different demands. According to CTBUH criteria, a single-function tall building is defined as one where 85 percent or more of its total height is dedicated to a single function. Office, residential and hotel are considered as major functions, and a mixed-use building contains two or more functions where each of the functions occupies a significant proportion. Single function, especially office function was common before 2000's (Figure 2.5.). Buildings with residential and mixed-use functions have increased rapidly after it is noticed that they are in demand as well in the city centers, and mixed-use buildings give different opportunities to not only investors but also occupants.



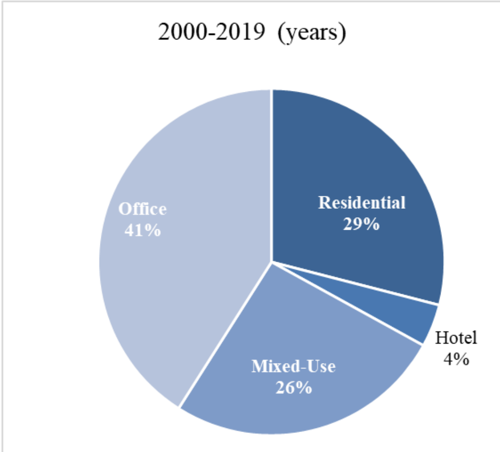


Figure 2.5. Function distribution according to years (Source: CTBUH database, retrieved in 20 April 2019)

Office buildings require column-free spaces due to its purposes whereas residential buildings allow flexible design since they contain divided spaces. Moon (2015) claims that it is important to design the living spaces close to natural light in residential function buildings, however, natural light is less important for office buildings, and deeper rental spaces are desired more. Since each function needs its own entrance, parking space, vertical transportation and MEP solutions, designing a mixed-use building is more complicated than a single function. More service area leads to increase in core area which inevitably decreases the leasable area. In order to prevent the reduction in leasable area, each function and their needs must be examined carefully during the whole design process.

From rentability point of view, facilities should be located like; below grade for parking, the ground level for commercial, lower level of tower for offices, the next level for hotel and top of the building for residential. From the structural point of view, residential and hotel function should be located at lower levels of the tower, since these functions require shorter column span. Most efficient solution can be done by combining these two considerations properly. Effective service area for each function and occupants should be provided while raising the profit for investors (Kim & Elnimeiri, 2004).

Since mixed-use buildings require more challenging design process not only architectural, but also structural point of view, some solutions are specified as follows:

- An office building demands large span; however, a residential building is suitable for separating the units. Therefore, tapered tall buildings, with commercial office functions on the lower levels and residential functions on the upper levels, is a very functional solution architecturally. Furthermore, this placement enhances the structural system's efficiency, since tapering increases the stiffness and reduces the lateral loads as building height increases (Moon, 2015).
- Setbacks are feasible in order to change the building function when a reduction is needed from larger to narrow spaces. Since setbacks decrease the wind loads, the structural system becomes less susceptible to higher lateral loads as the building rises (Ho, 2007).
- A special function such as observatory deck at the top of the building may decrease the space efficiency. In that case, a sky-lobby can make the building more functional (Kim & Elnimeiri, 2004).

Different functions require different services in terms of elevator quality and quantity as it seen in Table 2.2. It must be provided faster service response and more capacity in office function, however, since the number of elevators in office buildings is generally greater than the buildings with residential or hotel function, core size enlarges as well.

Table 2.2. *Elevator requirements for different functions (Source: Loon, 2004)*

ELEVATOR TRAFFIC ANALYSIS: SUMMARY OF RECOMMENDATIONS			
KEY FACTORS	TYPES OF BUILDING		
	Office Buildings	Hotels	Apartments
Population	• Floor areas	• Number of rooms	• Number of bedrooms
Traffic Conditions	• Morning up: normally prime determinant • Noon two-way • Evening down	• Morning down • Evening two-way: normally prime determination	• Two-way
Quality of Service	• 30 sec intervals • 20-25 sec waiting times • 150 sec system service time	• 35-45 sec intervals • 25-30 sec waiting time • 180 sec system service time	• 45-90 sec intervals • 30-60 sec waiting time • 240 sec system service time
Quantity of Service	• 10% - 15% up handling capacity	• 6%-9% two-way handling capacity	• 5% two way handling capacity

Lastly, comfort criterion differs according to the limited peak acceleration for different functions, and this should be considered during structural design. Regulations and previous researches show that residential function is more sensitive against acceleration, however, office function is more adaptable. Sarkisian (2012) claims that residential peak acceleration limit should be between 5 - 7.5 milli-g while office limits should be within 10 - 13 milli-g. Alternatively, Choi (2009) states that building acceleration limit (10-year wind) should be 10 - 15 milli-g for residential, 15 - 20 milli-g for hotel, 20 - 25 milli-g for office and 25+ milli-g for retail function in US. Ferrareto *et al*. (2014) express that CTBUH peak acceleration limit (10-year return period) for residential buildings is approximately between 10 - 15 milli-g while 20 - 25 milli-g in office buildings.

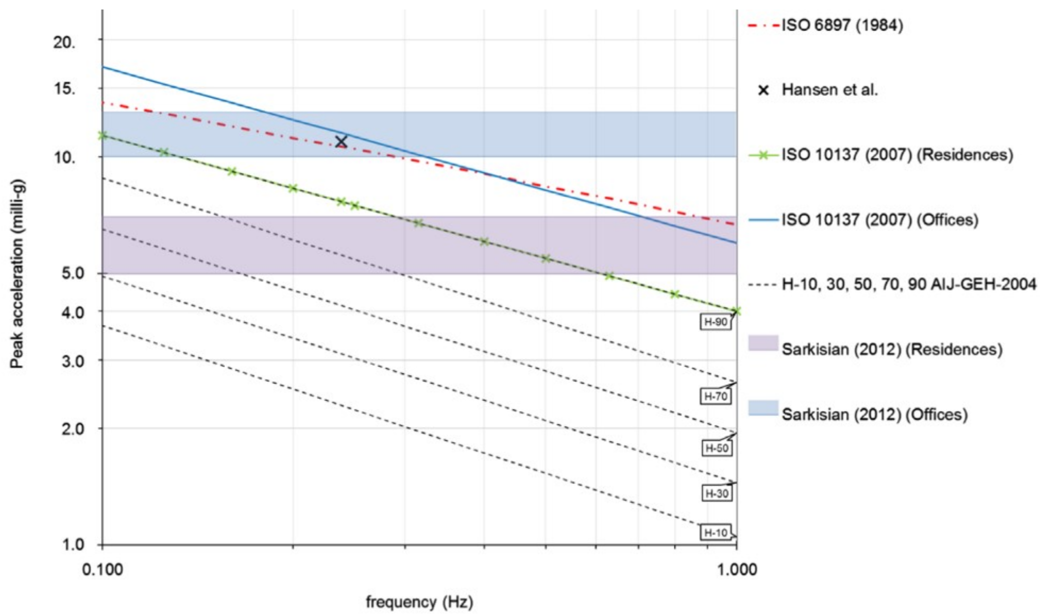


Figure 2.6. Peak acceleration criteria, 10-year period of return (Source: Ferrareto *et al*., 2014)

2.1.1.4. Building Height

Floor height can be classified as floor to floor height and floor to ceiling height. Although floor to ceiling height is the clear distance between slab and ceiling, there is also a space for mechanical and electrical equipment in floor to floor height. A small difference in a single floor height may have a major impact on the overall height when the total number of storeys is considered.

Floor height is directly related to the function of the building. For instance, the 100 storeys John Hancock Center is not taller than the 88 storey Jin Mao Building. John Hancock Center has 27 floors for office and 48 floors for residential purpose. Actual height of 27 office floors is 104m, whereas 48 residential floors is 136m which means that, floor to floor height is 2.85m for residential and 3.85m for offices approximately (Kim & Elnimeiri, 2004). It is found that the most common floor to floor height is about 4m (where an average floor to ceiling height is 2.7m) according to collected data from highest 10 buildings from Asia Pacific countries (Ho, 2007). In addition, CTBUH accepts floor to floor height as 3.1m for a residential building, and 3.9 m for an office building in general (Figure 2.7.) (Saroglou *et al*., 2017). Ali and Armstrong (1995) expressed that ceiling heights should be between 2.7m and 3.7m for commercial buildings, 2.5m and 2.7m for office function and 2.4m and 2.7m for hotels and residential buildings.

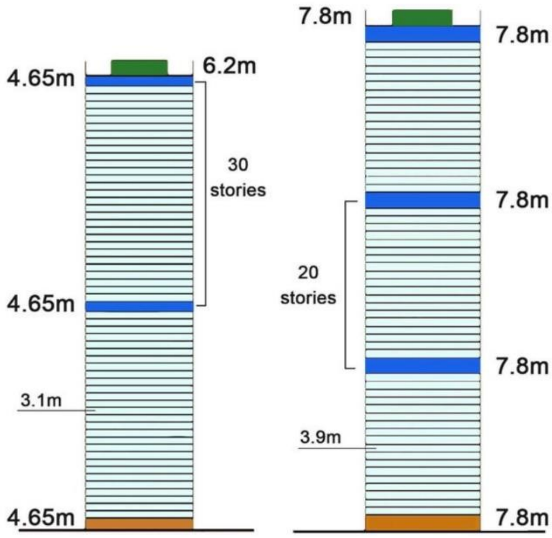


Figure 2.7. (Left) 60 storey residential building (206.15 m); (Right) 60 storey office building (273m) (Source: Saroglou *et al.*, 2017)

2.1.1.5. Aspect Ratio

Aspect ratio is usually defined as the ratio of its height to its smallest whole-base dimension (Baker, 2013). Since there is a limitation for plan dimensions due to urban land and regulations, as height increases buildings get slender; however, dealing with the lateral loads becomes more complex when buildings get slender. According to Baker (2013), it may be easier to design a 80 storeys tower with a large base against wind load instead of a very slender 40 storeys tower. Ali and Moon (2007) accept that predictable aspect ratio range is between 6 and 8. Ali and Al-Kodmany (2012) claim that wind load dynamic influence becomes important when aspect ratio is more than 4.

Günel and Ilgın (2014) state that for buildings below 40 storeys with aspect ratio below 6, the values predicted in design codes can be used in order to determine the wind loads. For buildings higher than 40 storeys or more slender buildings, dynamic wind effect and building dynamic response due to sudden wind changes must be considered.

One way to reduce the aspect ratio is to utilize the entire width of the building in resisting the overturning moments. From 1960s to 1980s, tall buildings were generally constructed with a structural system which primarily located on the perimeter of the building, and this resulted with small spacing between columns and limited openings. In the last 30 years, interior shear resisting systems which are connected to perimeters at different levels are more preferred rather than exoskeletons (Baker, 2013).

As the building becomes taller and its aspect ratio increases, the building tends to act more like a bending beam; hence, overturning moment increases (Moon, 2010). Wind forces, especially in the cross-wind direction, become more critical for tall buildings due to higher aspect ratios, and base moment increases as aspect ratio increases (Wang *et al.*, 2012). Since slender buildings require higher stiffness, structural systems should provide more efficiency or be less susceptible to wind forces. In order to improve the behaviors of a structural system, high strength materials can be used, floor width can be increased, or building shape can be modified considering wind forces.

2.1.1.6. Building Shape and Wind Modifications

Building shape is the key to create remarkable buildings, and it has a huge impact on structural behavior. Irwin and Baker (2006), Scott *et al.* (2007), Ho (2007), Ali and Moon (2007), Irwin *et al.* (2008), Wang *et al.* (2012), Zhou *et al.* (2014), Günel and Ilgın (2014), Moon (2015) investigate the influences of building shape on the structural performance, and state that it is possible to reduce the lateral loads with modifications on building shape.

According to Moon (2015), the shape of the buildings can be classified as prismatic, twisted, tilted, tapered and free form (Figure 2.8.). Although it is possible to design a building in a single shape, a proper combination of these shapes can be selected for a tall building. However, prismatic geometries are cost-friendly due to simple installation details and repetition of floor plates and facades.

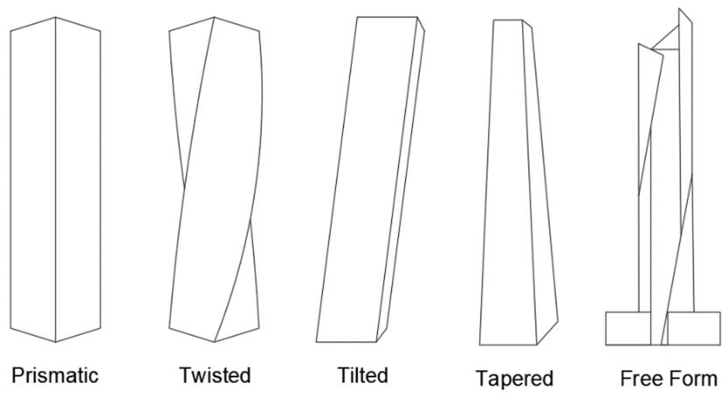


Figure 2.8. Fundamental variations for building shape in accordance with the study of Moon (2015)

On the other hand, twisted, tilted, tapered and free form buildings give opportunities to create monumental effect compared to simple geometries. The most important point to design a non-prismatic building is to manage the different floor plates. The key to make these buildings cost-friendly lies in the architect's ability to arrange a repetition plane program. Maximum repetition should be provided for installation details and floor plates in order to prevent additional cost (Scott *et al.,* 2007).

Zhou *et al.* (2014) designed a 405m height (90 storeys) building in different shapes in order to compare the effect of different shapes. The area of the facade subjected to wind load of each sample and the wind load were equal. According to the analysis, the overall displacement is minimum with the triangle elevation, while maximum with the inverted trapezoid (Figure 2.9.).

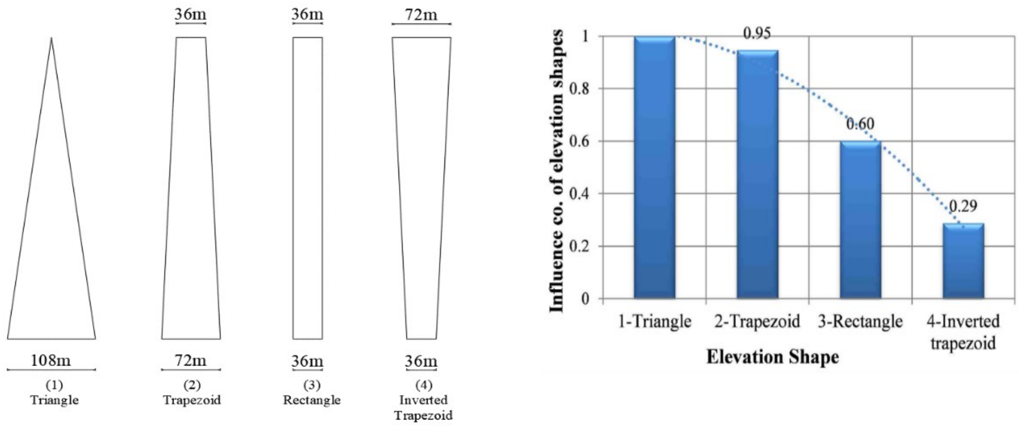


Figure 2.9. Influence coefficient of different building shapes (Source: Zhou *et al.,* 2014)

Wind Modifications

Although tall buildings suffer from high wind, seismicity and gravity loads, wind is the dominant force compared to other forces that arise due to height of the buildings.

Building shape has a major impact on not only building aesthetic, but also wind loads. According to Baker and Pawlikowski (2015), building shape is able to reduce the wind forces by creating an environment that "confuses the wind". When building has a constantly changing building shape, wind vortices cannot get organized, since wind encounters a different tier.

Tall buildings require stiffness-based design to prevent excessive vibration and swing. The effects of wind on building are directly dependent to the shape of the building, and it gets more challenging for slender buildings due to their more sensitive nature against wind (Irwin *et al.*, 2008).

There are some strategies against wind forces in order to increase the stiffness of the buildings. The most common strategies are sorted as follows:

- Orient the buildings regarding both windward and across-wind directions. In most cases, the lateral motion in the across-wind direction due to vortex shedding is much greater than the motion in the windward direction (Moon *et al.*, 2007) (Sev & Başarır, 2011).

- Step-backs and tapering throughout the building is a way to provide confused wind vortices, and may reduce the wind forces. (Ali & Moon, 2007; Irwin *et al.*, 2008; Taranath, 2012). Baker and Pawlikowski (2015) claim that "Starting from a slender top the building spreads out as the gravity and wind forces accumulate. As a result, even though the global forces are large, the forces in the individual members are not."
- Y shape plan is an efficient way to deal with wind forces, and furthermore, this layout is feasible for hotel and residential function, since it maximizes the view (Baker & Pawlikowski, 2015).
- Corner modification is an efficient strategy against wind, since softened corners can reduce the wind forces. (Irwin *et al.*, 2008; Günel & Ilgın, 2014) The corners on Taipei 101 which are stepped in order to reduce crosswind respond and drag, result in a 25% reduction in base moment. Taranath (2012) claims that rounded floor planes minimize building response to wind loads compared to sharp-edged plans.
- Porosity and openings allow air to run through the building; thus, vertices disrupt and get weak. Using openings on facade or in different levels of the building reduces vortex-shedding effect (Irwin e*t al.*, 2008; Taranath, 2012).
- Dampers are also another strategy which is widely used in tall buildings. They can be divided into two categories as active and passive dampers. Passive dampers do not require energy, and they perform intended without any activator. On the other hand, active dampers need an energy source to modify the system properties against ever-changing loads. Active dampers are more efficient than passive dampers due to instant response motions, however, passive systems are more common worldwide due to their economy and reliability (Ali & Moon, 2007). A cost benefit analysis showed that it is possible to save $400,000-500,000 with a Tuned Sloshing Dampers (TSD) system (Irwin *et al.,* 2008).

Through wind tunnel testing, one can get the wind forces on building facade accurately and can reduce the design wind loads by making modifications in building shape. Wind tunnel tests are also necessary to obtain the design wind loads for unusual building shapes or locations when standards and building codes are not applicable (Mendis *et al.,* 2007).

2.1.1.7. Floor Plan Configurations

Floor plan configurations are important because of their impact on structural efficiency and leasable area. Square floor plan is the most common plane shape, since it offers same stiffness in both directions against lateral loads. (Kim & Elnimeiri, 2004) (Sev & Özgen, 2009) (Ho, 2007)

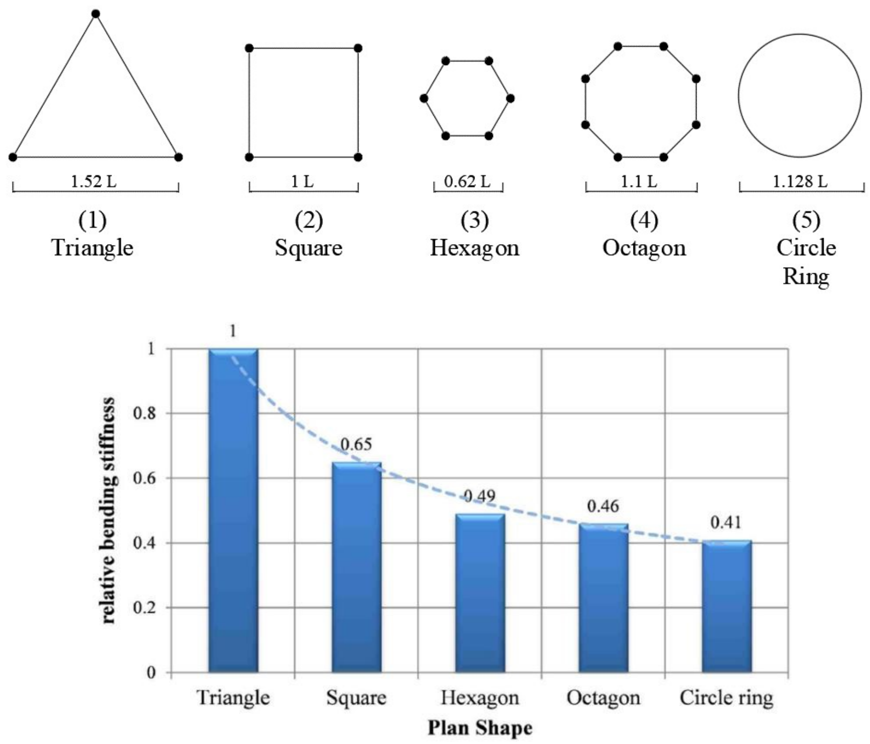


Figure 2.10. Relative bending stiffness of different floor plan shapes (Source: Zhou *et al.,* 2014)

In order to compare the impacts of the plan shapes on structural system, Zhou *et al.* (2014) designed triangle, square, hexagon, octagon and circle shape planes with equal plan area and section area of vertical members, and the vertical members are arranged uniformly in each of the polygon corners (Figure 2.10.). Results show that floor plan in triangular shape has the maximum bending stiffness. Since the bending stiffness decreases as number of edges increases, the plane bending stiffness is minimum in circular plane.

Zhou *et al.* (2014) also examined the impacts of the column size and orientation in floor plans. Total area of floors and vertical members are assumed as equal. According to this assumption, the results showed that when vertical members are placed in four corners of a square, the bending stiffness gets maximum. However, if the vertical members are placed in the middle of the edges of a square, lateral stiffness decreases to 50% (Figure 2.11.).

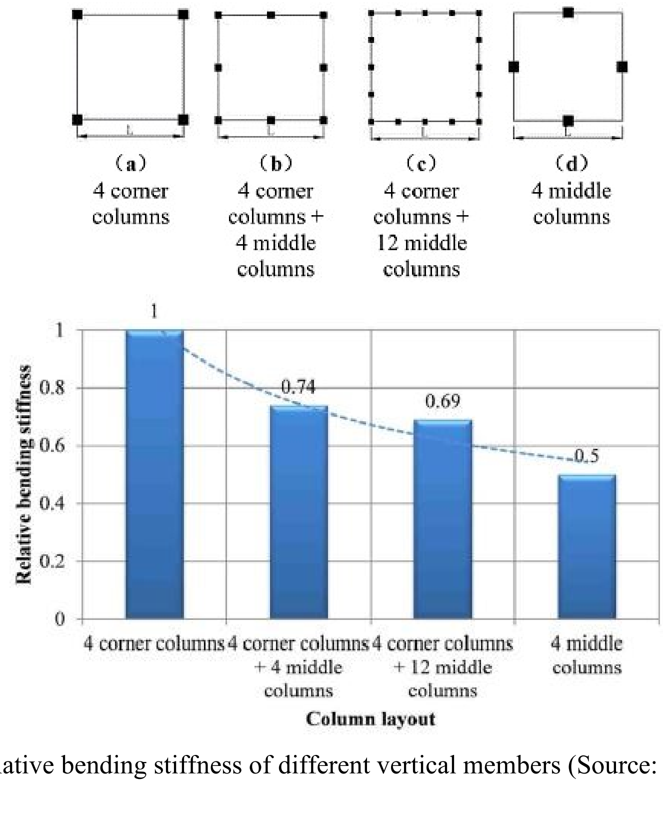


Figure 2.11. Relative bending stiffness of different vertical members (Source: Zhou *et al.,* 2014)

2.1.1.8. Floor Type

Since there are many storeys in a tall building, floor type has a great impact on cost, building height and floor to floor height.

Flat plate/slab systems maximize the net floor height which is a major architectural advantage of this system. From structural point of view, these systems are insufficient compared to rigid frames, since they cannot provide enough depth for beams. Although shear walls added to the flat plate/slab system can increase the resistance against lateral loads, these systems is suitable up to 25 storeys from structural and economic point of view (Günel & Ilgın, 2014).

Zhao *et al.* (2014) claim that widely used floor systems among the tall buildings are reinforced-concrete and steel-beam composite floor systems. The slab of the composite floor systems can be divided into three as the open-trough profiled deck system, the flat-profiled deck system and the steel-bar truss deck system. The open-trough profiled deck system is lightweight, costs less, and builds easily. The flat-profiled deck floor system is thinner and has better fire-resistance performance. The steel-bar truss deck composite floor system is often used in areas with complex stresses such as in mechanical floors. But its construction is more complicated, and it costs higher.

The weight of the floor system is about 20%-50% of the total weight in reinforced concrete tall buildings, and total cost of floor system is about 20%-30% of the overall cost. It is possible to decrease the floor weight by using steel-composite floor system, lightweight concrete floor or lightweight partition walls. On the other hand, floor thickness affects the stiffness and resistance against lateral loads directly. In a seismic region, the weight of the building should be decreased in order to reduce the seismic action of the structure (Zhao *et al.,* 2014).

2.1.1.9. Location

Location has remarkable impacts on cost, and it affects not only the structural material preferences due to local labor and availability of the material, but also the structural system due to physical site conditions such as wind load and soil type.

Location is determinant on structural system, since regulations and building codes for structural systems are different according to countries as it seen in Table 2.3. Especially, China code requires better structural response rather than other countries.

Table 2.3. *Drift limitations according to countries (Source: Choi, 2009)*

Overall Building Drift: no P-Delta		
US/Dubai	10 - 20 year wind	H / 400 – H / 500
Korea	50 - 100 year wind	H / 500
Inter-story Wind Drift: no P-Delta		
US/Dubai	10 - 20 year wind	H / 350
Korea	50 - 100 year wind	H / 350
China	100 year	H / 500 – H / 800 Depends on H

Kaihai and Yayong (2012) state that ground motion for seismic design and site class acceptances are different for China, American and Europe codes. The probability level of fortification earthquake is not same as well. Seismic design forces specified by Chinese response spectrum is larger than the US at the same seismic hazard level, and more rigorous inter-storey drift is compulsory in Chinese code as stated in Lu *et al.* (2015) Most of the time, these two aspects lead to a requirement for a dual system which contains a core and an exterior framing as it can be seen in existing buildings in China.

Occasionally, unexpected problems can occur because of the other buildings around, such as limitation of foundation, over reflection caused by facades and microclimates. Due to fact that existing tall buildings can change the behavior of winds, it must be considered before design stages.

601 Lexington Avenue had a different situation which resulted in changing the orientation of the structural members (Figure 2.12.). This building rises on 4 mega columns in the ground level, and these four mega legs were designed on the corner of the square plan in the beginning. However, there was a church in the land, and one of the mega columns was supposed to rise above that church. Therefore, orientation of columns had been changed, and columns have built in the midpoint of each edge of the square.

Figure 2.12. 601 Lexington Avenue (Source: Gobetz,W. www.flickr.com)

2.1.1.10. Leasable Span

Leasable span is the distance between core and building envelope, and space efficiency simply describes as the ratio of Net Floor Area (NFA) to Gross Floor Area (GFA) (Sev & Özgen, 2009). Since there are so many parameters which affect the space efficiency, leasable span is a concern for each phase of the construction.

Building function directly affects the leasable span. It is easy to design a single function building rather than mixed-use building due to serviceability. When the building has a single function, service requirement and the core area decrease. Multi-function buildings desire separate entrances, elevators, parking spots, MEP solutions; thus, core area enlarges.

Non-prismatic building shapes such as twisted, tilted, tapered or free form decrease the leasable span due to irregular floor plans.

There is a different consideration other than structural concerns. The regulations on natural light penetration shorten the lease spans in tall buildings, especially in Europe. For instance, the allowable depth in Germany is different than that in USA which is 15m, and smaller leasable spans allow to occupants to benefit from the natural lighting more (Jappsen, 2002 as cited in Ko *et al*., 2008). "According to Ali and Armstrong (1995) the depth of lease span must be between 10m and 14m for office function, except where very large single tenant groups are to be accommodated" (Sev & Özgen, 2009).

Although leasable span depends on different considerations, it can be basically increased by reducing the core area within acceptable limits. The service core of a tall building is about 25% to 35% of the floor. In order to increase the rentable area, the web shear walls in higher storeys can be omitted, or parts of the fin shear walls can be replaced by gravity columns (Sha *et al.*, 2014).

2.2. Studies on Structural Design Considerations

In the scope of this study, different structural systems are examined in terms of core and column ratio by investigating existing buildings in order to find the loss of leasable span which is used for structural components. In this section, previous studies based on case study methodology are reviewed.

Sev and Özgen (2009) investigated space efficiency in tall buildings by examining 10 tall buildings with a height range between 367m - 509m around the world and 10 tall buildings with a height range between 136m – 181m from Turkey. According to that study, all buildings in Turkey made of concrete, since they are not so high. Other samples around the world are composite except Central Plaza. Sev and Özgen (2009) compared the buildings in terms of GFA, NFA, columns layout and floor plan. The results showed that, buildings in Turkey are not as efficient as buildings out of Turkey in terms of leasable area, although their average height is almost the half of the other samples group.

Ho (2007) compared core location, floor height, structural system, plan shape and building form of the Asia Pacific's 10 tallest buildings according to Emporis (A global building information provider) database. The author states that the most common structural system is outriggered frame with mega columns and tube in tube structures. Tapered building geometry and central core is commonly used among the samples, and the common lease span is defined as approximately 12 m.

Kim and Elnimeiri (2004) analyzed 10 multi-function buildings in terms of function distribution, elevator distribution with respect to function and structural system. The authors state that in buildings with single function, space efficiency can be higher, and special features at the top of the buildings such as sky-deck may decrease the space efficiency.

Martin (2007) examined the advances in analysis techniques, structural systems and concrete technology by comparing 4 different buildings that are made of reinforced concrete with heights ranging between 90m - 300m by 3D computer modelling. Martin (2007) monitored and discussed the sway and shortening results of each sample.

Ilgın (2018) investigated 91 tall buildings in terms of structural system decision, structural material, building function and core configuration. Although the author presented the trend among those samples statistically, a comparison between different structural systems with respect to structural components is not given in his study.

In this study, 141 samples are gathered around the world and 75 of which are analyzed. Core and column ratio for each sample is calculated and compared with respect to different structural systems considering region, structural material and function of the building. NFA is investigated as well in order to compare the space efficiency of different structural systems.

2.3. Critical Review of the Literature

The literature review showed that, an efficient structural system reduces the overall cost and, leasable depth has an enormous impact on design strategy of the buildings. Structural design considerations of tall buildings are examined in order to specify the most important parameters. According to literature review, location, building function and structural material are defined as the parameters which are determinant on structural systems. Each parameter is mentioned briefly to highlight the important points as follows.

Structural material preferences generally based on local labor and material sources. Concrete is more comparable to steel now because of the new pumping technologies and high strength concrete innovations. Since concrete elements tend to have larger mass, concrete structures provide more inherent damping. As a result, composite is a great solution which includes both advantages of concrete and steel. Steel and composite frame can increase the lease span since their cross-sectional area is smaller. However, the average or approximate core and column area for different structural materials have not been specified. For instance Sha *et al.* (2014) claim that average core ratio is between 25%-35%; however, the impact of the structural material or structural systems on this ratio has not been discussed. In this study, it is aimed that to specify the average column and core ratio for different structural materials.

Building function is also important for structural design. Residential buildings and hotels allow small column spaces and divided areas, in contrast, larger spans are in demand for office function. Single function buildings may provide higher space efficiency according to the literature review. This study aims to provide the average net floor area and leasable span for both single and multi-function buildings by examining existing buildings.

Location has an impact on the structural system. Each location has its own climate, soil and ground conditions, and wind loads depend on location. Furthermore, each country has its own regulations and limitations about constructions. For instance, China code requires higher structural performance at the same hazard level compared to US Code. In this study, samples are classified based on their regions and compared to each other with respect to structural components. The impact of the location on the footprint of the structural components are investigated, and the average core and column ratio for different regions are specified.

An enlarged core area which increases structural efficiency, decreases the leasable span. Therefore, net leasable area is directly related with the structural components. Interior structures may decrease the space efficiency, since these systems requires strong cores or trusses. The impacts of different structural systems on leasable area are investigated in the scope of this study.

Structural systems are compared so many times by considering different parameters (Ali & Moon, 2007; Zhou *et al.,* 2014; Moon, 2012). In this study, the footprints of structural components are investigated with respect to structural systems, and average core and column area are specified for different structural systems.

CHAPTER 3

MATERIALS AND METHODS

The aim of this study is to present the statistical analysis results of tall buildings in terms of structural components in order to provide a preliminary knowledge for early designs and estimations. For this purpose, an extensive database is prepared, and 141 tall buildings are investigated.

In the materials section, determination of samples, required parameters for analyses, and software used are expressed while in methodology section, gathering data, analysis stages and evolution of the sample group are explained step by step.

3.1. Research Material

All buildings are selected from The Skyscraper Center which is global tall building database of the CTBUH, and the height of the buildings is between 100 m and 1000 m. Since there is a hardness in data collection because of the security issues, the main determinant factor for the sample selection is the availability of the data.

In this research, data on 141 tall buildings are obtained. 7 of which are “Under Construction”, 17 of which are “Architecturally Topped Out”, 5 of which are “On Hold” and 112 of which “Completed” according to January 2019 CTBUH database.

3.1.1. Required Parameters for the Analyses

Since the aim of this research is to investigate different structural systems in terms of footprints of structural components, several building data such as floor size, column dimensions, core size are required for each sample in order to analyze.

Some data on samples such as floor plate size, function, location is needed in order to analyze the samples, and each required information for the samples is described as an individual 'parameter' in this study. These parameters are specified and divided into three groups as "identity parameters", "architectural parameters" and "structural parameters". Identity parameters include basic information about buildings while architectural parameters include the data on building height and floor plate size. Lastly, structural parameters include the data on structural system (Table 3.1.).

Table 3.1. *Required parameters for analyses*

Identity Parameters	Architectural Parameters	Structural Parameters
•Year of Completion •Designers •Location •Function	•Number of Storey •Height •Floor plate Size •Floor Plate Area •Leasable Span •Aspect Ratio	•Structural Material •Structural Systems •Special Features •Core Size •Core Area •Column Size •Column Area

All identity parameters and some of the architectural parameters such as number of storey and building height are taken from CTBUH database.

Floor plan of the buildings is required in order to calculate some variables such as floor plate area, aspect ratio, leasable span, and core and column ratio. These plans are supplied from different sources, and these sources are given in Table 3.2. Although buildings with a red triangle on the top right corner in the cells have more than one name, official names accepted by The Skyscraper Center are given in the table.

In this section, parameters are described, and the important points of these parameters are highlighted.

Table 3.2. *List of references of the buildings*

NO	BUILDINGS (Ascending Order of Height)	FLOOR PLAN	MATERIAL	STRUCTURAL SYSTEM DETAILS
1	O-14	Reiser et al., 2010	CTBUH	Günel&Ilgın, 2014
2	ALDAR HEADQUARTERS	www.archdaily.com; Sketchup 3D Warehouse	CTBUH	www.arup.com
3	THE PLAZA ON DEWITT	-	CTBUH	Günel&Ilgın, 2014
4	PIRELLI BUILDING	Günel&Ilgın, 2014; www.bmiaa.com	CTBUH	Günel&Ilgın, 2014
5	TORRE GLORIES	Günel&Ilgın, 2014	Günel&Ilgın, 2014	Günel&Ilgın, 2014
6	STRATA	Günel&Ilgın, 2014; commons.wikimedia.org	CTBUH	Günel&Ilgın, 2014
7	SEAGRAM	Günel&Ilgın, 2014	Günel&Ilgın, 2014	Günel&Ilgın, 2014
8	FIRST CANADIAN CENTRE	Iyengar, 1992; Günel&Ilgın, 2014	CTBUH	Iyengar, 1992; Günel&Ilgın, 2014
9	ONTERIE CENTER	-	CTBUH	Günel&Ilgın, 2014
10	780 3RD AVENUE	Günel&Ilgın, 2014; www.loopnet.com	CTBUH	Günel&Ilgın, 2014
11	30 ST MARY AXE	www.fosterandpartners.com	CTBUH	Günel&Ilgın, 2014
12	HEARST TOWER	Günel&Ilgın, 2014; faculty.arch.tamu.edu	CTBUH	Günel&Ilgın, 2014
13	ALLIANZ TOWER	Bayır, 2016	CTBUH	Bayır, 2016
14	TURNING TORSO	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014
15	LAKE POINT TOWER	-	CTBUH	Günel&Ilgın, 2014
16	MODE GAKUEN COCOON TOWER	Hikone et al, 2009; Tange & Minami, 2009	CTBUH	Hikone et al, 2009; Tange & Minami, 2009
17	ONE MAGNIFICENT MILE	-	CTBUH	Günel&Ilgın, 2014
18	OLYMPIA CENTER	Iyengar, 1992; Günel&Ilgın, 2014	CTBUH	Iyengar, 1992; Günel&Ilgın, 2014
19	THE LEADENHALL BUILDING	Young et al., 2013	CTBUH	Young et al., 2013
20	WORLD TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; Martin, 2007
21	KINGTOWN INTERNATIONAL CENTER	Sarkisian, 2012	CTBUH	Sarkisian et al., 2010
22	SOUTHEAST FINANCIAL CENTER	-	CTBUH	Günel&Ilgın, 2014
23	CCTV HEADQUARTERS	-	CTBUH	Günel&Ilgın, 2014
24	8 SHENTON WAY	Günel&Ilgın, 2014	Günel&Ilgın, 2014	Günel&Ilgın, 2014
25	BAHRAIN WORLD TRADE CENTER	Günel&Ilgın, 2014; Khani Arshad&Halford, n.d.	Günel&Ilgın, 2014	Günel&Ilgın, 2014
26	TORRE REFORMA	Boy, 2017; www.archdaily.com	CTBUH	Boy, 2017
27	EVOLUTION TOWER	Nikandrov, 2015	CTBUH	Nikandrov, 2015
28	HIGHCLIFF	-	CTBUH	Günel&Ilgın, 2014
29	LANGHAM PLACE OFFICE TOWER	www.oneday.com.hk; www.langhamplace.com.hk	CTBUH	www.arup.com
30	COMMERZBANK TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014
31	WATER TOWER PLACE	-	CTBUH	Günel&Ilgın, 2014

NO	BUILDINGS (Ascending Order of Height)	FLOOR PLAN	MATERIAL	STRUCTURAL SYSTEM DETAILS
32	AL FAISALIAH	Günel&Ilgın, 2014; Viswanath, et al., 1997	Günel&Ilgın, 2014	Günel&Ilgın, 2014
33	601 LEXINGTON	Günel&Ilgın, 2014; faculty.arch.tamu.edu	Cheung & Chau, 2005	Günel&Ilgın, 2014
34	CHEUNG KONG CENTRE	Günel&Ilgın, 2014	Günel&Ilgın, 2014	Günel&Ilgın, 2014; Wong, n.d.
35	ONE LIBERTY PLACE	Binder, 2006	CTBUH	Binder, 2006; Zaknic et al., 1998
36	PLAZA 66	Günel&Ilgın, 2014; Tomasetti et al., 2001	CTBUH	Günel&Ilgın, 2014
37	311 SOUTH WACKER DRIVE	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014
38	CHINA WORLD TRADE CENTER PHASE 3B	Cheung & Chau, 2005; www.cwtc.com	CTBUH	Cheung & Chau, 2005
39	COMCAST CENTER	-	CTBUH	Günel&Ilgın, 2014
40	EUREKA TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; Martin, 2007
41	ONE ISLAND EAST CENTRE	-	CTBUH	Günel&Ilgın, 2014
42	TORRE COSTANERA	web.archive.org	CTBUH	CTBUH
43	ASPIRE TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014
44	GOLDEN EAGLE TIANDI TOWER C	-	CTBUH	Ilgın, 2018
45	NBK TOWER	-	CTBUH	Ilgın, 2018
46	ABENO HARUKAS	-	CTBUH	Ilgın, 2018
47	SHENZHEN ZHONGZHOU HOLDINGS F. C.	-	CTBUH	Ilgın, 2018
48	CAPITAL CITY MOSCOW TOWER	-	CTBUH	Ilgın, 2018
49	KINGDOM CENTRE	skyscraperpage.com; architizer-prod.imgix.net	Günel&Ilgın, 2014	skyscraperpage.com; www.architectmagazine.com
50	GREENLAND PULI CENTER	-	CTBUH	Ilgın, 2018
51	JIANGXI N. G. CENTRAL PLAZA, PARCEL A	-	CTBUH	Ilgın, 2018
52	JIANGXI N. G. CENTRAL PLAZA, PARCEL B	-	CTBUH	Ilgın, 2018
53	TWO PRUDENTIAL PLAZA	Binder, 2006; Choi et al., 2012	CTBUH	Choi et al., 2012; Zaknic et al., 1998
54	ONE MANHATTAN WEST	-	CTBUH	Ilgın, 2018
55	WUXI MAOYE CITY - MARRIOTT HOTEL	-	CTBUH	Ilgın, 2018
56	NORTHEAST ASIA TRADE TOWER	-	CTBUH	Ilgın, 2018
57	THE SHARD	Parker, 2012	CTBUH	Parker, 2012
58	CAYAN TOWER	Baker et al., 2010; architizer.com	CTBUH	Baker et al., 2010; architizer.com
59	BURJ RAFAL	-	CTBUH	Ilgın, 2018
60	PEARL RIVER TOWER	Tomlinson et al., 2014; tr.redsearch.org	CTBUH	Tomlinson et al., 2014; tr.redsearch.org
61	MENARA TM	-	CTBUH	Günel&Ilgın, 2014
62	OCEAN HEIGHTS	-	CTBUH	Ilgın, 2018

NO	BUILDINGS (Ascending Order of Height)	FLOOR PLAN	MATERIAL	STRUCTURAL SYSTEM DETAILS
63	U.S. Bank Tower	Taranath, 2012	CTBUH	Taranath, 2012)
64	BANK OF AMERICA PLAZA	Taranath, 2012)	CTBUH	Taranath, 2012)
65	KING POWER MAHANAKHON	Chanvaivit, 2015	CTBUH	Chanvaivit, 2015
66	NEW YORK TIMES TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; Barben et al., 2009
67	CHRYSLER BUILDING	Günel&Ilgın, 2014; www.archdaily.com	CTBUH	Günel&Ilgın, 2014; nypost.com
68	SINAR MAS CENTER 1	-	CTBUH	Ilgın, 2018
69	53 WEST 53RD	-	CTBUH	Ilgın, 2018
70	PALAIS ROYALE	-	CTBUH	Ilgın, 2018
71	BURJ AL ARAB	-	CTBUH	Ilgın, 2018
72	Q1 TOWER	-	CTBUH	Günel&Ilgın, 2014
73	SALEFORCE TOWER	-	CTBUH	Ilgın, 2018
74	GOLDEN EAGLE TIANDI TOWER B	-	CTBUH	Ilgın, 2018
75	CHINA WORLD TOWER	-	CTBUH	Ilgın, 2018
76	LCT RESIDENTIAL TOWER B	-	CTBUH	Ilgın, 2018
77	SHIMAO INTERNATIONAL PLAZA	-	CTBUH	Ilgın, 2018
78	WILSHIRE GRAND CENTER	www.wilshiregrandcenter.com	CTBUH	Joseph et al., 2016
79	TIANJIN WORLD FINANCIAL CENTER	-	CTBUH	Ilgın, 2018
80	TIANJIN MODERN CITY OFFICE TOWER	-	CTBUH	Ilgın, 2018
81	LCT RESIDENTIAL TOWER A	-	CTBUH	Ilgın, 2018
82	875 NORTH MICHIGAN AVENUE	Günel&Ilgın, 2014; app.vts.com	CTBUH	Günel&Ilgın, 2014
83	NEVA TOWERS 2	Taşçı, 2017	CTBUH	Taşçı, 2017
84	THE CENTER	Günel&Ilgın, 2014; http://www.primeoffice.com.hk	Günel&Ilgın, 2014	Ho, 2007
85	AON CENTER	Zaknic et al., 1998; preservationchicago.org	CTBUH	Zaknic et al., 1998
86	85 SKY TOWER	-	CTBUH	Ilgın, 2018
87	RAFFLES CITY CHONGQING T3N	-	CTBUH	Ilgın, 2018
88	RAFFLES CITY CHONGQING T4N	-	CTBUH	Ilgın, 2018
89	SINAO STEEL INTERNATIONAL PLAZA T2	-	CTBUH	Ilgın, 2018
90	GREENLAND GROUP SUZHOU CENTER	-	CTBUH	Ilgın, 2018
91	HANKING CENTER	Xu et al., 2015; www.archdaily.com	CTBUH	Xu et al., 2015; www.archdaily.com
92	ALMAS TOWER	Shahdadpuri et al., n.d.; Chandunni&Berahman, 2010	Shahdadpuri et al., n.d	Shahdadpuri et al., n.d.; Chandunni&Berahman, 2010
93	BANK OF CHINA	Günel&Ilgın, 2014; www.pcf-p.com	CTBUH	Günel&Ilgın, 2014; www.pcf-p.com

NO	BUILDINGS (Ascending Order of Height)	FLOOR PLAN	MATERIAL	STRUCTURAL SYSTEM DETAILS
94	GOLDEN EAGLE TIANDI TOWER A	-	CTBUH	Ilgın, 2018
95	FEDERATION TOWER	-	CTBUH	Ilgın, 2018
96	CENTRAL PLAZA	Keskin, 2012; Cheung&Chau, 2005	CTBUH	Ayres & MacArthur, 1993; P. Ho, 2007
97	ELIT RESIDENCE	-	CTBUH	Ilgın, 2018
98	EMPIRE STATE BUILDING	Günel&Ilgın, 2014; Keskin, 2012	CTBUH	Günel&Ilgın, 2014
99	BURJ MOHAMMED BIN RASHID	-	CTBUH	Ilgın, 2018
100	SHUN HING SQUARE	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; Ho, 2007
101	PIF TOWER	Soto&Al-Shihabi, 2015	CTBUH	Soto&Al-Shihabi, 2015
102	SHUM YIP UPPER HILLS TOWER 1	-	CTBUH	Ilgın, 2018
103	CITIC PLAZA	Keskin, 2012	Günel&Ilgın, 2014	Günel&Ilgın, 2014
104	23 MARINA	-	CTBUH	Ilgın, 2018
105	CHINA RESOURCES HQ	-	CTBUH	Ilgın, 2018
106	LCT LANDMARK TOWER	-	CTBUH	Ilgın, 2018
107	TWO INTERNATIONAL FINANCE CENTER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; Cheung & Chau, 2005
108	AL HAMRA TOWER	-	Ilgın, 2018	Ilgın, 2018
109	PRINCESS TOWER	-	Ilgın, 2018	Ilgın, 2018
110	WORLD TRADE CENTER (TWINS)	Günel&Ilgın, 2014; 911research.wtc7.net	CTBUH	Günel&Ilgın, 2014
111	JIN MAO	Günel&Ilgın, 2014; www.officesasia.com	CTBUH	Günel&Ilgın, 2014
112	TRUMP INTERNATIONAL TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; W. Baker et al., 2009
113	MARINA 101	-	CTBUH	Ilgın, 2018
114	432 PARK AVENUE	Marcus, 2015; Seeward, 2014	CTBUH	Günel&Ilgın, 2014
115	HAIKOU TOWER 1	-	CTBUH	Ilgın, 2018
116	AKHMAT TOWER	-	CTBUH	Ilgın, 2018
117	111 WEST 57TH STREET	Marcus, 2015; Shop Architects, 2014	CTBUH	Marcus, 2015; Shop Architects, 2014
118	GUANGZHOU INTERNATIONAL FIN CENT.	Kwok & Lee, 2017; forum.skyscraperpage.com	CTBUH	Kwok & Lee, 2017
119	KK100	www.archdaily.com	CTBUH	Baker, 2013, www.arup.com
120	WORLD ONE TOWER	Berman & Faschan, 2011	CTBUH	Berman & Faschan, 2011; www.pcf-p.com
121	WILLIS TOWER	Günel&Ilgın, 2014; en.wikiarquitectura.com	CTBUH	Günel&Ilgın, 2014
122	ZIFENG TOWER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014
123	PETRONAS TWIN TOWERS	Günel&Ilgın, 2014; www.archute.com	Günel&Ilgın, 2014	Günel&Ilgın, 2014; Ho, 2007
124	LAKHTA CENTER	AskariNejad, 2014; www.metallbau-magazin.de	CTBUH	AskariNejad, 2014

NO	BUILDINGS (Ascending Order of Height)	FLOOR PLAN	MATERIAL	STRUCTURAL SYSTEM DETAILS
125	CHENGDU GREENLAND TOWER	Poon et al., 2015	CTBUH	Poon et al., 2015
126	WUHAN GREENLAND CENTER	Fu et al., 2012; Fu, 2012	CTBUH	Fu et al., 2012; Fu, 2012
127	INTERNATIONAL COMMERCE CENTER	Günel&Ilgın, 2014	CTBUH	Günel&Ilgın, 2014; Tang, 2016
128	SHANGHAI WORLD FINANCIAL CENTER	Günel&Ilgın, 2014	CTBUH	Katz&Robertson, 2008; Günel&Ilgın, 2014
129	TAIPEI 101	Günel&Ilgın, 2014; www.slideshare.net	CTBUH	Poon et al., 2004; Günel&Ilgın, 2014
130	EVERGRANDE IFC T1	-	CTBUH	Ilgın, 2018
131	CITIC TOWER	Peng et al., 2014; Peng, 2014	CTBUH	Peng et al., 2014; Peng, 2014
132	TIANJIN CTF FINANCE CENTER	W. Ho, 2014; Lee et al., 2016	CTBUH	W. Ho, 2014; Lee et al., 2016
133	GUANGZHOU CTF FINANCE CENTER	Ho et al., 2014; Chan, 2016	CTBUH	Ho et al., 2014; Chan, 2016
134	ONE WORLD TRADE CENTER	www.onewtc.com; www.archdaily.com	CTBUH	Rahimian & Eilon, 2015
135	LOTTE WORLD TOWER	Kim et al., 2015	CTBUH	Kim et al., 2015
136	GOLDIN FINANCE	Liu et al., 2012	CTBUH	Liu et al., 2012
137	PING AN	Malott & Poon, 2012; Malott et al., 2012	CTBUH	Malott & Poon, 2012; Malott et al., 2012
138	SHANGHAI TOWER	Günel&Ilgın, 2014	CTBUH	Xia et al., 2010
139	MERDEKA PNB 118	Fender, 2016	CTBUH	Fender, 2016
140	BURJ KHALIFA	Günel&Ilgın, 2014	Günel&Ilgın, 2014	B.Baker&Pawlikowski, 2015
141	JEDDAH TOWER	-	CTBUH	Ilgın, 2018

3.1.1.1. Structural Systems

Gunel and Ilgın (2014) have provided a structural system classification for tall buildings except for buttressed core system, which is relatively new. Since Baker and Pawlikowski (2015) classify Burj Khalifa as buttressed core, this system is included to classification of Gunel and Ilgın (2014). In this study, structural systems are specified according to the classification given below and acceptances provided by Günel and Ilgın (2014).

- Shear-frame System
    - Shear Trussed Frame (Braced Frame) System
    - Shear Walled Frame System
- Mega Column (Mega Frame, Space Truss) System
- Mega Core System
- Outriggered Frame System
- Tube System
    - Framed-tube System
    - Trussed-tube System
    - Bundled-tube System
- Buttressed Core system

Structural systems are determined based on the information which are taken from books, journal papers, conference proceedings, conference videos, and technical reports. These sources are given in Table 3.2. in detail.

3.1.1.2. Structural Material

CTBUH defines structural materials as steel, reinforced concrete, precast concrete, timber, mixed-structure and composite, and considers not only vertical/lateral structural elements, but also floor spanning systems while deciding the structural material. On the contrary, Günel and Ilgın (2014) do not take the material of floor spanning systems into consideration while deciding the material of the structure. In this study, shear walls, core walls, columns, beams, braces and outriggers are accepted as the determinants of structural material, similar to Günel and Ilgın (2014).

Tall buildings are generally made of concrete, steel or composite, and composite structures can be generated in two different ways:

- A composite component in the structural system (e.g. composite columns)
- A combination of steel or concrete components (e.g. steel columns + concrete core)

In this study, if all load bearing system is constructed with the same material, structural material is specified according to that single material. However, if load bearing components are constructed with more than single material, structural material is accepted as composite.

3.1.1.3. Building Function

According to data on function of the buildings which is taken from CTBUH, samples have been built for mixed-use, office, residential and hotel purpose mostly. Nevertheless, there is one building constructed for educational purpose in the sample group which is Mode Gakuen Cocoon Tower in Tokyo, Japan.

3.1.1.4. Number of Storey

The data on number of storey is taken from CTBUH, and it refers to number of storey ‘above’ the ground. Mechanical penthouses or plant rooms above the general roof area are not counted as a storey according to the CTBUH height criteria.

3.1.1.5. Height of the Building

There are three different height criteria according to CTBUH which are ‘Height to Tip’, ‘Architectural Height’ and ‘Occupied Height’. CTBUH describes these criteria as follows:

- Height to Tip: The highest point of the building, irrespective of material or function of the highest element.
- Height to Architectural Top: Architectural top of the building which include spires but not antenna, signage, flagpoles or other functional-technical equipment.
- Height to Highest Occupied Floor: The finished floor level of the highest occupiable floor within the building (CTBUH, n.d.).

Since architectural height is employed to define the CTBUH rankings of the “World’s Tallest Buildings,” height data in this study represents ‘architectural height’ (Figure 3.1.).

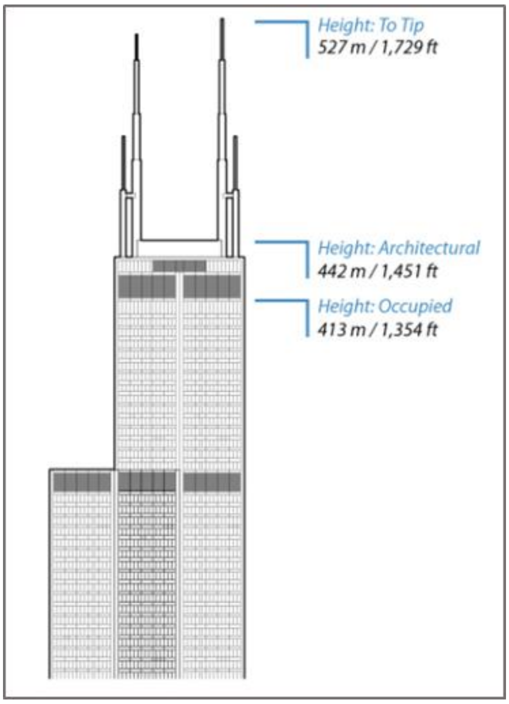


Figure 3.1. CTBUH height criteria (Willis Tower, Chicago, USA Source: CTBUH)

3.1.1.6. Floor Plate, Core and Column Size and Area

Size of the floor plate, core and columns are determined according to redrawn floor plans. Redrawing process of these plans is explained in Section 3.2.1. Process of Collecting Sample.

Core ratio is calculated by dividing total core area by floor plate area. Other structural components such as braces are considered in column area, and column ratio is calculated by dividing total column area by floor plate area. In this study, floor plate area means the area of a single storey.

3.1.1.7. Aspect Ratio

Aspect ratio is calculated by dividing the architectural height to narrow structural depth of the building (AR: H/B). Structural depth is accepted the longest span between the outer edge of columns (Figure 3.2.).

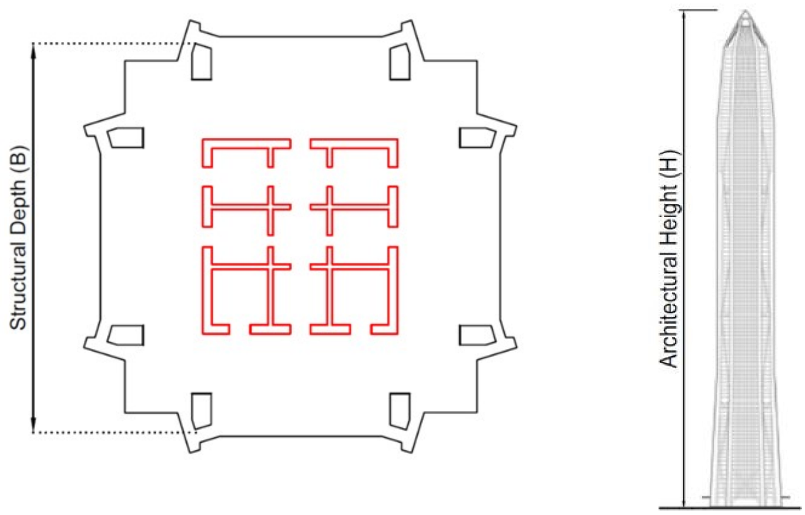


Figure 3.2. Ping An Finance Center floor plan and elevation

In this study, aspect ratio values of the buildings are generally more than 6. However, there are exceptional cases where the aspect ratio is less than 4. Although these buildings are not slender, they have iconic forms compared to conventional buildings.

O-14 (AR: 3.52), 30st Mary Axe (AR: 3.75) and Aldar Headquarters (AR: 3.96) are some of those buildings which are built with trussed tube structural system (Figure 3.3.).

Figure 3.3. (Left) O-14 (Dubai); (Middle) 30st Mary Axe (London); (Right) Aldar Headquarters (Abu Dhabi) (Source: CTBUH)

3.1.1.8. Special Features

Dampers, wind slots, corner modifications, set-backs, wind gaps at different levels of buildings, tapered form and wind turbines are identified as 'special features.' Buildings with special features are presented briefly in 'Results and Discussion' chapter.

3.1.1.9. Leasable Span and Net Floor Area (NFA)

Leasable span is the distance between core and building envelope, and it can be changeable due to shape of the buildings, so the largest distance between core and building envelope is accepted as leasable span in this study.

Net floor area is specified as the floor plate area without service core and other components of load bearing system such as columns and braces. In this study, NFA ratio is calculated by dividing net floor area by floor plate area.

3.1.1.10. Location

Data on location is taken from CTBUH, and location analysis is executed regionally. CTBUH classifies the regions as Africa, Asia, Central America, Europe, Middle East, North America, Oceania and South America. In the beginning of this study, Central, North and South America are considered together as 'America,' and Europe and Oceania are accepted as 'Others' because of the number of samples. After evaluation on samples, buildings are divided as 'China' and 'Others' in further stages of the study as explained in '3.2.3. Evolution of Sample Groups' section. Since there is a small number of high-rise buildings in Africa, no sample has been taken from this region.

3.1.2. Used Software

AutoCAD 2018 - Student Version is used for 2D plan drawings whereas all charts, graphs and calculations are made in Microsoft Excel, Office 365.

Scatter and Box & Whisker charts are two of the tools in Excel, and both tools and their statistical basics are explained in '3.2.4. Charts Used in Analyses' section.

3.2. Research Methodology

According to described parameters in "3.1. Research Material" section, samples are collected. As a first step, samples are categorized, and the categories are entitled. After describing sample groups in terms of identity and architectural parameters, building samples are analyzed. Analysis process of this study generally has three stages:

First stage: Samples are evaluated together based on their heights. By evaluating the results, this study identified whether further sub-classifications are required or not. Further classifications have been applied where necessary according to the correlation among parameters.

Second Stage: Structural system, building function, structural material and location are some of the parameters which primarily influence the structural design (Kim & Elnimeiri, 2004; Ho, 2007; Baker, 2013; Kaihai & Yayong, 2012; Choi, 2009; Ali & Moon, 2007). Therefore, buildings are examined in terms of these parameters at second stage of the analyses.

Final Stage: According to the correlations and dependency among parameters, classifications of the samples are modified, and final analyses are performed according to the final categorizations.

Research methodology is explained step by step in following sections.

3.2.1. Process of Collecting Sample Buildings

Samples have been selected among the buildings with the status of 'under construction', 'structurally topped out', 'architecturally topped out' and 'completed.' Only Twin Towers (1972-2001) in World Trade Center Complex (New York) which are in demolished status are considered in this study, since Twin Towers had been accepted as a landmark of the city for about 30 years as well as a structural milestone in tall buildings history.

Since floor plan is required to determine the size of building components such as floor plate, core and column areas, an extensive database is composed. Obtained floor plans from different sources are accepted as a reference and used as an underlay while redrawing floor plans in AutoCAD. Since buildings withstand the highest shear forces at the bottom of the building, structural systems are mainly designed considering the ground floor, and components have larger cross-sections in lower levels. Therefore, generally ground floor plans or the floor which is as close as possible to the ground floor is selected as reference floor plan.

Missing data in floor plans are determined according to the verified floor plans in scale by proportioning with supplied information. Dimensions either measured or estimated about structural components of the buildings are crosschecked with different sources and then finalized.

3.2.2. Defining Methodology of Analyses

141 samples from different locations are collected by following principles mentioned above and named as 'Sample Group - 1' (SG1). Due to the scarcity of available data on dimensions of the buildings, 59 out of 141 buildings in SG1 have only identity parameters, structural system classifications and structural material information. SG1 is further scrutinized in order to provide structural system distribution. 82 out of 141 samples have all data which are required for this study, and these samples are named as 'Sample Group - 2' (SG2).

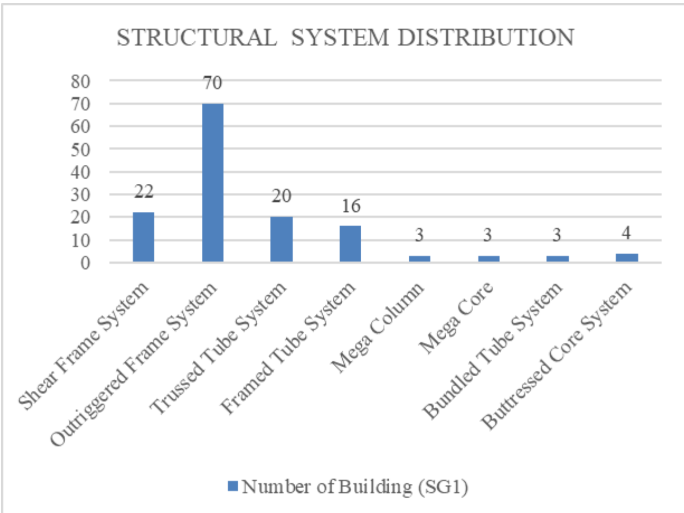


Figure 3.4. Structural system distribution

According to structural system distribution, outriggered frame system, shear frame system, trussed tube system and framed tube system are the common structural systems respectively for tall buildings. Figure 3.4. shows that, it is not appropriate to draw a conclusion about mega core, mega column and buttressed core structural systems due to the limited number of samples. Although it is not common worldwide, bundled tube structures are also considered in this study, since they perform similar structural behavior to trussed and framed tube structures. Therefore, shear frame system, outriggered frame system and tube system as sub-classes of frame tube, trussed tube and bundled tube are defined as the structural systems to investigate for this study. Structural system of 75 buildings in SG2 are built with any of these systems and named as SG3 (Figure 3.5.). Therefore, buildings in SG3 are analyzed mostly in the scope of this study. However, SG2 is examined and displayed with graphs in order to describe the sample group.

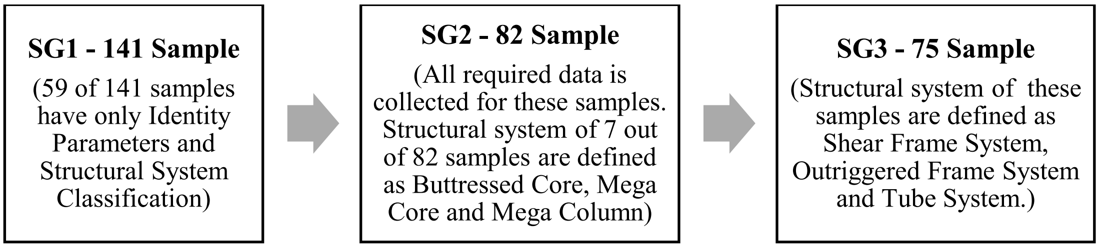


Figure 3.5. Determination of sample groups

As a first step, distribution of the samples in SG2 and SG3 are obtained in terms of different parameters such as height, building function, aspect ratio and location. Then, SG3 is analyzed in detail.

In the first stage of the analyses, all 75 samples in SG3 are evaluated together by scatter charts. The relationships between height of the buildings and other parameters such as floor area, aspect ratio and core and column ratio are examined, and the level of correlations are investigated.

Literature review shows that structural system, location, building function and structural material are primary parameters for the structural design of a tall building. Therefore, samples are analyzed considering these variables in the second stage of analyses (Figure 3.6.). Each variable in classified groups are investigated in terms of height, core ratio and column ratio. At this level of the study, not only the correlation between parameters but also the change in correlation with respect to the sub-classification for a given parameter is observed.

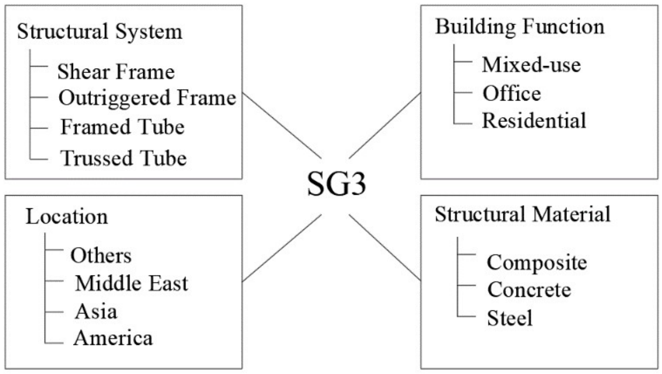


Figure 3.6. Sample separations in SG3

When samples are investigated regarding a single parameter, the other three parameters have been ignored with this separation. For instance, if buildings are examined based on structural system, the impacts of location, building function and structural material have not taken into consideration. Therefore, sample groups are modified.

3.2.3. Evolution of Sample Groups

Location is one of the key factors for structural design due to different site conditions such as wind loads and local design requirements. Especially buildings in China must respond to more severe structural requirements than other countries as mentioned in literature review. According to previous studies and national design codes, samples are divided based on their locations as 'China' and 'Others' for final analyses.

Building function has an influence on structural design, since each function have different requirements. For instance, residential buildings require divided spaces, whereas column-free area is in demand for office buildings. Since residential and hotel function require similar spaces, they are evaluated together as non-office buildings, and named as 'others.' Single function office buildings and each combination with office function are considered together and accepted as 'office' (Figure 3.7.).

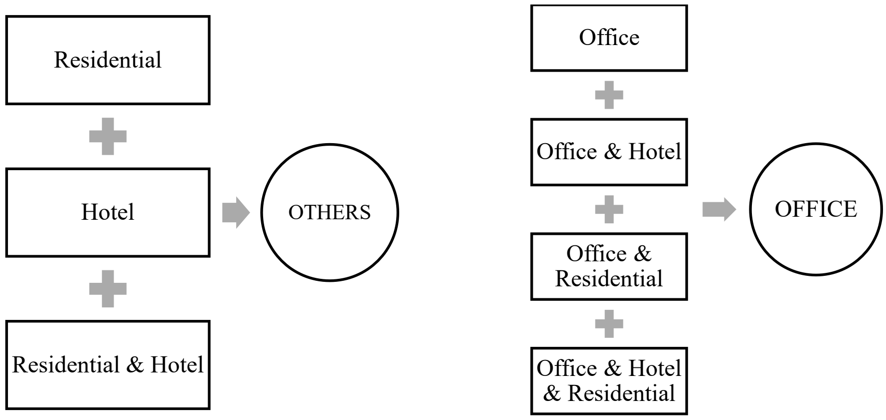


Figure 3.7. Separation of building function

According to pathway summarized above, buildings were separated by considering all parameters together instead of evaluating separately as in second stage of the analyses (Figure 3.8.). The classification of the building samples in the final stage can be describe as following process:

- Buildings are divided according to their location as China and others,
- Sub-classes are generated as office and others
- Further categorization based on structural systems as outriggered, tube and shear frame system are performed.
- Fourth level sub-classes are generated according to the structural material of tall buildings.

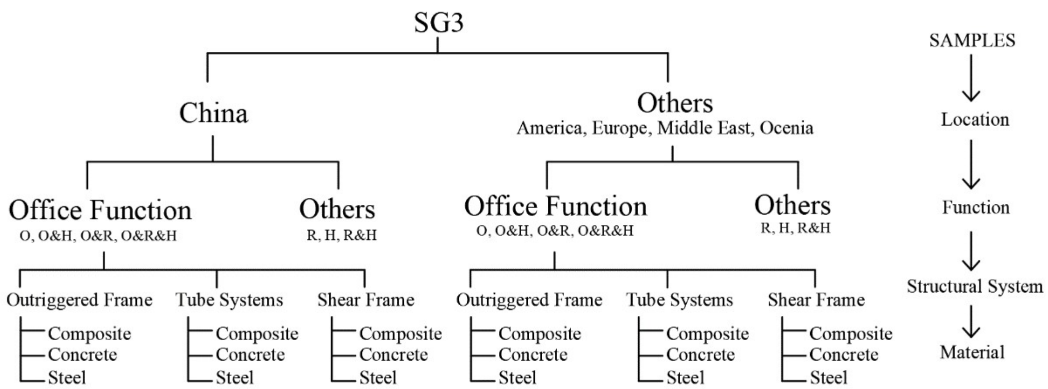


Figure 3.8. Separation of samples in SG3

After these sub-classifications, building samples are investigated in terms of several height ranges. However, each new criterion introduced further decreases the number of samples inevitably which may prevent to obtain consistent and unbiased information. Thus, some classes are re-unified, if reasonable, such as the use of tube system together instead of framed tube, trussed tube and bundled tube.

3.2.4. Charts Used in Analyses

Two charts which are frequently used in this study are explained in this section.

Scatter Chart

Scatter chart is a XY chart which shows the relation between two variables. It is possible to add a trendline between all points in scatter chart, and this trendline can be specified as exponential, linear, logarithmic, polynomial and power according to dataset. Scatter chart calculates R squared value and gives an equation for each trendline. The greater the R value is the stronger the correlation between two variables. According to Pearson Correlation, the type of correlation can be categorized by considering what happens to a variable when the other variable changes.

- Positive correlation: Both variables increase regularly
- Negative correlation: One of the variables decreases while the other increases regularly.
- No correlation: Both variables are independent of each other

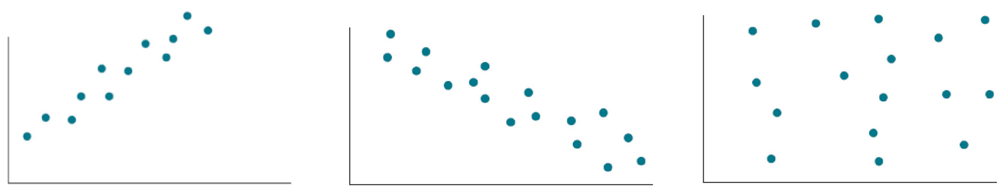


Figure 3.9. Pearson correlation: (Left) Strong positive relationship; (Middle) Strong negative relationship; (Right) No relationship (Source: Montgomery & Runger, 2018)

Correlations below R= | 0.5 | are generally considered weak and correlations above R= | 0.8 | are generally considered strong (Montgomery & Runger, 2018).

Box & Whisker Chart

Box & Whisker chart can be used in order to show the distribution of data when dataset has outliers or distribution is skewed. Boxes are the rectangles, and the whiskers are the lines extending vertically from the box. Any point outside those lines or whiskers is considered an outlier. Bottom point of the line shows the minimum value in the dataset (when the outliers are removed) whereas top point shows the maximum, and the box is drawn from 1st quartile to 3rd quartile. Horizontal line in the box states the 'Median' value of the distribution, and X letter means 'Mean' value (Figure 3.10.).

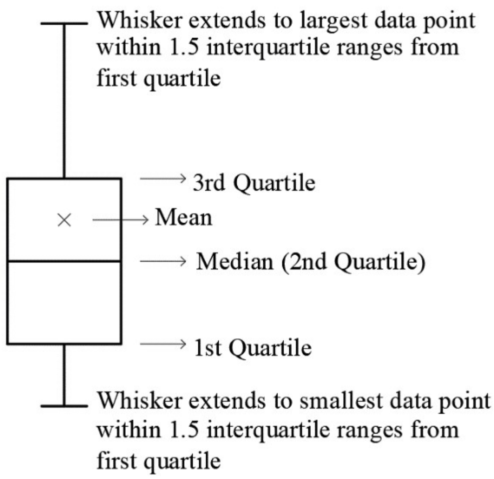


Figure 3.10. Definition of the points in a Box & Whisker chart (Source: Montgomery & Runger, 2018)

Outliers

An outlier is a data point which is so far from the main body of data. In order to find the outliers, steps given in below should be followed:

- Find the 1st and 3rd quartile (Q1 and Q3) of the dataset
- Find the IQR value:

IQR = Q3 - Q1

- Calculate the Maximum:

Q3 + 1.5 x IQR

- Calculate the Minimum:

Q1 - 1.5 x IQR

All data point larger than [Q3 + 1.5 x IQR] and smaller than [Q1 - 1.5 x IQR] can be accepted as an outlier (Montgomery & Runger, 2018).

First and Third Quartile

First quartile is the median of the lower half of the dataset and denoted by Q1. Similarly, third quartile is the median of the upper half of the dataset and denoted by Q3 (Figure 3.11.).

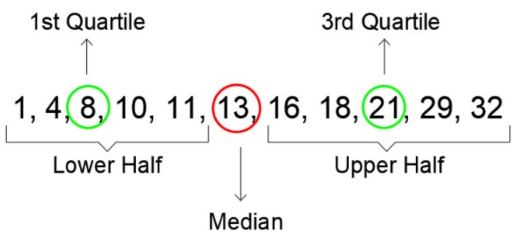


Figure 3.11. Quartiles of a dataset

Mean and Median Value

Mean is the average value of dataset which is calculated by dividing the sum of all data by the number of the data. Median is the point in the middle of the dataset when dataset is in an ascending order. When there are two points in the middle, median is the average of these two numbers. Mean gives the central tendency of a dataset, and it is more proper when there is a normally distributed dataset. Since median is not sensitive to outliers, it can be appropriate to use median when the distribution is skewed.

Montgomery and Runger (2018) state that there are several different choices for the point estimator of a parameter. For example, in order to estimate the mean of a population, it might consider the sample mean, the sample median, or perhaps the average of the smallest and largest observations in the sample as point estimators.

In this study, both the median and mean values of the data have been given through Box & Whisker charts.

CHAPTER 4

RESULTS AND DISCUSSION

This study aims to present a database on tall buildings regarding their structural components to provide information for preliminary estimations. For this purpose, data on 141 existing buildings have been collected and analyzed. Two critical points have been specified before analyses, and these are given as follows:

- Collecting enough number of samples
- Classifying samples properly based on their common features such as structural system, structural material, building function and location.

Since there was a trade-off between these two considerations, it was a challenging task to categorize the samples appropriately. As it is explained in 'Materials and Methods' Chapter, SG1, SG2 and SG3 have been created and analyzed.

In this chapter, results of the analyses are expressed and discussed.

4.1. Characteristics of Sample Groups

This section expresses descriptive information about samples in terms of location structural system, structural material, height of the building and building function, and represents observed trends in SG1, SG2 and SG3.

4.1.1. Location

Number of buildings from Asia is significantly higher than other regions due to overpopulation in Asian countries. Almost half of the samples in SG1 are in Asia which is followed by America having the quarter of the samples. Location distribution is generally similar in three sample groups (Figure 4.1.).

SAMPLE GROUP - 1		SAMPLE GROUP - 2		SAMPLE GROUP - 3	
Location	Number of Buildings	Location	Number of Buildings	Location	Number of Buildings
America	35	America	25	America	25
Asia	67	Asia	35	Asia	32
Middle East	21	Middle East	10	Middle East	8
Others	18	Others	12	Others	10
Total	141	Total	82	Total	75

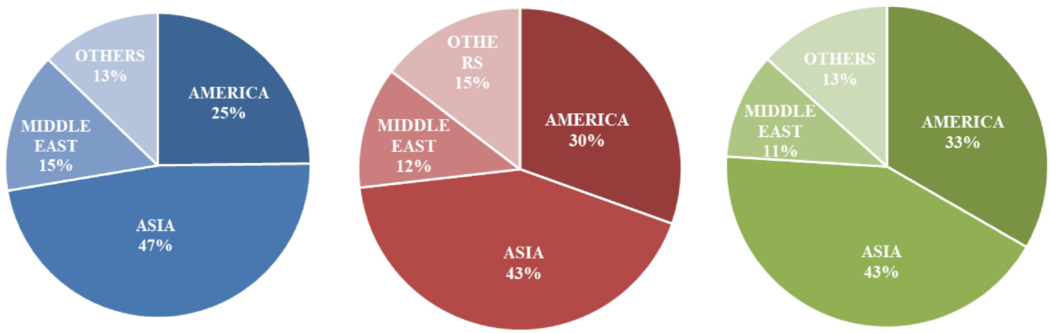


Figure 4.1. Location distribution of sample groups

4.1.2. Building Function

The number of office buildings was more than residential and mixed-use buildings before 2000's. Since it is noticed that residential buildings and hotels are in demand as well, the number of residential and mixed-use buildings is rapidly growing since then. Nevertheless, office is still the mostly preferred function among the samples used in this study, and mixed-use buildings follows it. SG2 and SG3 represent similar distributions to SG1 (Figure 4.2.).

SAMPLE GROUP - 1		SAMPLE GROUP - 2		SAMPLE GROUP - 3	
Function	Number of Buildings	Function	Number of Buildings	Function	Number of Buildings
Residential	25	Residential	8	Residential	7
Hotel	2	Hotel	0	Hotel	0
Mixed-use	47	Mixed-use	27	Mixed-use	23
Education	1	Education	1	Education	1
Office	66	Office	46	Office	44
Total	141	Total	82	Total	75

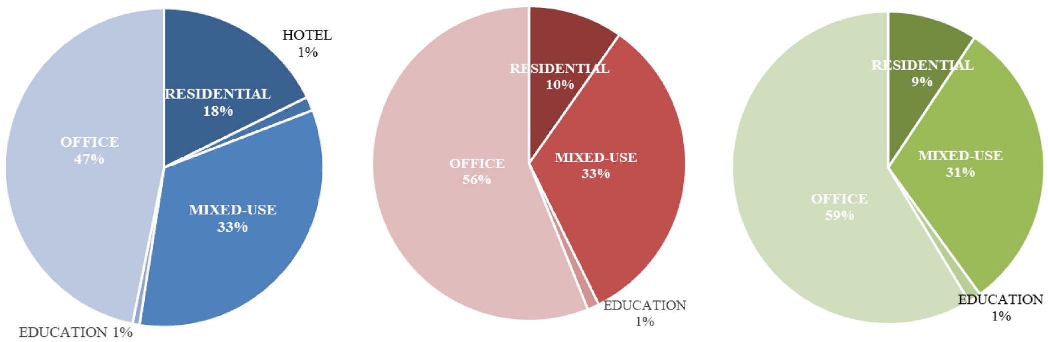


Figure 4.2. Function distribution of sample groups

4.1.3. Structural Material

Since tall buildings had been constructed mostly in America, steel was the most common material up to 1990s as mentioned in literature review. Thanks to improvements in material science and developments in construction technology, high-strength concrete has become more popular. Likewise, composite is widely used for tall buildings, since it combines the advantages of both steel and concrete. This trend can be observed also in the building samples, and according to results, composite is the most common structural material in sample groups.

SAMPLE GROUP - 1		SAMPLE GROUP - 2		SAMPLE GROUP - 3	
Structural Material	Number of Buildings	Structural Material	Number of Buildings	Structural Material	Number of Buildings
Concrete	57	Concrete	31	Concrete	27
Steel	16	Steel	13	Steel	13
Composite	68	Composite	38	Composite	35
Total	141	Total	82	Total	75

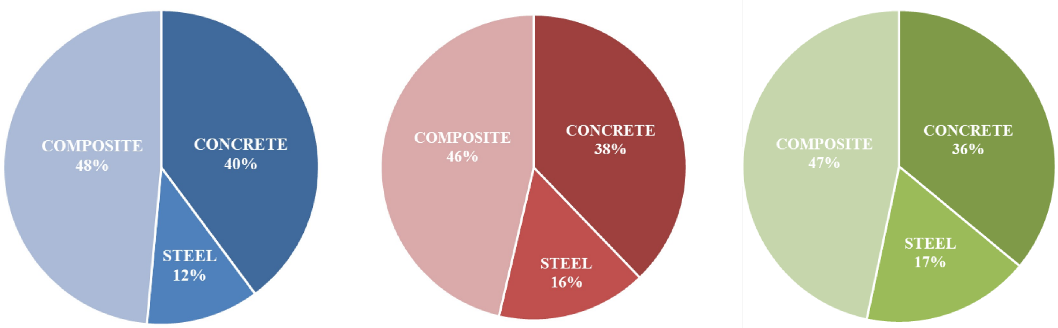


Figure 4.3. Material distribution of sample groups

Core and column materials of the tall buildings in SG2 and SG3 are investigated (Figure 4.4). Concrete is the most preferred material for core in both SG2 and SG3 sample groups. Although number of buildings with concrete and composite columns are similar, buildings with steel column are significantly less than other samples.

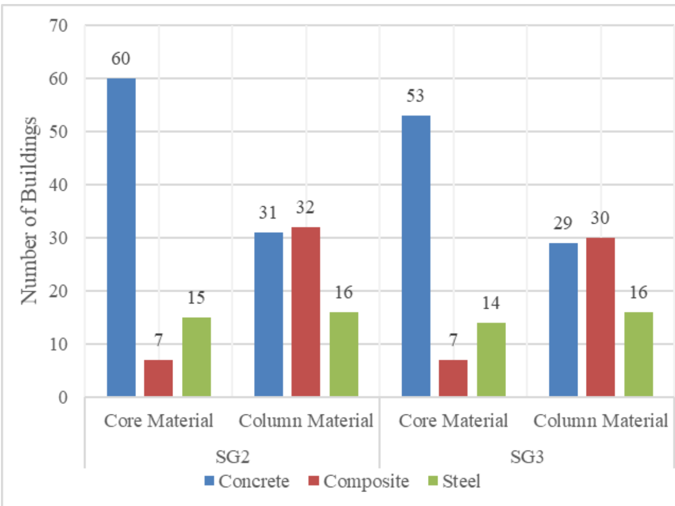


Figure 4.4. Core and column material distribution in SG2 and SG3

Steel components are generally lighter than concrete elements, and less mass often results in lower seismic force and less foundation cost. In addition, steel is also dimensionally more stable due to creep and shrinkage effects. According to Baker (2013) the behavior of steel structures tends to be more predictable. Although the advantage of steel, steel is not common among the samples. Possible explanations can be specified as follows:

- Steel requires additional fire resisting systems. The strength of the steel can be significantly compromised when heated to extreme temperatures. Therefore, steel requires to be covered by additional fire-resistant materials.
- Differential strain between inside and outside columns due to thermal changes can affect member and connection forces (Scarangello *et al.,* 2008). Therefore; structural elements may require additional thermal precautions.
- Availability of the material: Local labor and material source may affect the decision of the structural material.

4.1.4. Building Height and Aspect Ratio

There are 141 existing tall buildings between 105m and 1000m in SG1, and average building height of the SG1 is 346.6m, whereas median building height is 322.5 m. SG2 and SG3 has similar height distributions as it seen in Figure 4.5.

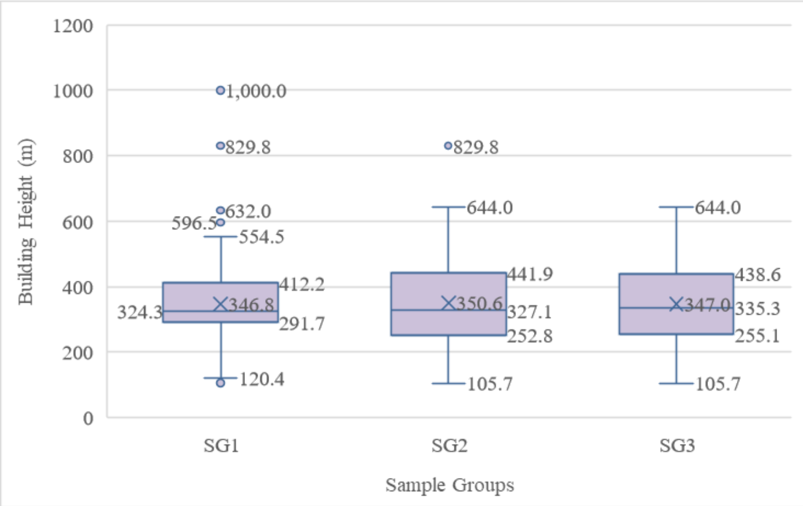


Figure 4.5. Height distribution of sample groups

Aspect ratio distribution of sample groups are investigated as well. Empire State and Chrysler Buildings are excluded while analyzing aspect ratio statistics of the buildings, since these buildings are rising above a significantly expanded base.

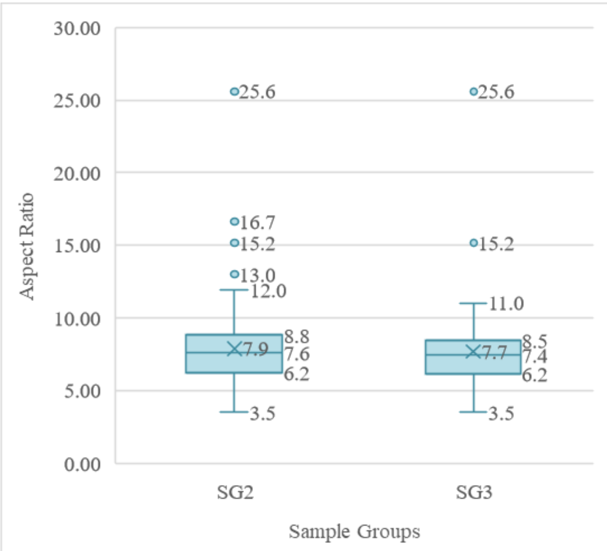


Figure 4.6. Aspect ratio distribution of sample groups

Aspect ratio distribution is given for SG2 and SG3, because AR data could have been collected for these samples, and these groups have similar AR values according to Figure 4.6. AR of the samples are mostly around 6, 8 and 10 (Figure 4.7.). Building height generally distributes between 150 m and 550 m, and samples are mostly around 300 m, 400 m, 200m and 500m respectively.

Figure 4.7. Height and AR distribution among samples

Changes in AR value over the years is investigated in order to observe the improvements in building technology and structural systems. Wuhan Greenland (475.6 m, Wuhan) and World One Tower (442 m, Mumbai) are “on hold” according to CTBUH database (retrieved in May 2019); therefore, they are accepted as if they are going to be completed after 2019. Pirelli Building (1958) is the oldest building among the evaluated samples, and AR value rises constantly since then. According to this result, it is possible to claim that, improvements in materials, new construction techniques and new developments in structural system design help to build more slender buildings by years.

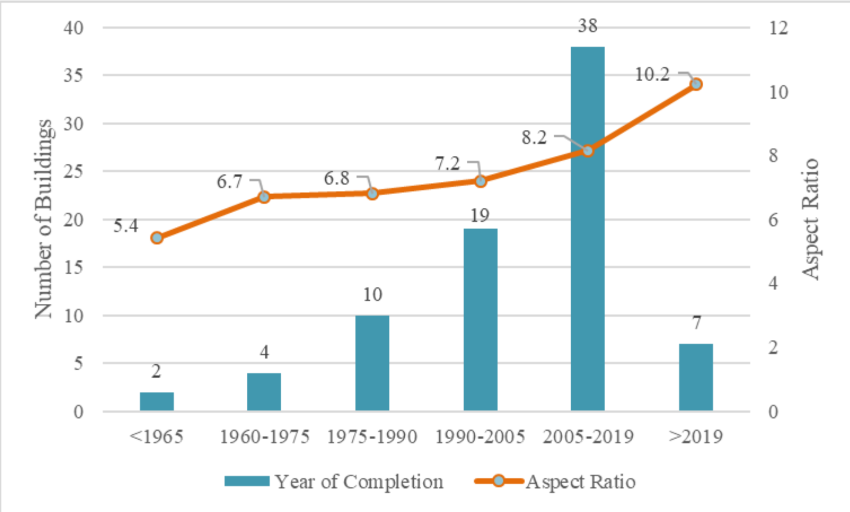


Figure 4.8. Aspect ratio distribution over the years

4.1.5. Structural System

SG2, but mostly SG3 analyzed in terms of structural system, since there is not enough number of samples for mega core (3 samples), buttressed core (3 samples), and mega column (1 sample) systems. Therefore, outcomes for these structural systems are required great attention in order to avoid biased results.

Tallest building in the world, Burj Khalifa (829.8 m), and the building which will be the tallest when it is completed, Jeddah Tower (+1000 m), are built with buttressed core structural system. Shear frame, mega core and mega column systems are generally preferred when the building height is less than 300 m. Both outriggered frame and tube systems have wide range of height; however, the average height of the outriggered frame buildings in SG3 is higher than the tube buildings (Figure 4.9.).

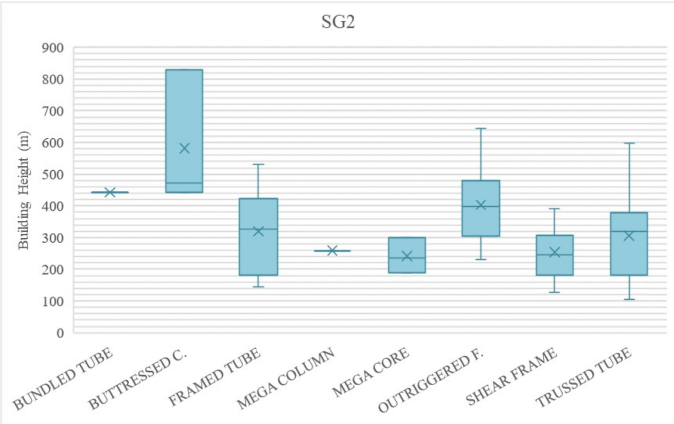


Figure 4.9. Height distribution of structural systems

Aspect ratio distribution with respect to structural system is analyzed as well, and the most slender building is built as outriggered frame system. Structural systems except mega core can be sorted by descending order of their median aspect ratio values as; buttressed core, outriggered frame, trussed tube, shear walled frame, framed tube, bundled tube and mega column (Figure 4.10.).

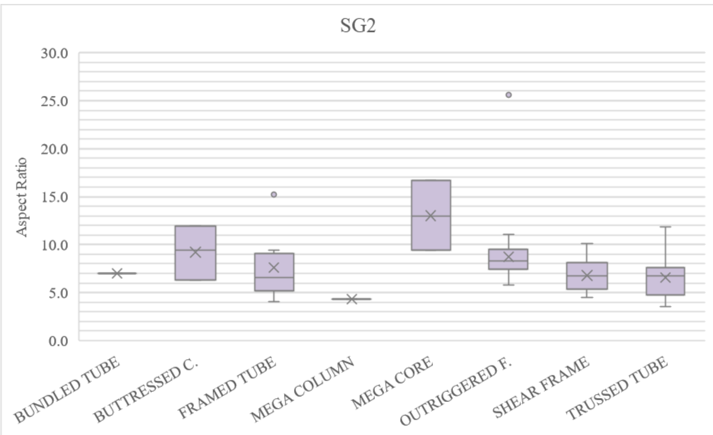


Figure 4.10. Aspect ratio distribution of structural systems

This sorting only reflects the slenderness ratio of the samples and this result should not be attributed to the structural efficiency of these systems. Mega core structure resists all horizontal loads by its core, and this core is generally in circular shape in order to provide equal resistance in all directions. Since, the structural depth of mega core systems is the diameter of the core, AR of these structures is significantly higher than other buildings. AR values should be considered with height distribution of the samples (Figure 4.9.) Although exterior structures give opportunity to build slender buildings, the average aspect ratio of tube samples is about 7. Since tube structures in sample groups are generally between 200m and 400m, the mean AR value is smaller than expected. However, as it can be observed from the Figure 4.10., aspect ratio value of the samples which are built with trussed tube systems can rise up to 15.

Core and column ratios are investigated considering structural systems for SG2 (Figure 4.11.). Core ratio is generally between 20%-27%, whereas column ratio is mostly between 1.5%-4% according to median value in the dataset of each structural system. According to literature review, exterior structures resist the lateral loads with their structural components mainly located at the perimeter of the building. Therefore; it is expected to observe smaller core area and larger column area among tube systems. Although frame tube systems generally have smaller core area compared to other structural systems, there is not a significant different among the samples in terms of core area. Service requirements of the buildings such as vertical transportation and shafts may be the explanation of this situation.

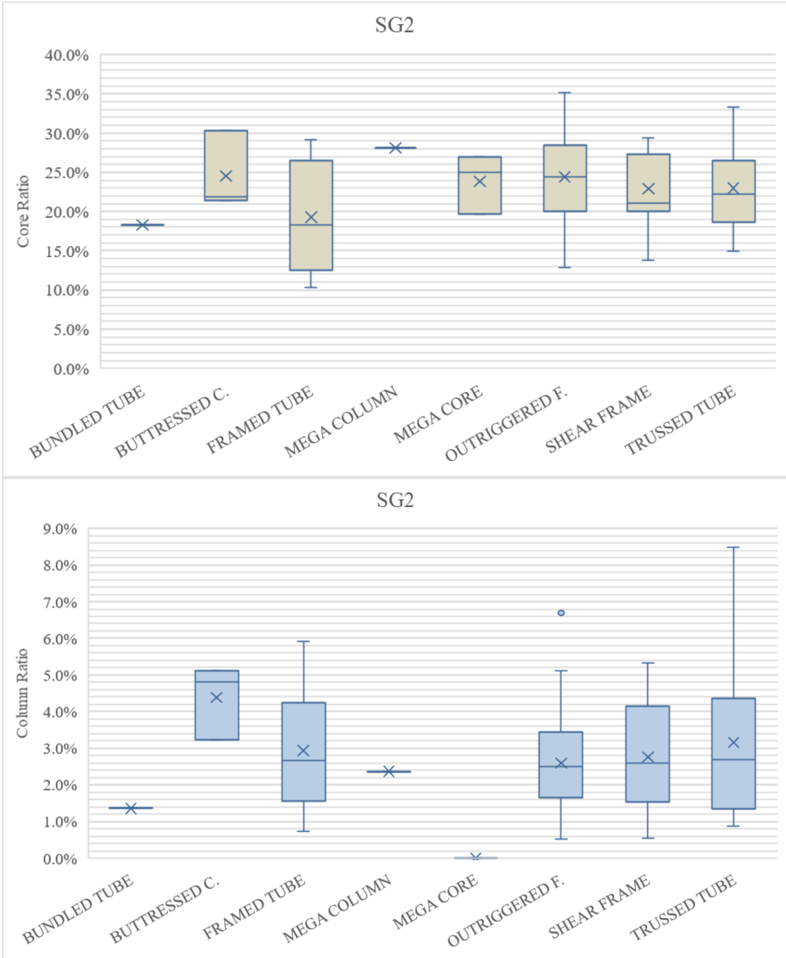


Figure 4.11. Relationship between core and column ratio and structural system

Relationship between core and column ratio is examined with respect to different structural systems based on predefined height ranges. According to Figure 4.12., overall core ratio generally increases as building height increases; however, correlations between height and core and column ratios are relatively weak as shown in graphs. It must be considered that, special features such as dampers and wind sluts may affect the results.

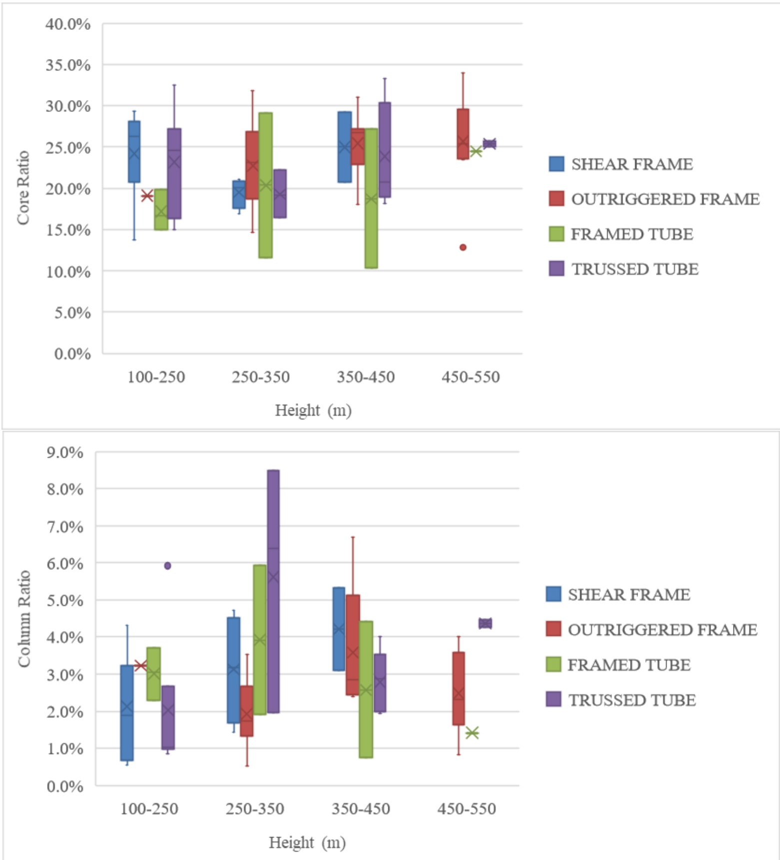


Figure 4.12. Core and column ratio distribution based on different height range in different structural systems in SG3

Impacts of location on different structural system are also investigated (Figure 4.13.). Core ratio in Asia is generally higher than other locations; however, a consistent trend is not observed for column ratio.

*Figure 4.13.*Core and column ratio based on different location in different structural systems in SG3

4.1.6. Special Features

Buildings are examined in terms of special features such as dampers and wind modifications. Nine of the samples (601 Lexington, Eureka Tower, Taipei 101, Shanghai Tower, Shanghai World Financial Center, Ping An, Petronas Twin Towers, 432 Park Avenue and 111 West 57th Street) have dampers which are mostly Tuned Mass Dampers (TMD). Two of the samples have wind turbine (Strata and Bahrain WTC,), and two of them have huge gap at the top of the building (Kingdom Centre and Shanghai WFC). Three of them have wind slots (432 Park Avenue, Wuhan Greenland Center and Ping An). Building shape of most of the buildings is tapered or concave, and setbacks and corner modifications are widely preferred in order to increase the structural performance of the buildings against wind forces.

According to literature, special features such as porosity in façade, wind slots and dampers improve the structural performance of the buildings. For instance, Smith (2008) reports the dampers at Shangri-La Place reduce building accelerations by 35% of the original value with a damping ratio of 7.5% of critical damping (Choi & Joseph, 2012). Therefore; these features can change the requirements of the structural system of the building, and it may lead to inconsistency in results.

Core walls not only resist the lateral loads but also carry some portion of the self-weight and suspended components. In other words, core withstands both the lateral and gravity loads at the same time. However, in some cases, core only carries gravity loads and do not support the lateral load bearing system, especially in tube structures. In this study, if the core of the building does not response to lateral loads, that core is accepted as non-structural. Although, 7 of the tube system samples have non-structural core, these buildings are considered in core analyses (Hearst Tower, World Twin Towers, 875 North Michigan Avenue, Willis Tower, Bank of China, Central Plaza, Chrysler Building).

4.2. Correlations Between Different Parameters

Samples in SG3 are investigated based on the relation between height and other parameters such as floor area, aspect ratio and core and column ratio in the first stage of the analyses. Floor plan area increases as building height increases (Figure 4.14.) Although the existence of outliers, there is a positive linear relation between building height and AR as well. According to floor plate area and aspect ratio distribution, it is possible to say, samples are built with generally same AR values in order not to have super slender buildings.

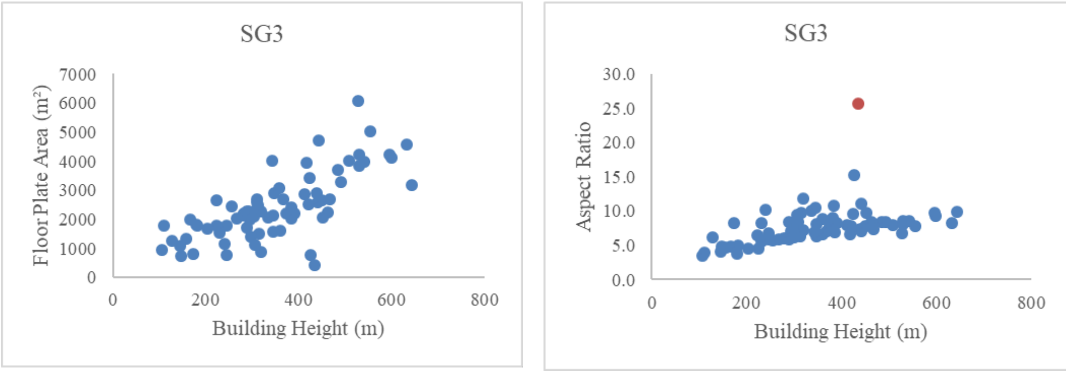


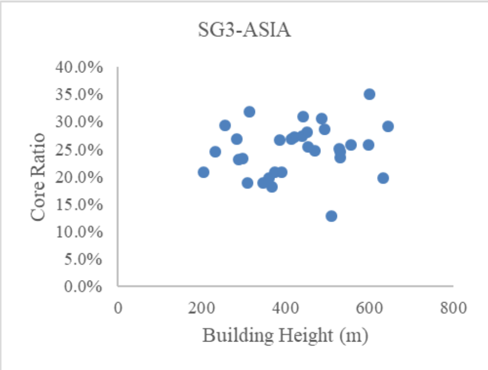
Figure 4.14. Correlations of building height

The red point which is an outlier in dataset is 111 West 57th Street Building. This building has a 436.8m base area whereas its height is 435.3 m; therefore, AR value is extremely high compared to other samples. This building is a residential building and has 3 level of outriggers which are two storey height.

Studies on height and other parameters do not reveal a strong relationship. Corresponding graphs are given in Appendix B. Since relationships between height and other parameters do not represent a strong trend, it is decided to investigate the samples by further categorizing based on their location, structural material, building function and structural system in the second stage of the analyses. The results are given in the following sections.

4.2.1. Location Based Correlations

SG3 is investigated in terms of different regions (Asia, Middle East, America, Others) in the second stage of the analyses, and according to results, the relationship between height and structural components are not strong (Figure 4.15.). According to literature review, each country has its own hazard level and design codes; therefore, structural requirements of the buildings can be different. When analyses are made in continental scale, results are not consistent. Asia has the largest number of buildings; therefore, only Asia is presented in this section, and other regions are given in Appendix B.



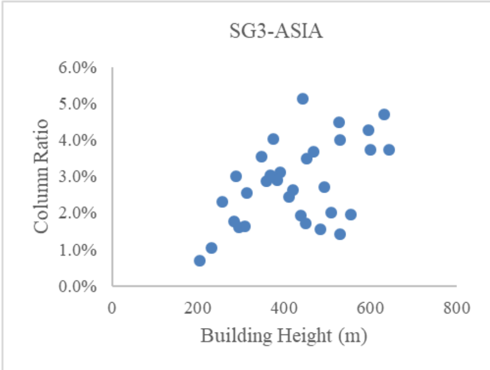


Figure 4.15. Correlation between height and core and column ratio in SG3 based on location

Figure 4.16. shows the distribution of the structural components with respect to the location of the buildings. Samples in Asia have larger core area, whereas samples in America have larger column area. Since China design codes require dual system, median core and column ratio is higher in Asia. According to graph, when core ratio is higher, column ratio gets lower except Asia. For instance, the median core ratio in Middle east is 23.2% whereas median column ratio is 2.22%. Similarly, median core ratio in Others is 20.6% whereas median column ratio is 2.63%.

Figure 4.16. Intercorrelation between core and column ratio and location in SG3

Since site conditions are not same for different locations, countries have different codes for structural design; thus, ground motions, seismic hazard characteristics and site classification are different as well. As it mentioned in "3.2.3. Evolution of Sample Groups," China design code requires some additional constraints compared to other countries. Therefore, it is decided to evaluate the samples by separating as 'China' and 'Others' in the final stage of analyses. Other countries in Asia Region except China, America, Middle East, Europe and Oceania are accepted as 'Others', and evaluated together. The result of these analyses is are given in "4.3. Recent Sample Groups After Evaluation"

4.2.2. Structural Material Based Correlations

Correlation between building height and core and column ratio in SG3 is examined considering structural materials (Figure 4.17.). A strong relationship cannot be observed between these parameters. Since the number of composite buildings are larger among samples, the results of composite buildings are presented in this section, and charts of the other structural materials are given in Appendix B.

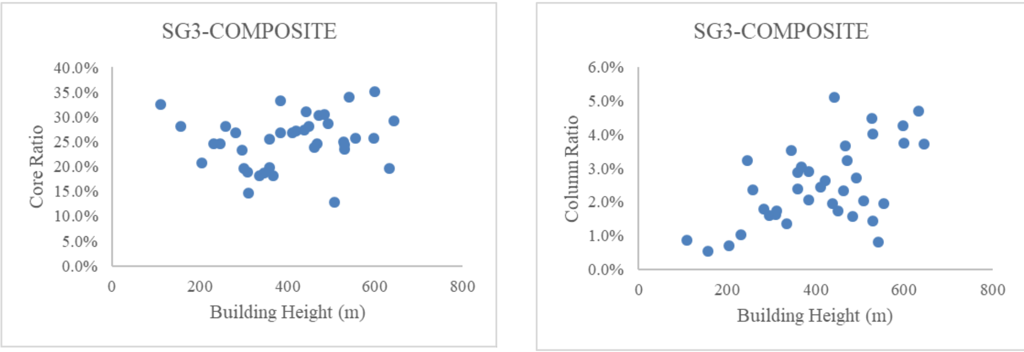


Figure 4.17. Correlation between height and core and column ratio in SG3 based on structural material

Distribution of core and column ratio in SG3 is given based on structural material (Figure 4.18.). According to results, concrete buildings have lower core ratio compared to other structural materials. Likewise, column area of steel samples is less than others.

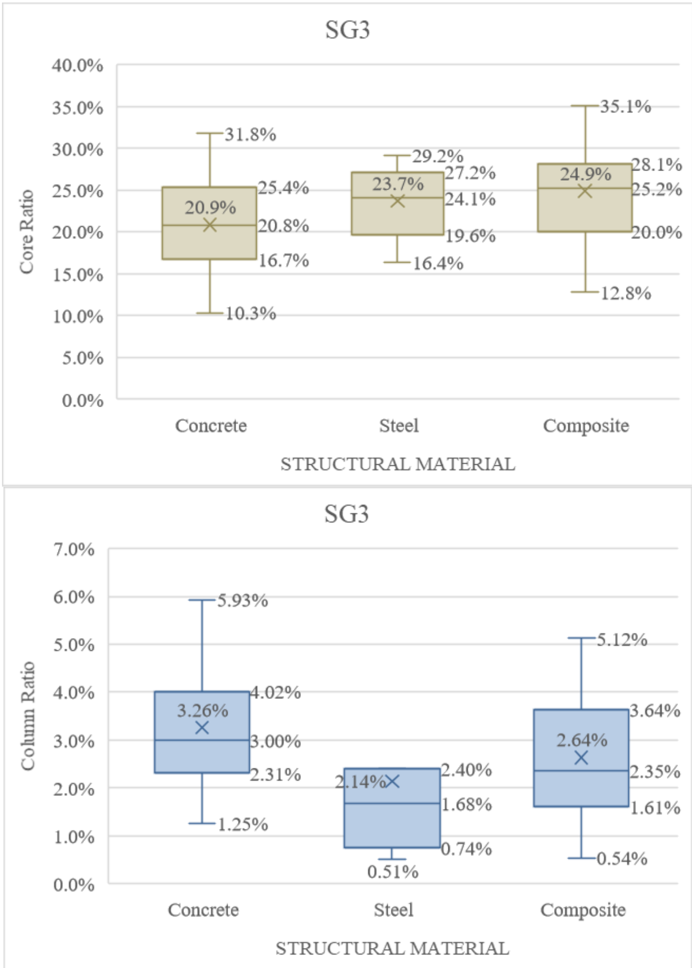


Figure 4.18. Relationship between core and column ratio and structural material in SG3

There can be two possible explanations why concrete buildings have lower core area:

- First, as it is known, steel is a lightweight material compared to concrete or composite materials. Due to its lightness and ductility; steel has great advantage against seismic loads compared to concrete. On the other hand, wind is the most critical lateral load for the tall buildings because of the building height. Therefore, steel core ratio may have been increased in order to keep the top displacement within acceptable limits for occupants.
- Secondly, height distribution based on structural materials is shown in Figure 4.19., and concrete buildings in the sample group are shorter than steel and composite buildings. Concrete samples might require less core area because of the building height.

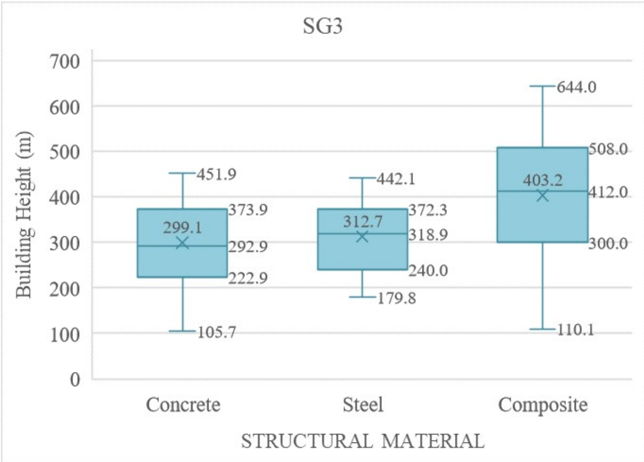


Figure 4.19. Height distribution according to structural material in SG3.

4.2.3. Building Function Based Correlations

Impacts of the building function on structural components are investigated, and core and column ratios of buildings in SG3 are analyzed. The results did not reveal any correlation between these parameters (Figure 4.20.). Core and column ratio distribution of office buildings are given in this section due to number of samples, and charts of other building functions are given in Appendix B.

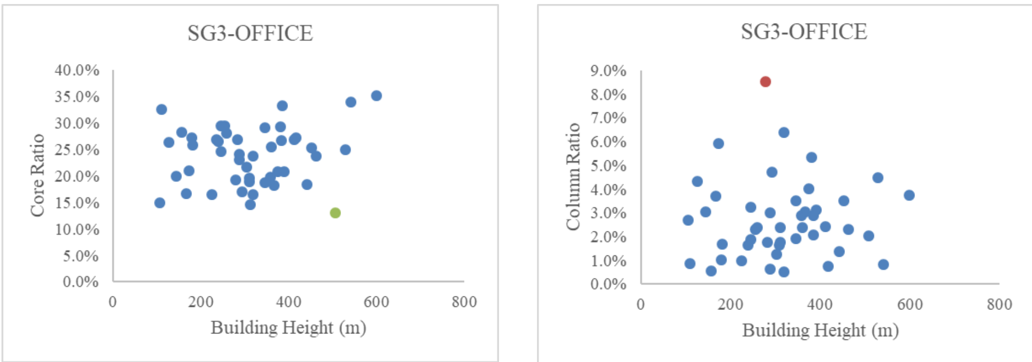


Figure 4.20. Correlation between height and core and column ratio in office buildings in SG3

The red point in Figure 4.20. which is an outlier in dataset is 601 Lexington Building. This building rises on 4 mega columns in the ground level as explained in 2.1.1.9. Location section, and its height is 278.9m; therefore, its core ratio is extremely high when considered its height.

The green point represents Taipei 101. In this building, eight 8-storey modules standing atop a tapering base, but its core is generally in the same size in each floor; therefore, its core ratio is low when considered its height. However, the structural system of this building is designed to resist huge earthquake and typhoons loads. It has a dual system which is a combination of multiple outriggers and perimeter moment framing (Poon *et al.,* 2004).

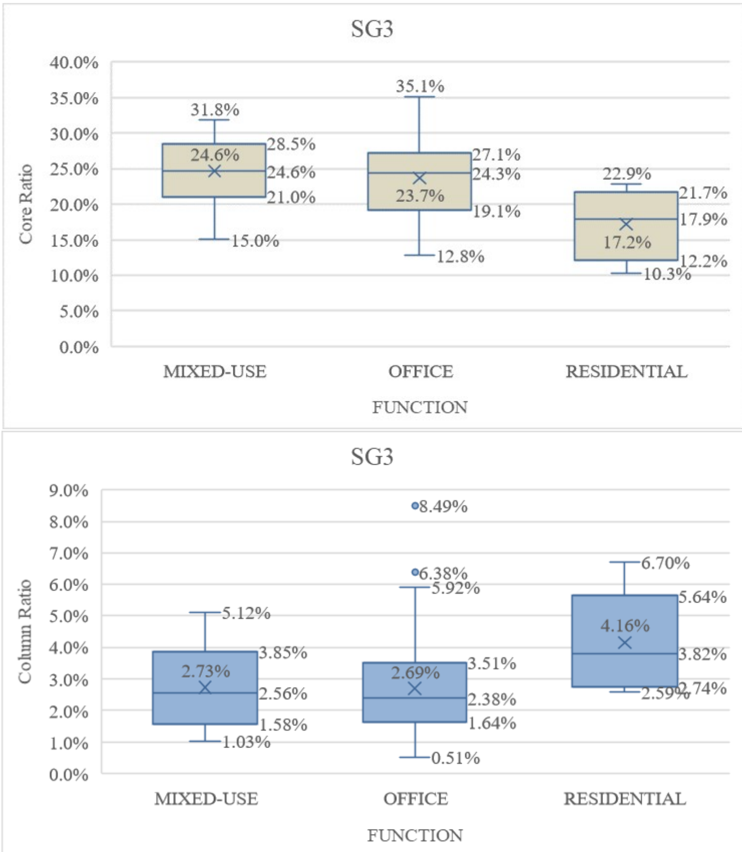


Figure 4.21. Relationship between core and column ratio and building function in SG3

Core and column ratio based on building functions are given in Figure 4.21. According to results, residential buildings are significantly different in terms of core and column ratio. Smaller core and larger column area in residential buildings in SG3 can be explained by relatively less demands on circulation space (which directly related with the core area) and column free areas buildings compared to others., Therefore, this function is distinguished as mentioned in “3.2.3. Evolution of Sample Groups” for the final stage of the analyses. The result of these analyses is given in “4.3. Recent Sample Groups After Evaluation.”

4.2.4. Structural System Based Correlations

SG3 is analyzed in terms of their structural systems, and correlation between core and column ratio and building height is presented (Figure 4.22.). Since the relationships between these parameters are weak, only outriggered frame structures are shown in this section, and other charts are given in Appendix B. The red point represents 111 West 57th Street Building. As explained in 4.2. Correlation Between Different Parameters section, this building is extremely slender compared to other samples (AR: 25.6); therefore, its column area is larger in order to provide structural efficiency and decrease the top displacement.

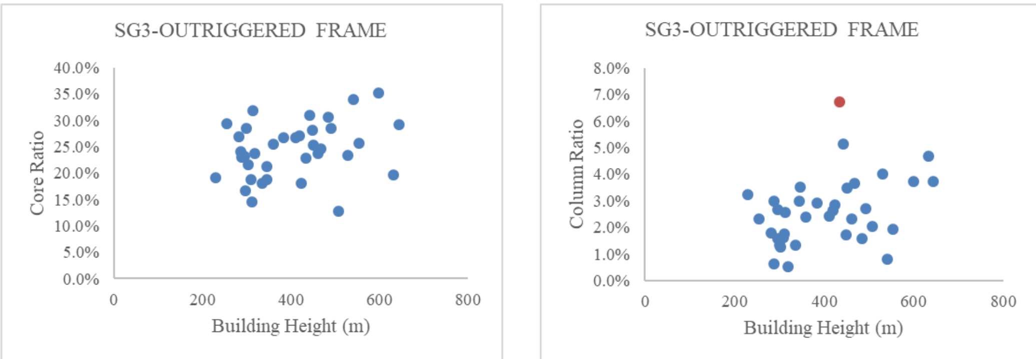


Figure 4.22. Correlation between height and core and column ratio in SG3 based on structural system

Results of the second stage of the analyses show that samples need to be further categorized. Nevertheless, separating samples so many times reduces the members of the sample groups; therefore, some structural systems are combined based on the similarity in their structural behavior and evaluated together.

Non-residential tube samples between 105m – 600m are compared as it shown in Figure 4.23., and core and column ratio of these samples present similar values. Therefore, it is decided to evaluate framed and trussed tube structures together.

Similarly shear walled frame and shear trussed frame systems are considered together as mentioned in "3.2.3. Evolution of Sample Groups."

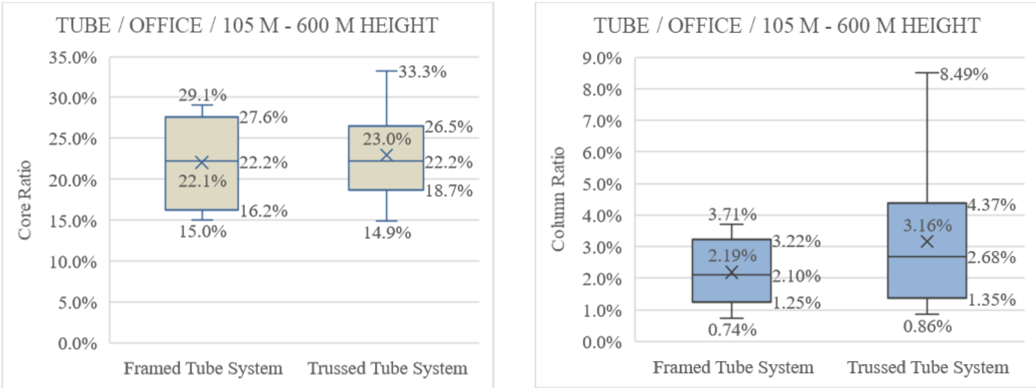


Figure 4.23. Correlation between height and core and column ratio in SG3 based on structural system

4.3. Recent Sample Groups after Evaluation

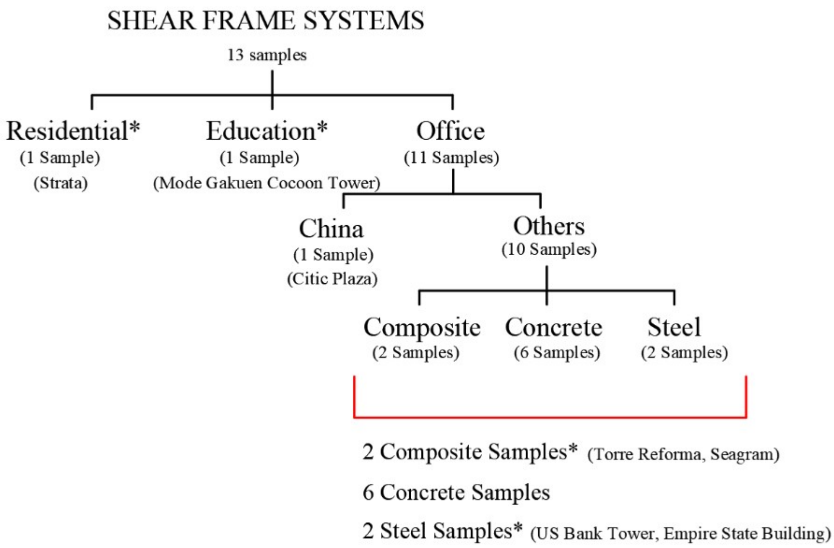
The impact of structural system, building function, structural material and location on structural design is investigated separately in the second stage of the analyses in this study. Results of the first and second stage of the analyses have revealed the fact that dividing the SG2 further may clarify the trends, if any, between the parameters under investigation. Therefore, buildings are scrutinized again with a different classification as explained in "3.2.3. Evolution of Sample Groups" section. Differently from previous analyses, following modifications are made:

- Tube systems and shear frame systems are considered together as it explains in '4.2.4. Structural System Based Correlations.'
- Residential buildings are analyzed separately as explained in '4.2.3. Building Function Based Correlations.'
- Since China design code requires relatively strict constraints on structural systems, samples are divided as 'China' and 'others' according to their regions as explained in '4.2.1. Location Based Correlations.'

Results of the analyses of the samples are displayed with respect to their structural system in following sections.

4.3.1. Shear Frame Systems

Shear frame structures have less samples than other structural systems, and most of these structures are made of concrete. Since samples are supposed to reclassify as explained before, only 6 concrete samples are investigated for shear frame systems (Figure 4.24.). Subgroups which have not enough number of samples are excluded from the analyses and marked with an asterisk.



(*Samples are not considered during analyses.)

Figure 4.24. Shear frame system sample distribution

According to results, core ratio is generally between 17%-29% while column ratio is between 1.4% - 4.7% in overall. Core and column ratio distribution among concrete shear frame samples are represented based on their heights in Figure 4.25.

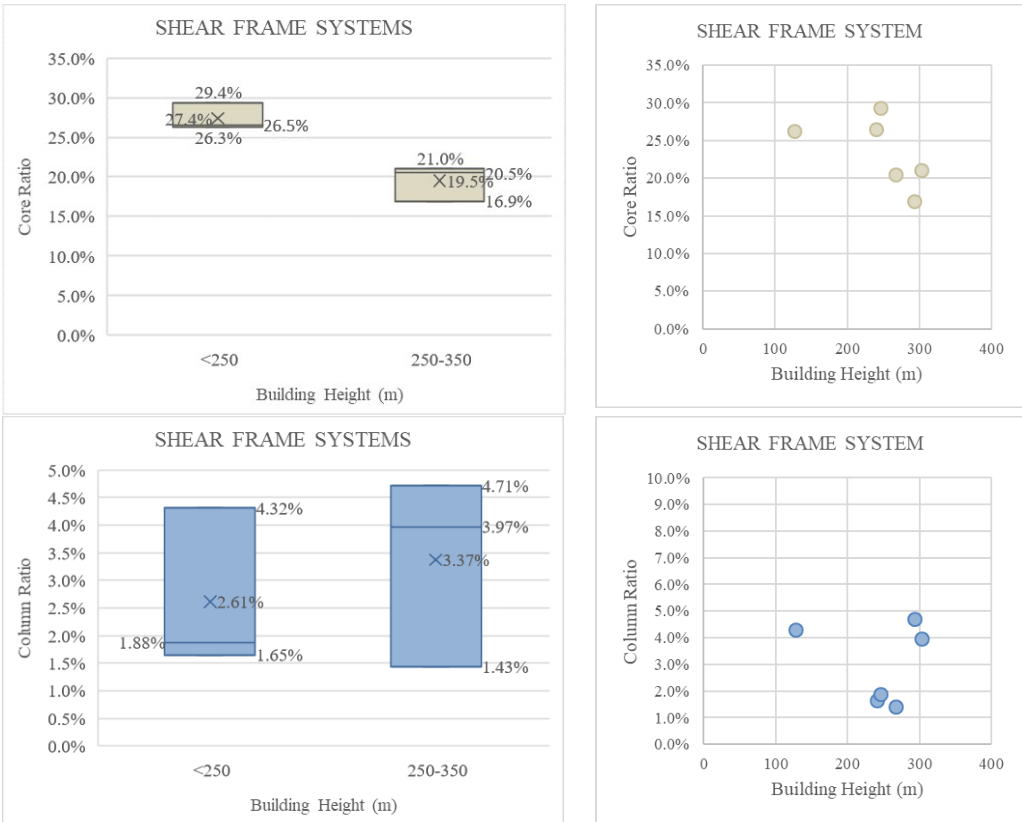


Figure 4.25. Correlation between height and core and column ratio in concrete shear frame systems

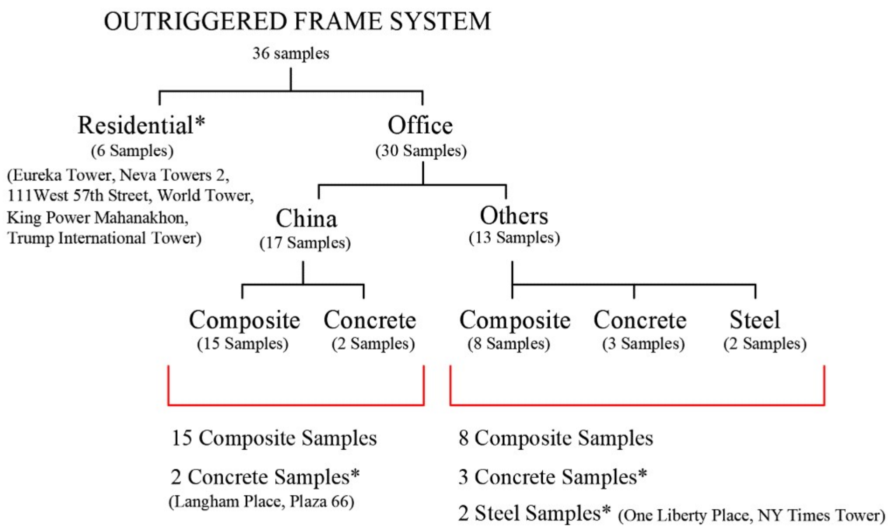
As it can be seen in scatter chart, the relationship between height and core and column ratio is not strong. Unexpectedly, buildings higher than 250m has lower core area compared to buildings shorter than 250m. Therefore, the buildings are evaluated individually to comment on these results.

- Pirelli Building (127.1m): Although this building is under 150m, its core ratio is calculated as 26%. This building has been completed in 1958, and such a high core ratio for this height is probably caused by old technology or not giving enough attention to leasable area due to time requirements.
- Bahrain WTC (240m): These buildings are jointed to each other with 3 level of wind turbines, and this can be the reason for higher core ratio (26.5%). In addition, these buildings have central split core and the core in the middle of the floor plane are not continuous along the building because of the tapered shape of the building.

- Evolution Tower (246m): These building has twisted shape and the overall twist reaches 156 degrees clockwise (Nikandrov, 2016). Since twisted buildings withstand the torsional forces primarily with their core, this is the possible reason for such a high core ratio (29.4 %) in order to fulfil structural requirements.
- 311 South Wacker Drive (292.9m): Relatively lower core ratio (16.9%) of this building is related with its column ratio (4.71%) which is higher than average.

4.3.2. Outriggered Frame Systems

Outriggered Frame Systems are widely used around the world, and the number such samples are higher than other structural systems in this study. On the other hand, the number of residential buildings and buildings made of only steel or concrete are relatively less. Thus, these are excluded from the analyses (Figure 4.26., excluded subclasses are marked with an asterix). Only 15 composite buildings from China and 8 composite buildings from all other countries are analyzed in this section.



(*Samples are not considered during analyses.)

Figure 4.26. Outriggered frame system sample distribution

According to results, median height for composite buildings is 436.5m for China and 485m for Others (Figure 4.27.). Scatter charts show the height distribution of samples, and the relation between height and core ratio in Others is stronger than buildings in China relatively. Core ratio in China is generally between 19% and 35% when the building height is between 280m and 630m. Buildings higher than 500m and shorter than 300m have inconsistent core area.

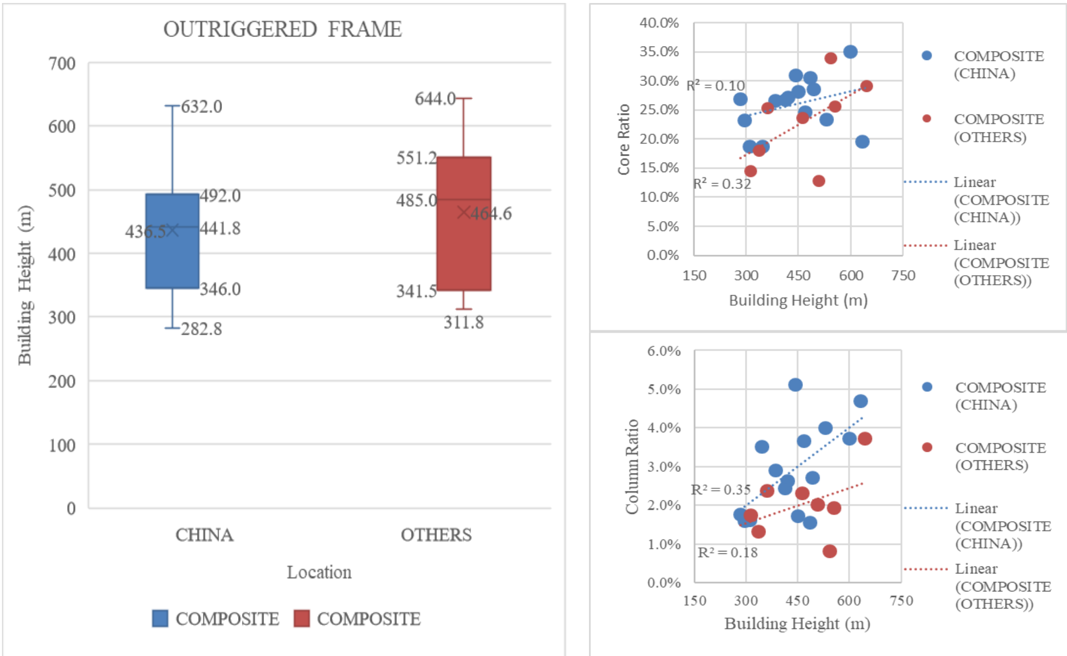


Figure 4.27. Height distribution among composite outriggered frame systems based on location

Buildings in China have higher core and column ratio, although the buildings in Others are taller than buildings in China according to Figure 4.28., and this proves that China design code requires more resistant buildings. In China, median core ratio is 26.8%, whereas median column ratio is 2.72%, and the core area of buildings is mostly between 23% - 29% of the floor area. Column ratio range is wider in China, and mostly between 1.50% - 5.1%. Core ratio in Others is between 13% - 28%, and median core ratio is 24.6%. Column ratio is between 1% - 3.7%, whereas median column ratio is almost 2.0%.

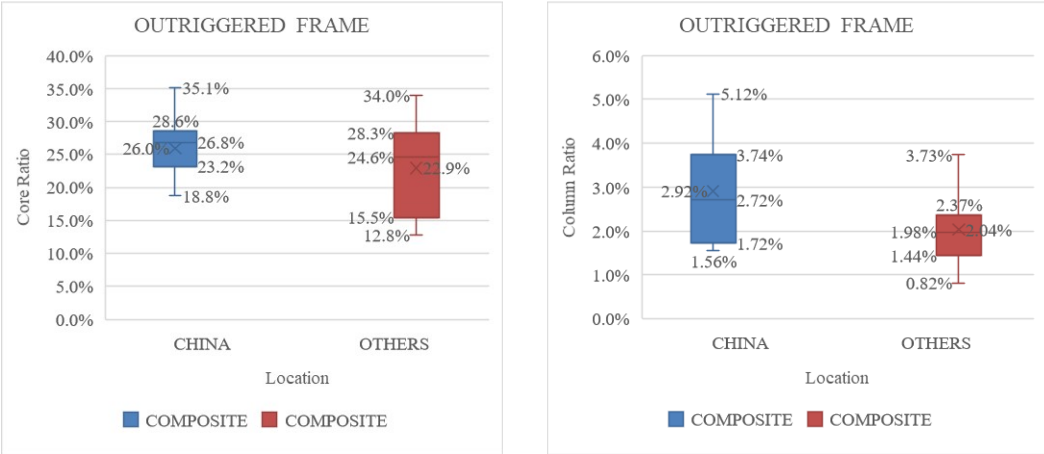


Figure 4.28. Interrelation between core and column ratio and location in composite outriggered frame systems

Composite outriggered frame system samples are investigated in terms of their height as well (Figure 4.29.). Core and column ratio of the samples in both locations generally increase as building height increases except samples between 450m and 550m in height. Buildings higher than 450m may require additional advanced solutions; therefore, core and column ratio can be changed with extra precautions such as dampers or wind modifications. For instance, three of the buildings higher than 450m have dampers (Ping An, Petronas Twin Towers and Taipei 101), three of them have setbacks (Petronas Twin Towers, Taipei 101 and Guangzhou CTF) and most of the samples are in tapered shape.

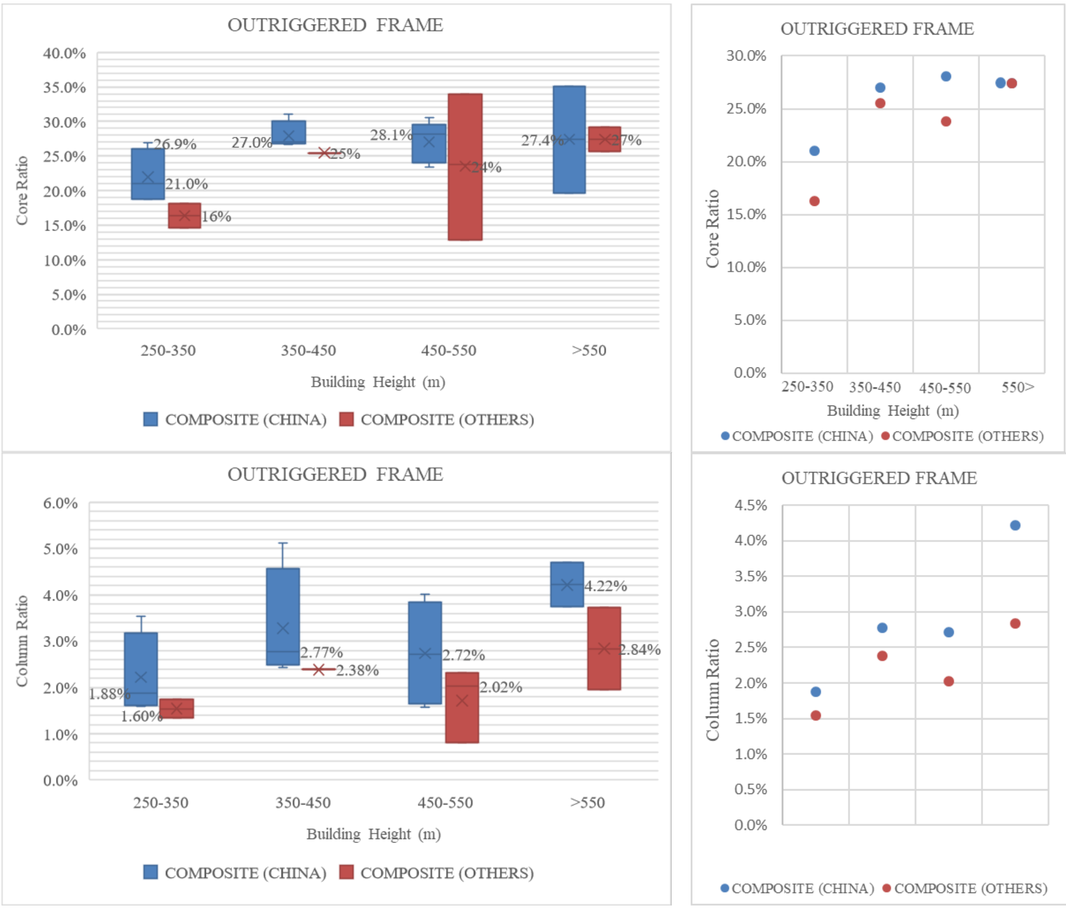


Figure 4.29. Interrelation between core and column ratio and location in composite outriggered frame systems based on building height

According to Box & Whisker chart on the left, median core and column ratio is specified, and scatter chart (on the right) is prepared with median values for given height ranges in Figure 4.29. Scatter chart helps to display the difference between structural requirements of China and Others.

Characteristics of Outriggers

Data on number of outriggers and outrigger height is collected in the scope of the study. As mentioned before, outriggered frame system is the most common structural system among the samples; however, outrigger data can be gathered for 28 out of 36 samples. Since Eureka Tower has a special outrigger application which is 54 storey high, this building is excluded while evaluating the outriggers. List of the 28 buildings with outriggers are given in Appendix C.

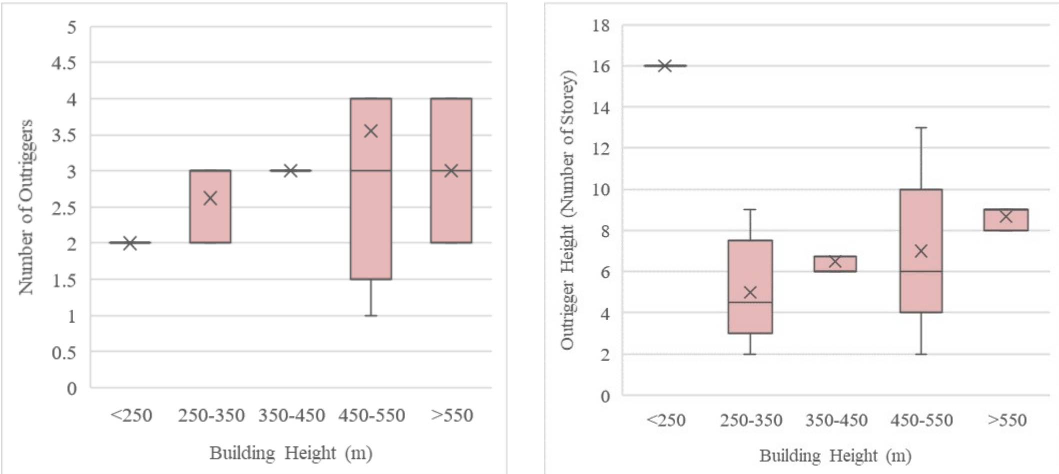
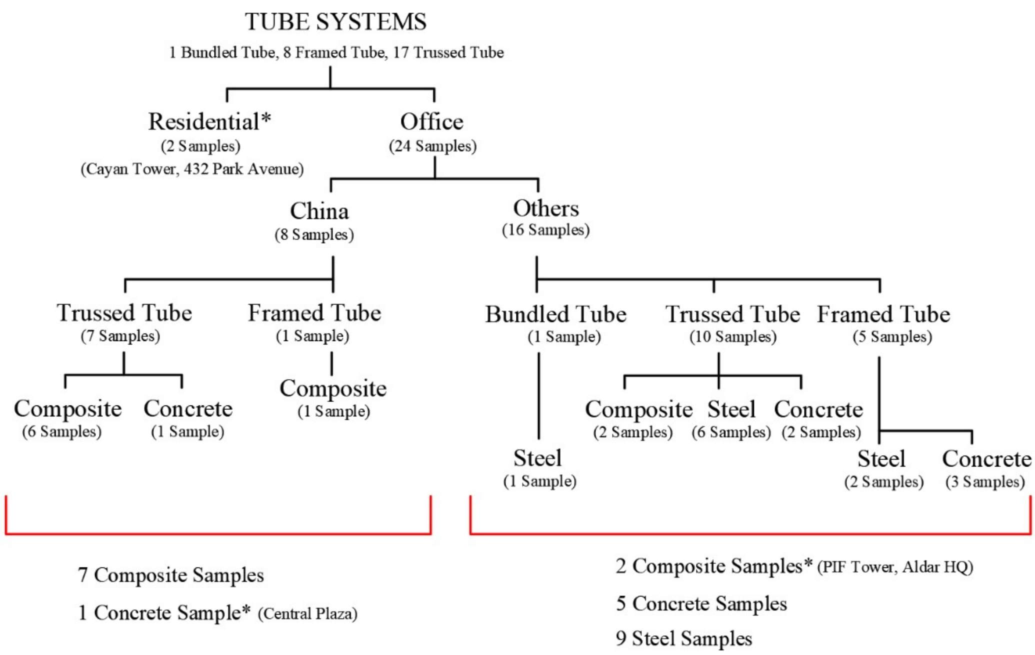


Figure 4.30. Outrigger distribution of the samples

Median and average outrigger height increase as building height increases except the one sample under 250m (World Tower, 230m) which can be assumed as an exception. Average number of outriggers increases as building height increases, except buildings more than 550m in height, and the median number of outrigger level is found as 3 (Figure 4.30.). A possible reason for this circumstance can be explained with the efficiency of the outriggers, since the efficiency of each new outrigger is less compared the former one. According to gathered data, belt truss is put in order to support the outriggers in half of the cases.

4.3.3. Tube Systems

Tube systems are considered together as mentioned before. Residential buildings and some samples are not considered during analyses due to number of samples (Figure 4.31.). Only 7 composite buildings from China, 5 concrete buildings and 9 steel buildings from Others are analyzed. Since all sample groups are made of different structural materials, it is not possible to compare the structural materials with respect to locations for tube systems.



(*Samples are not considered during analyses.)

Figure 4.31. Tube system sample distribution

Scatter charts for core and column ratio of tube systems are created. Besides, median values of these quantities are presented by Box & Whisker charts (Figure 4.32). The results showed that, steel samples shorter than 250m have bigger core ratio than steel samples between 250-350m. On the contrary, column ratio of steel buildings between 250-350m is four times bigger than steel buildings shorter than 250m. In tube buildings the structural system is on perimeter. However, by making use of service core, which is already there as a structural core, one can reduce the size of the columns at perimeter. Core and column ratio for composite tube buildings generally increase as building height increases except one sample (Kingtown International Center) shorter than 250m. Box & Whisker chart for height distribution of different materials in tube systems is given in Appendix D.

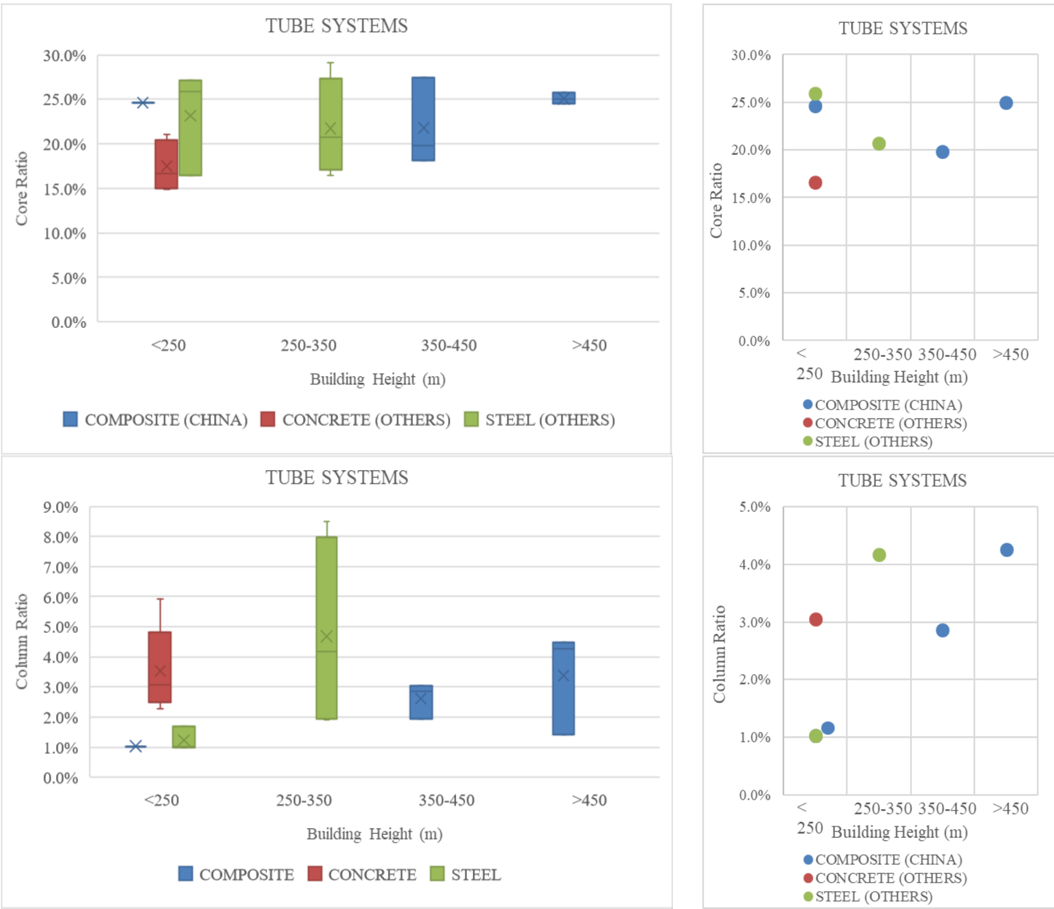


Figure 4.32. Material distribution in tube systems based on height

Figure 4.33 depicts the core and column ratio values and height distribution of the samples based on the structural material. According to the results, height range of tube samples is between 125m and 200m for concrete buildings, between 190m and 410m for steel buildings and between 250m and 600m for composite buildings.

Core ratio for composite buildings is between 18% - 27%, and median height for these samples is 438.6m. Column ratio is mostly between 1.0% - 4.5% for composite buildings, and median column ratio is specified as 2.87%.

For steel samples, median height is 318.9m, core area is mostly between 15% - 21% of floor area, and median core ratio is 22.2%. Column ratio is generally between 1.00% - 8.50%, and median column ratio is 1.68%.

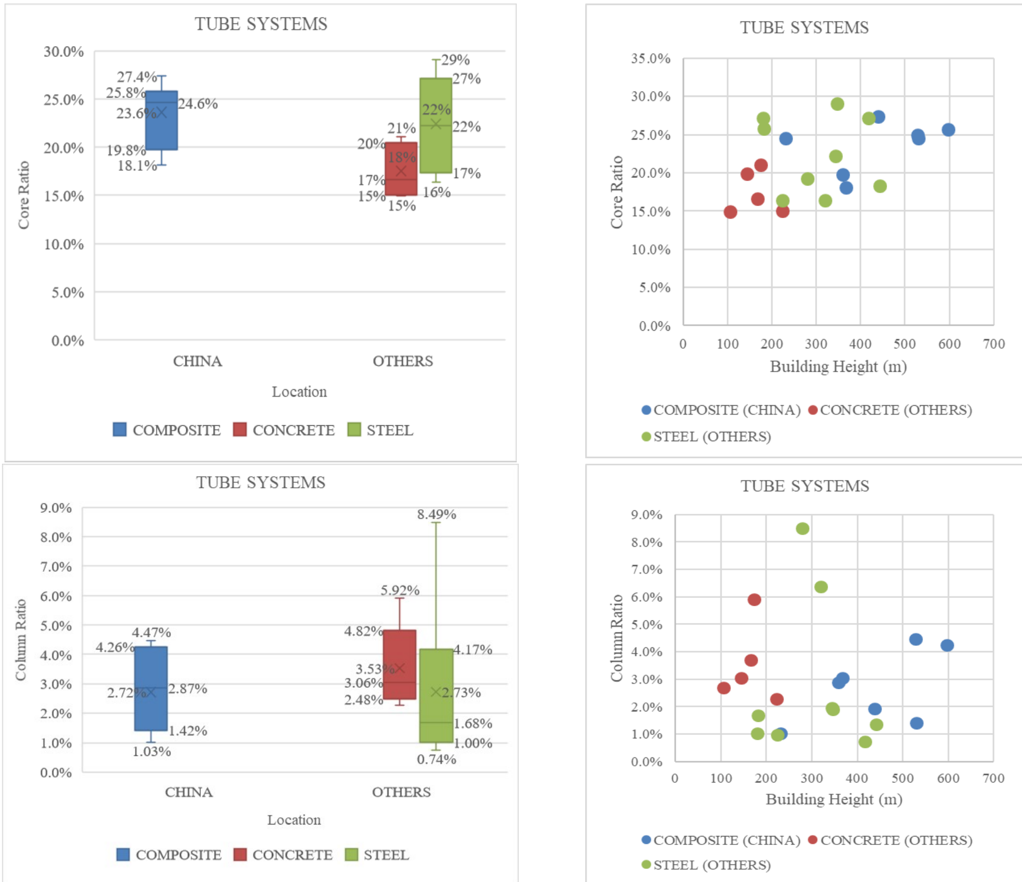


Figure 4.33. Interrelation between core column ratio and material in tube systems

As mentioned before, concrete is preferred for shorter buildings, and medium height of concrete buildings is found as 166.7m. Although core ratio is less than other samples, column ratio is the highest for concrete buildings among tube samples. Composite and steel materials provide better structural performance compared to concrete; therefore, column ratio of concrete samples is higher than other materials. Since concrete buildings are shorter than 230m, service core requirement of these samples is less.

4.4. Leasable Span and NFA

SG3 contains 75 samples, and some samples are excluded from the analyses as mentioned in 4.3.1., 4.3.2. and 4.3.3. sections. Therefore, 50 out of 75 samples are analyzed in terms of leasable span and NFA ratio (net floor area divided by floor area) 6 of which is shear frame, 23 of which is outriggered frame and 21 of which is tube systems. According to results, structural system has not a significant impact on leasable area. Median value for leasable span changes between 13m and 15m with respect to different structural systems. Median NFA ratio is varied between 71% and 75% among the samples.

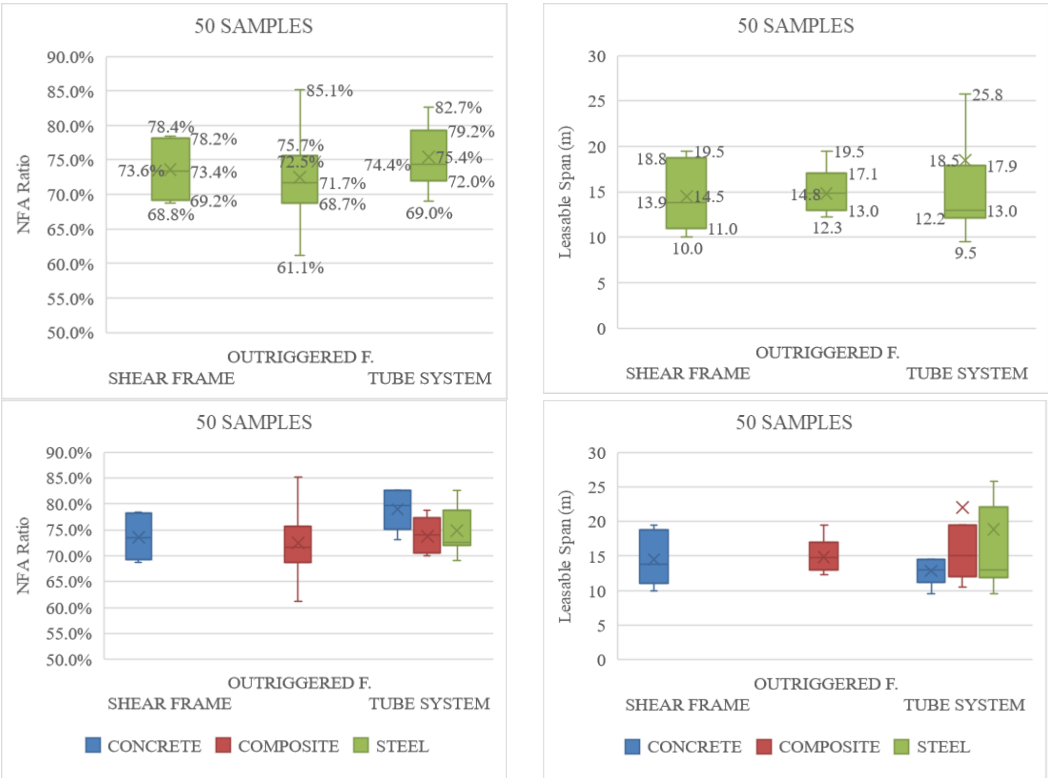


Figure 4.34. Leasable area distribution for different structural systems

The impacts of building height on NFA is analyzed as well. According to results, space efficiency generally decreases as building height increases. However, NFA ratio is generally similar among tube systems. Moreover, tube systems can be described as the most efficient system in terms of leasable area (Figure 4.35.)

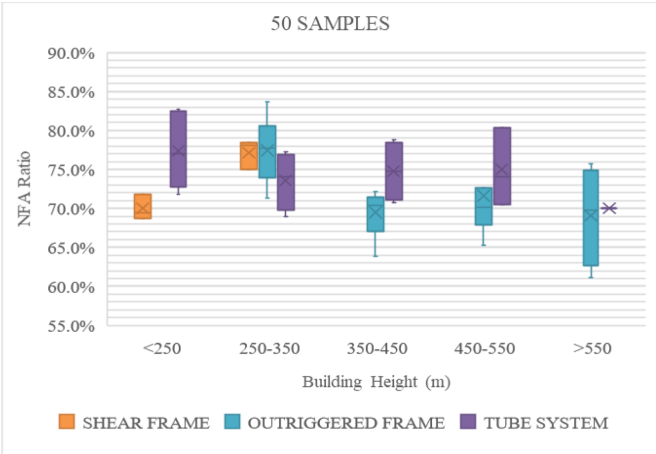


Figure 4.35. NFA ratio of different structural systems considering height

The impact of the building function on leasable span is investigated in the scope of this study (Figure 4.36.). All samples in SG3 has been used for the function comparison except one education building (Mode Gakuen Cocoon Tower). 9 out of 75 samples in SG3 is constructed for residential and residential and hotel purpose. Since floor plan layout of hotels and residentials are similar, all 9 samples are named as residential as mentioned before. According to analyses, residential buildings have shorter spans, although they are more efficient in terms of leasable area.

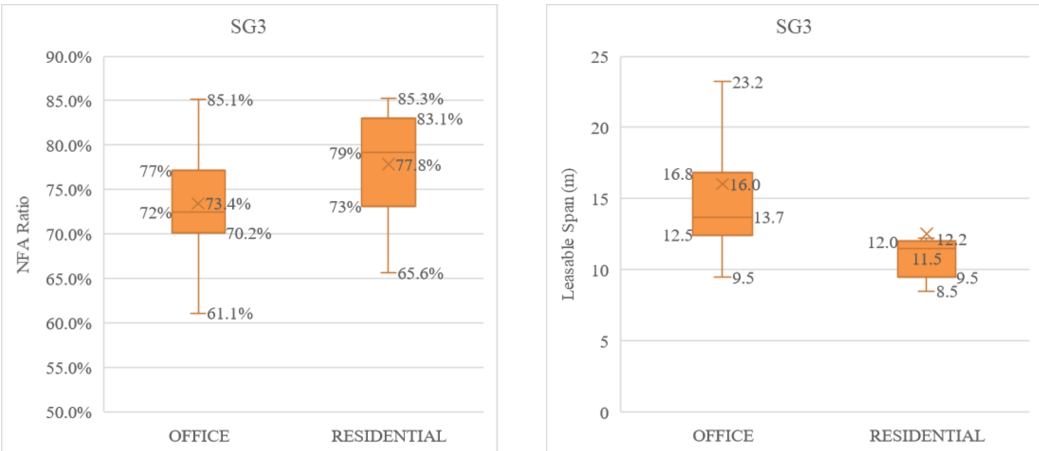


Figure 4.36. Leasable area efficiency of office and residential samples

4.5. Comparison of Outriggered Frame, Tube and Shear Frame Systems

Core and column ratios of different structural systems are investigated considering different parameters such as height, location, function and material in previous sections. Since shear walled frame is generally preferred when building height is less than 300m and most of the outriggered frame and tube systems are higher than 300m, a table is not prepared for shear frame systems. Some of the comparison charts and tables are given in Appendix E.

A table is created for outriggered frame and tube systems according to minimum and maximum values in the dataset (when the outliers are removed). Since all samples have different site conditions and design considerations, results do not follow a regular path. Still, these values can be useful for preliminary design and planning considerations of outriggered frame and tube systems (Table 4.1. and Table 4.2.). If there is no sample for given height range and material, that cell is left blank.

Table 4.1. *Core and column ratio range for outriggered frame systems*

* This data is obtained from only one sample; therefore, it may not reflect the general characteristics.

	OUTRIGGERED FRAME SYSTEM							
	COMPOSITE (CHINA)				COMPOSITE (OTHERS)			
	CORE RATIO		COLUMN R.		CORE RATIO		COLUMN R.	
HEIGHT (m)	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
250-350	18.8%	26.9%	1.60%	3.53%	14.6%	18.1%	1.34%	1.74%
350-450	26.7%	31.0%	2.44%	5.12%	*25%	-	*2.4%	-
450-550	23.4%	30.5%	1.56%	4.01%	12.8%	34.0%	0.82%	2.32%
>550	19.6%	35.1%	3.70%	4.70%	25.2%	29.2%	1.94%	3.73%

Table 4.2. *Core and column ratio range for tube systems*

* This data is obtained from only one sample; therefore, it may not reflect the general characteristics.

	TUBE SYSTEM											
	COMPOSITE (CHINA)				CONCRETE (OTHERS)				STEEL (OTHERS)			
	CORE RATIO		COLUMN R.		CORE RATIO		COLUMN R.		CORE RATIO		COLUMN R.	
HEIGHT (m)	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
<250	*24,5%	-	*1%	*1%	14.9%	21.0%	2.28%	5.92%	16.4%	27.1%	0.98%	1.68%
250-350	-	-	-	-	-	-	-	-	16.4%	29.1%	1.91%	8.49%
350-450	18.1%	27.4%	1.94%	3.04%	-	-	-	-	-	-	-	-
>450	24.5%	25.8%	1.42%	4.47%	-	-	-	-	-	-	-	-

Core ratio of buildings in China is higher than other locations in both structural systems. Although the effect of the building height on structural system cannot be observed significantly, maximum values generally increase; therefore, this can be related to height. Core and column ratio charts for outriggered frame systems in Section 4.3.2 expresses apparently the impacts of height. Since outriggered frame system has a lot of samples, results are more reliable for this structural system.

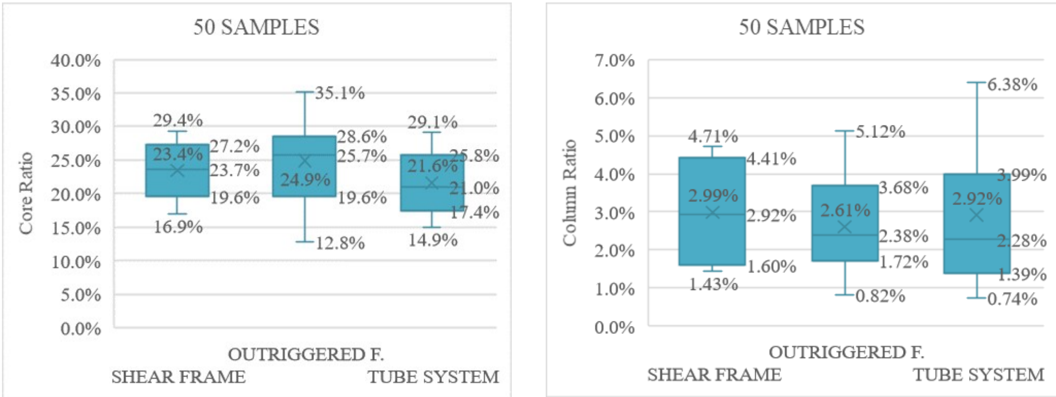


Figure 4.37. Core and column ratio for different structural systems

Lastly, structural systems of 50 samples which are investigated in NFA analyses are compared in terms of core and column ratio, and following outcomes are found:

- Outriggered frame systems have larger core area than other structures.
- Tube systems have less core area than outriggered frame systems; however, the average column ratio is higher than outriggered frame system.
- Although their average height is significantly less than other two structural systems, shear frame systems have similar core and column ratio to outriggered frame systems.

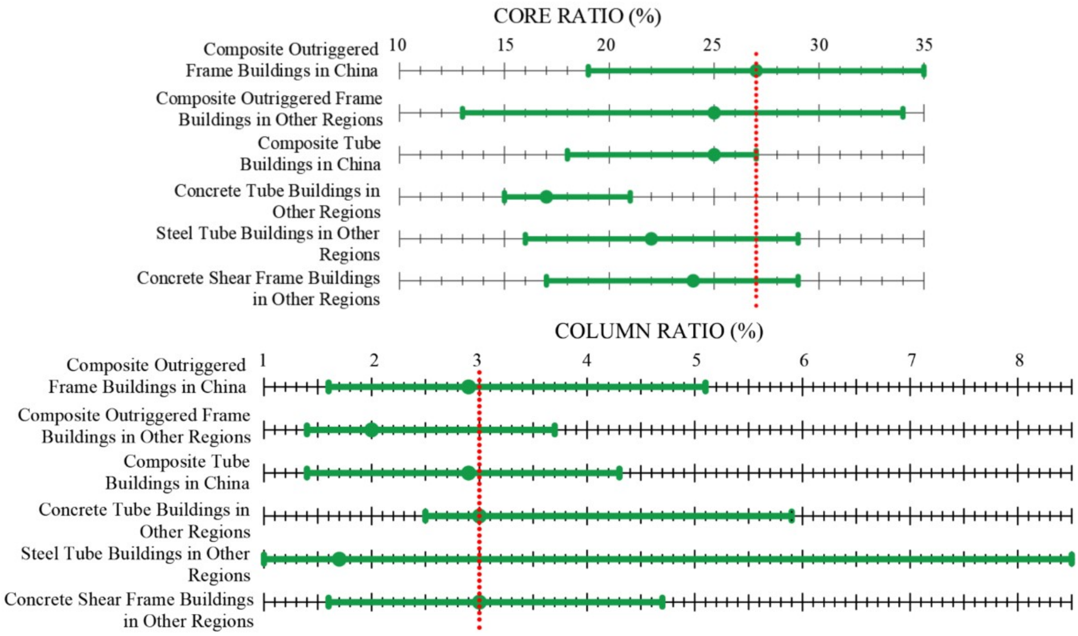


Figure 4.38. Core and column ratio for different structural systems

Figure 4.38 shows the distribution of the core and column ratios for different sample groups. The limits of each green line show the minimum and maximum values (when the outliers are not considered) of the sample set for a given structural system, material and region. The green circle shows the median value of the sample set for each subgroup. The results showed that, column area ratio and core area ratio in tall buildings can change between 1% - 8.5% and 13% - 35%, respectively, for a given structural system, structural material and region trio. Considering the highest median values among all subgroups (red dashed lines), 27% of a core area ratio and 3% of a column area ratio can be used as conservative central values for the preliminary design of tall buildings for any kind of structural system or material.

CHAPTER 5

CONCLUSION

5.1. Summary and Conclusion

Since tall buildings must withstand excessive lateral loads compared to conventional buildings, advanced structural systems are needed and thus have been developed within decades. Consequently, both the structural systems as well as the components of these structural systems are different than conventional buildings. This study investigates number and size of structural components of different structural systems. For this reason, a comprehensive literature survey is done about structural design considerations of tall buildings. Identity, architectural and structural parameters are grouped to compare different structural systems. Identity parameters are collected for 141 existing buildings, whereas only 82 of the buildings with all required information for this study can be gathered because of the limited data on published trustworthy sources. The most common structural systems of building samples are specified like shear frame, outriggered frame, framed tube and trussed tube systems. Although bundled tube system is relatively rare, this system is considered as well because of some similarities in structural behavior with other tube systems.

Samples are classified in terms of building function, location, structural material and height, and then structural components of the buildings are analyzed. Analyses have been completed in three stages because of the alternative classification strategies of the samples. In the first two level of grouping, samples are investigated separately; but, significant relationships between samples cannot be observed. Consequently, in the final stage of the analyses, samples are reclassified considering their common features and number of samples in each sub-group. Then, core and column ratio of different structural systems are reinvestigated. Moreover, leasable span and NFA are calculated according to the core and column ratios obtained in this study. Comparisons on leasable area and NFA with respect to different structural systems were performed. Additionally, outrigger height and number of outriggers, core configurations, special features such as dampers and wind modifications are examined briefly for the sake of completeness of this study.

After the first analyses, there have been found constructive results. These results are utilized in reclassification and grouping process and promote the improvement of the study in the further stages. Constructive results of the study can be specified as follows:

- Number of buildings in China is higher than other countries, and average building height of these buildings is more than other samples around the world.
- Office is the most preferred function worldwide, and mixed-use, residential, hotel and other functions follow it respectively.
- Composite is the most common structural material among the samples, and these buildings are usually taller than reinforced concrete and steel buildings. On the other hand, high-strength concrete is becoming more popular thanks to the new technologies and developments. As a matter of fact, world's tallest buildings are made of concrete. Steel is not common except America, and only 10% of the samples around the world is made of steel.
- Most of the shear frame buildings are made of concrete while composite is more common among outriggered frame system buildings.
- According to aspect ratio analyses, AR increases over the years, and this shows that buildings have become more slender.
- Outriggered frame is generally used when the building is higher than 350m. The height range of the buildings is generally between 200m and 400m for tube systems and 200m and 300m for shear frame systems.

- 1/3 of the tube system samples locate in China, and almost all these samples are made of composite. Most of the other tube system buildings locate in America, and steel is common for those.
- Although exterior structures are more efficient than interior structures, outriggered frame system is the most common structural system in worldwide. This circumstance can be explained by:
  - Outriggered frame structures interrupt the view less compared to tube systems.
  - Although, there is not a consensus in literature on this subject, Ali and Moon (2007) claimed that outriggered structural systems are efficient up to 150 storey, whereas tube systems are efficient between 60 and 110 storey.

According to analyses, main outcomes are specified in the scope of the study and listed as follows:

- Although the material of building's core is mostly concrete, concrete and composite are equally preferred for columns.
- Core and column ratio analyses based on location showed that buildings in China have larger core area compared to other locations.
- According to investigation on outriggers, outrigger height generally increases as building height increases, and 3 levels of outrigger is the most preferred set for outriggers.
- NFA ratio in tube systems is higher than NFA ratio in outriggered frame systems. Regarding leasable span, the average values are fairly similar for tube systems and outriggered frame systems.
- NFA ratio reduces as building height increases.
- According to analyses, residential buildings have lower leasable span while their NFA ratio is higher than other functions.

- The results showed that steel samples have similar core ratio with other building samples. The reason of this circumstance can be to keep top displacement of the buildings within acceptable limits for occupants' comfort, since wind plays a dominant role in design of high-rise buildings' structural system due to their heights. Besides, service requirements of the buildings may force to the core to be bigger in steel buildings.
- Core and column ratio of the buildings are specified according to maximum and minimum point of the box & whisker charts as follows:
    - Core ratio of an outriggered frame building in China which made of composite can be between 19% and 35%, mostly around 27%. Column ratio of these buildings can be between 1.6% and 5.1%, mostly around 2.9%.
    - Core ratio of an outriggered frame building in other regions (America, Europe, Middle East, Oceania and other Asian Countries except China) which made of composite can change between 13% and 34% with respect to structural and architectural considerations of the buildings. However, buildings have a core mostly around 25% of the total area in these regions. Column ratio of these buildings can be between 1% and 3.7%, mostly around 2%.
    - Core ratio of a tube building China which made of composite can be between 18% and 27%, mostly around 25%. Column ratio of these buildings can be between 1.4% and 4.5%, mostly around 2.9%.
    - Core ratio of a tube building in other regions which made of concrete can be between 15% and 21%, mostly around 17%. Column ratio of these buildings can be between 2.5% and 5.9%, mostly around 3%.
    - Core ratio of a tube building in other regions which made of steel can be between 16% and 29%, mostly around 22%. Column ratio of these buildings can be between 1% and 8.5%, mostly around 1.7%.

  - Core ratio of a shear frame building in other regions which made of concrete can be between 17% and 29%, mostly around 24%. Column ratio of these buildings can be between 1.4% and 4.7%, mostly around 3%.
- NFA ratio is generally between 70% and 77% for an office building and 73% and 83% for a residential building according to first and third quartile values in the dataset. Leasable span is between 12.4m and 16.8m for an office building and 9.5 and 12m for a residential building. Leasable span can be increased up to 23m in office buildings.
- NFA ratio of office buildings is between 69% and 76% for outriggered frame systems, 69% and 78% for shear frame systems and 72% and 79% for tube systems according to first and third quartile values in the dataset.

The results showed that, for preliminary design of a tall building regardless of its structural system, location, structural material or height, 27% and 3% can be taken as conservative central values of core and column area ratio, respectively.

5.2. Research Limitations

This study investigates different structural system by examining 141 existing building all around the world. Number of the samples cannot be further increased; due to the limitations on reaching data. If the architects or structural engineers of these buildings were allowed to share more details on these buildings, the sample size would be increased.

This database is composed for only academic purpose. All dimensions are determined according to reference floor plans. Floor plans are redrawn, and size of components is specified. Although all parameters are collected rigorously, some data may slightly differ from original. Nevertheless, this study mainly focuses on average values of observed parameters. Thus, the effect of such small differences on the average values can be accepted as negligible.

5.3. Recommendations for Further Studies

In this study, an extensive database is composed, and samples are analyzed in order to examine the structural components of different structural systems. All processes of this study such as collecting data, grouping, reclassification and analyses are completed rigorously.

3D models can be designed according to outcomes of this study by a structural analysis software in order to provide preliminary estimation for designers and investors. Then, these models can be used to verify observed column and core ratios by using design loads. Some height range can be specified for 3D models (such as buildings between 150m and 250m, 250m and 350m, 350m and 450m, 450 and 550m and higher than 550m), and a 3D model can be designed for each of these height ranges. These 3D models can be created for different structural systems such as outriggered frame, tube and shear frame systems. In addition, this study can be improved by redesigning these models with different structural materials such as concrete, composite and steel.

From economic point of view, cost of the different structural systems can be compared in terms of initial cost and profit. For this purpose, initial cost can be obtained by calculating the consumption of structural materials, and profit can be determined according to return of leasable area.

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APPENDICES

A. List of Buildings

Sample Group 1 (141 Samples)
Sample Group 2 (82 Samples)
Sample Group 3 (75 Samples)

Table A.1. *List of the buildings*

NO	BUILDINGS (Ascending Order of Height)	LOCATION	YEAR	FUNCTION	HEIGHT (m)	AR	MATERIAL	STRUCTURAL SYSTEM	CORE RATIO	COLUMN RATIO	LEASE SPAN (m)
1	O-14	Un.Arab. Em.	2010	O	105.7	3.52	Concrete	TRUSSED TUBE SYSTEM	14.9%	2.68%	14.4
2	ALDAR HEADQUARTERS	Un.Arab. Em.	2010	O	110.1	3.96	Composite	TRUSSED TUBE SYSTEM	32.5%	0.86%	27
3	THE PLAZA ON DEWITT	USA	1966	R	120.4	-	Concrete	FRAMED TUBE SYSTEM	-	-	-
4	PIRELLI BUILDING	Italy	1958	O	127.1	6.20	Concrete	SHEAR FRAME SYSTEM	26.3%	4.32%	18.5
5	TORRE GLORIES	Spain	2004	O	144.4	4.08	Concrete	FRAMED TUBE SYSTEM	19.9%	3.06%	14.5
6	STRATA	UK	2010	R	147.9	4.85	Concrete	SHEAR FRAME SYSTEM	13.8%	2.59%	12.15
7	SEAGRAM	USA	1958	O	157	4.62	Composite	SHEAR FRAME SYSTEM	28.1%	0.54%	13
8	FIRST CANADIAN CENTRE	Canada	1982	O	166.7	4.76	Concrete	FRAMED TUBE SYSTEM	16.6%	3.71%	13
9	ONTERIE CENTER	USA	1983	R, O	173.7	-	Concrete	TRUSSED TUBE SYSTEM	-	-	-
10	780 3RD AVENUE	USA	1986	O	173.7	8.27	Concrete	TRUSSED TUBE SYSTEM	21.0%	5.92%	9.5
11	30 ST MARY AXE	UK	2004	O	179.8	3.75	Steel	TRUSSED TUBE SYSTEM	27.1%	1.03%	11.5
12	HEARST TOWER	USA	2006	O	182	4.99	Steel	TRUSSED TUBE SYSTEM	25.9%	1.68%	12.3
13	ALLIANZ TOWER	Turkey	2015	O	185.5	5.98	Concrete	OUTRIGGERED FRAME SYSTEM	25.4%	1.26%	10.3
14	TURNING TORSO	Sweden	2005	R, O	190	13.01	Concrete	MEGA CORE	25.0%	NA	13.5
15	LAKE POINT TOWER	USA	1968	R	196.5	-	Concrete	SHEAR FRAME SYSTEM	-	-	-
16	MODE GAKUEN COCOON TOWER	Japan	2008	E	203.7	4.50	Composite	SHEAR FRAME SYSTEM	20.8%	0.68%	16.6
17	ONE MAGNIFICENT MILE	USA	1983	R, O	205.1	-	Concrete	BUNDLED TUBE SYSTEM	-	-	-
18	OLYMPIA CENTER	USA	1986	R, O	222.9	6.46	Concrete	FRAMED TUBE SYSTEM	15.0%	2.28%	12.85
19	THE LEADENHALL BUILDING	UK	2014	O	224	4.57	Steel	TRUSSED TUBE SYSTEM	16.4%	0.98%	49
20	WORLD TOWER	Australia	2004	R	230	8.21	Concrete	OUTRIGGERED FRAME SYSTEM	19.1%	3.23%	11.5
21	KINGTOWN INTERNATIONAL CENTER	China	2014	H, O	231.2	5.56	Composite	TRUSSED TUBE SYSTEM	24.6%	1.03%	10.5
22	SOUTHEAST FINANCIAL CENTER	USA	1983	O	232.8	-	Composite	BUNDLED TUBE SYSTEM	-	-	-
23	CCTV HEADQUARTERS	China	2012	O	234	-	Composite	TRUSSED TUBE SYSTEM	-	-	-
24	8 SHENTON WAY	Singapore	1986	O	234.7	9.39	Concrete	MEGA CORE	26.9%	NA	11.6
25	BAHRAIN WORLD TRADE CENTER	Bahrain	2008	O	240	10.14	Concrete	SHEAR FRAME SYSTEM	26.5%	1.65%	15.7
26	TORRE REFORMA	Mexico	2016	O	246	6.74	Composite	SHEAR FRAME SYSTEM	24.6%	3.22%	16.45
27	EVOLUTION TOWER	Russia	2015	O	246	5.81	Concrete	SHEAR FRAME SYSTEM	29.4%	1.88%	10
28	HIGHCLIFF	China	2003	R	252.3	-	Concrete	SHEAR FRAME SYSTEM	-	-	-
29	LANGHAM PLACE OFFICE TOWER	China	2004	O	255.1	5.78	Concrete	OUTRIGGERED FRAME SYSTEM	29.4%	2.31%	15.6
30	COMMERZBANK TOWER	Germany	1997	O	259	4.32	Composite	MEGA COLUMN	28.1%	2.36%	16
31	WATER TOWER PLACE	USA	1976	R, H	261.9	-	Concrete	FRAMED TUBE SYSTEM	-	-	-
32	AL FAISALIAH	Saudi Arabia	2000	H, O	266.9	5.93	Concrete	SHEAR FRAME SYSTEM	20.5%	1.43%	11.35
33	601 LEXINGTON	USA	1977	O	278.9	6.02	Steel	TRUSSED TUBE SYSTEM	19.2%	8.49%	13

NO	BUILDINGS (Ascending Order of Height)	LOCATION	YEAR	FUNCTION	HEIGHT (m)	AR	MATERIAL	STRUCTURAL SYSTEM	CORE RATIO	COLUMN RATIO	LEASE SPAN (m)
34	CHEUNG KONG CENTRE	China	1999	O	282.8	6.02	Composite	OUTRIGGERED FRAME SYSTEM	26.9%	1.78%	12.5
35	ONE LIBERTY PLACE	USA	1987	O	288	5.93	Steel	OUTRIGGERED FRAME SYSTEM	24.1%	0.64%	13
36	PLAZA 66	China	2001	O	288.2	8.48	Concrete	OUTRIGGERED FRAME SYSTEM	23.1%	3.00%	11.85
37	311 SOUTH WACKER DRIVE	USA	1990	O	292.9	7.11	Concrete	SHEAR FRAME SYSTEM	16.9%	4.71%	19.5
38	CHINA WORLD TRADE CENTER PHASE 3B	China	2017	H, O	295.6	6.57	Composite	OUTRIGGERED FRAME SYSTEM	23.2%	1.60%	12.25
39	COMCAST CENTER	USA	2008	O	296.7	-	Composite	SHEAR FRAME SYSTEM	-	-	-
40	EUREKA TOWER	Australia	2006	R	297.3	7.00	Concrete	OUTRIGGERED FRAME SYSTEM	16.7%	2.67%	10
41	ONE ISLAND EAST CENTRE	China	2008	O	298.1	-	Concrete	SHEAR FRAME SYSTEM	-	-	-
42	TORRE COSTANERA	Chile	2014	H, O	300	6.17	Concrete	OUTRIGGERED FRAME SYSTEM	28.5%	1.33%	12.7
43	ASPIRE TOWER	Qatar	2007	H, O	300	16.67	Composite	MEGA CORE	19.7%	NA	11.3
44	GOLDEN EAGLE TIANDI TOWER C	China	2019-ATO	O	300	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
45	NBK TOWER	Kuwait	2014	O	300	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
46	ABENO HARUKAS	Japan	2019-ATO	R, H, O	300	-	Steel	OUTRIGGERED FRAME SYSTEM	-	-	-
47	SHENZHEN ZHONGZHOU HOLDINGS F. C.	China	2015	R, H, O	300.8	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
48	CAPITAL CITY MOSCOW TOWER	Russia	2010	R	301.8	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
49	KINGDOM CENTRE	Saudi Arabia	2002	R, H, O	302.3	7.96	Concrete	SHEAR FRAME SYSTEM	21.0%	3.97%	12
50	GREENLAND PULI CENTER	China	2014	O	303	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
51	JIANGXI N. G. CENTRAL PLAZA, PARCEL A	China	2015	O	303	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
52	JIANGXI N. G. CENTRAL PLAZA, PARCEL B	China	2015	O	303	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
53	TWO PRUDENTIAL PLAZA	USA	1990	O	303.3	7.49	Concrete	OUTRIGGERED FRAME SYSTEM	21.6%	1.25%	13
54	ONE MANHATTAN WEST	USA	2019-ATO	O	303.3	-	Composite	SHEAR FRAME SYSTEM	-	-	-
55	WUXI MAOYE CITY - MARRIOTT HOTEL	China	2014	H	303.8	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
56	NORTHEAST ASIA TRADE TOWER	South Korea	2011	R, H, O	305	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
57	THE SHARD	UK	2013	R, H, O	306	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
58	CAYAN TOWER	Un.Arab. Em.	2013	R	306.4	9.43	Concrete	FRAMED TUBE SYSTEM	11.6%	5.93%	11.8
59	BURJ RAFAL	Saudi Arabia	2014	R, H	307.9	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
60	PEARL RIVER TOWER	China	2013	O	309.4	8.40	Composite	OUTRIGGERED FRAME SYSTEM	18.8%	1.63%	18.9
61	MENARA TM	Malaysia	2001	O	310	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
62	OCEAN HEIGHTS	Un.Arab. Em.	2010	R	310	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
63	U.S. Bank Tower	USA	1990	O	310.3	7.22	Steel	SHEAR FRAME SYSTEM	19.6%	2.40%	12.35
64	BANK OF AMERICA PLAZA	USA	1992	O	311.8	6.25	Composite	OUTRIGGERED FRAME SYSTEM	14.6%	1.74%	16

NO	BUILDINGS (Ascending Order of Height)	LOCATION	YEAR	FUNCTION	HEIGHT (m)	AR	MATERIAL	STRUCTURAL SYSTEM	CORE RATIO	COLUMN RATIO	LEASE SPAN (m)
65	KING POWER MAHANAKHON	Thailand	2016	R, H	314	9.75	Concrete	OUTRIGGERED FRAME SYSTEM	31.8%	2.56%	8.45
66	NEW YORK TIMES TOWER	USA	2007	O	318.8	7.25	Steel	OUTRIGGERED FRAME SYSTEM	23.7%	0.51%	15.3
67	CHRYSLER BUILDING	USA	1930	O	318.9	11.81	Steel	TRUSSED TUBE SYSTEM	16.4%	6.38%	9.5
68	SINAR MAS CENTER 1	China	6	O	320	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
69	53 WEST 53RD	USA	2017	R	320	-	Concrete	TRUSSED TUBE SYSTEM	-	-	-
70	PALAIS ROYALE	India	ON HOLD	R	320	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
71	BURJ AL ARAB	Un.Arab. Em.	1999	H	321	-	Composite	SHEAR FRAME SYSTEM	-	-	-
72	Q1 TOWER	Australia	2005	R	322.5	-	Concrete	SHEAR FRAME SYSTEM	-	-	-
73	SALEFORCE TOWER	USA	2018	O	326.1	-	Composite	SHEAR FRAME SYSTEM	-	-	-
74	GOLDEN EAGLE TIANDI TOWER B	China	2019-ATO	O	328	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
75	CHINA WORLD TOWER	China	2010	H, O	330	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
76	LCT RESIDENTIAL TOWER B	South Korea	2020-ATO	R	333.1	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
77	SHIMAO INTERNATIONAL PLAZA	China	2006	R, H, O	333.3	-	Concrete	MEGA COLUMN	-	-	-
78	WILSHIRE GRAND CENTER	USA	2017	H, O	335.3	9.98	Composite	OUTRIGGERED FRAME SYSTEM	18.1%	1.34%	14.3
79	TIANJIN WORLD FINANCIAL CENTER	China	2011	O	336.9	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
80	TIANJIN MODERN CITY OFFICE TOWER	China	2016	O	338	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
81	LCT RESIDENTIAL TOWER A	South Korea	2020-ATO	R	339.1	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
82	JOHN HANCOCK	USA	1969	R, O	343.7	6.87	Steel	TRUSSED TUBE SYSTEM	22.2%	1.97%	17.5
83	NEVA TOWERS 2	Russia	2020-ATO	R	345	10.45	Concrete	OUTRIGGERED FRAME SYSTEM	21.2%	2.98%	11.65
84	THE CENTER	China	1998	O	346	8.14	Composite	OUTRIGGERED FRAME SYSTEM	18.8%	3.53%	18.8
85	AON CENTER	USA	1973	O	346.3	6.35	Steel	FRAMED TUBE SYSTEM	29.1%	1.91%	13
86	85 SKY TOWER	Taiwan	1997	R, H, O	347.5	-	Steel	MEGA COLUMN	-	-	-
87	RAFFLES CITY CHONGQING T3N	China	2019-ATO	R	354.5	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
88	RAFFLES CITY CHONGQING T4N	China	2019-ATO	R	354.5	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
89	SINAO STEEL INTERNATIONAL PLAZA T2	China	ON HOLD	O	358	-	Composite	FRAMED TUBE SYSTEM	-	-	-
90	GREENLAND GROUP SUZHOU CENTER	China	2020-UC	R, H, O	358	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
91	HANKING CENTER	China	2018	O	358.9	6.70	Composite	TRUSSED TUBE SYSTEM	19.8%	2.87%	67.13
92	ALMAS TOWER	Un.Arab. Em.	2008	O	360	8.91	Composite	OUTRIGGERED FRAME SYSTEM	25.5%	2.38%	13.5
93	BANK OF CHINA	China	1990	O	367.4	7.07	Composite	TRUSSED TUBE SYSTEM	18.1%	3.04%	17.6
94	GOLDEN EAGLE TIANDI TOWER A	China	2019-ATO	H, O	368.1	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
95	FEDERATION TOWER	Russia	2016	R, O	373.7	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-

NO	BUILDINGS (Ascending Order of Height)	LOCATION	YEAR	FUNCTION	HEIGHT (m)	AR	MATERIAL	STRUCTURAL SYSTEM	CORE RATIO	COLUMN RATIO	LEASE SPAN (m)
96	CENTRAL PLAZA	China	1992	O	373.9	7.87	Concrete	TRUSSED TUBE SYSTEM	20.8%	4.02%	13.5
97	ELIT RESIDENCE	Un.Arab. Em.	2012	R	380.5	-	Concrete	FRAMED TUBE SYSTEM	-	-	-
98	EMPIRE STATE BUILDING	USA	1931	O	381	9.07	Steel	SHEAR FRAME SYSTEM	29.2%	5.33%	12
99	BURJ MOHAMMED BIN RASHID	Un.Arab. Em.	2014	R	381.2	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
100	SHUN HING SQUARE	China	1996	O	384	10.82	Composite	OUTRIGGERED FRAME SYSTEM	26.7%	2.91%	12.5
101	PIF TOWER	Saudi Arabia	2019-ATO	O	385	6.91	Composite	TRUSSED TUBE SYSTEM	33.3%	2.06%	11.25
102	SHUM YIP UPPER HILLS TOWER 1	China	2019-ATO	H, O	388.1	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
103	CITIC PLAZA	China	1996	O	390.2	8.30	Concrete	SHEAR FRAME SYSTEM	20.8%	3.11%	11.3
104	23 MARINA	Un.Arab. Em.	2012	R	392.4	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
105	CHINA RESOURCES HQ	China	2018	O	392.5	-	Composite	FRAMED TUBE SYSTEM	-	-	-
106	LCT LANDMARK TOWER	South Korea	2020-ATO	R, H	411.6	-	Concrete	OUTRIGGERED FRAME SYSTEM	-	-	-
107	TWO INTERNATIONAL FINANCE CENTER	China	2003	O	412	7.92	Composite	OUTRIGGERED FRAME SYSTEM	26.8%	2.44%	15
108	AL HAMRA TOWER	Kuwait	2011	O	412.6	-	Composite	SHEAR FRAME SYSTEM	-	-	-
109	PRINCESS TOWER	Un.Arab. Em.	2012	R	413.4	-	Concrete	FRAMED TUBE SYSTEM	-	-	-
110	WORLD TRADE CENTER (TWINS)	USA	1973	O	417	6.62	Steel	FRAMED TUBE SYSTEM	27.2%	0.74%	18.25
111	JIN MAO	China	1999	H, O	420.5	7.79	Composite	OUTRIGGERED FRAME SYSTEM	27.2%	2.63%	14.8
112	TRUMP INTERNATIONAL TOWER	USA	2009	R, H	423.2	9.55	Concrete	OUTRIGGERED FRAME SYSTEM	18.0%	2.86%	28
113	MARINA 101	Un.Arab. Em.	2017	R, H	425	-	Concrete	FRAMED TUBE SYSTEM	-	-	-
114	432 PARK AVENUE	USA	2015	R	425.5	15.20	Concrete	FRAMED TUBE SYSTEM	10.3%	4.41%	9.5
115	HAIKOU TOWER 1	China	2022-UC	R, H, O	428	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
116	AKHMAT TOWER	Russia	ON HOLD	R, O	435	-	Steel	FRAMED TUBE SYSTEM	-	-	-
117	111 WEST 57TH STREET	USA	2019-UC	R	435.3	25.61	Concrete	OUTRIGGERED FRAME SYSTEM	22.9%	6.70%	9.5
118	GUANGZHOU INTERNATIONAL FIN CENTER	China	2010	H, O	438.6	7.34	Composite	TRUSSED TUBE SYSTEM	27.4%	1.94%	12
119	KK100	China	2011	H, O	441.8	11.05	Composite	OUTRIGGERED FRAME SYSTEM	31.0%	5.12%	12.8
120	WORLD ONE TOWER	India	ON HOLD	R	442	9.40	Concrete	BUTTRESSED CORE SYSTEM	21.9%	4.80%	13
121	WILLIS TOWER	USA	1974	O	442.1	7.00	Steel	BUNDLED TUBE SYSTEM	18.3%	1.36%	25.8
122	ZIFENG TOWER	China	2010	H, O	450	7.76	Composite	OUTRIGGERED FRAME SYSTEM	28.1%	1.72%	19.5
123	PETRONAS TWIN TOWERS	Malaysia	1998	O	451.9	9.76	Concrete	OUTRIGGERED FRAME SYSTEM	25.4%	3.50%	13
124	LAKHTA CENTER	Russia	2019-ATO	O	462	8.40	Composite	OUTRIGGERED FRAME SYSTEM	23.8%	2.32%	13
125	CHENGDU GREENLAND TOWER	China	2021-UC	H, O	468	7.43	Composite	OUTRIGGERED FRAME SYSTEM	24.6%	3.68%	14.55
126	WUHAN GREENLAND CENTER	China	ON HOLD	R, H, O	472	6.29	Composite	BUTTRESSED CORE SYSTEM	30.3%	3.23%	14

NO	BUILDINGS (Ascending Order of Height)	LOCATION	YEAR	FUNCTION	HEIGHT (m)	AR	MATERIAL	STRUCTURAL SYSTEM	CORE RATIO	COLUMN RATIO	LEASE SPAN (m)
127	INTERNATIONAL COMMERCE CENTER	China	2010	H, O	484	8.38	Composite	OUTRIGGERED FRAME SYSTEM	30.5%	1.56%	16
128	SHANGHAI WORLD FINANCIAL CENTER	China	2008	H, O	492	8.48	Composite	OUTRIGGERED FRAME SYSTEM	28.6%	2.72%	13
129	TAIPEI	Taiwan	2004	O	508	8.99	Composite	OUTRIGGERED FRAME SYSTEM	20.5%	2.23%	13.9
130	EVERGRANDE IFC T1	China	2021-UC	R, H, O	518	-	Composite	OUTRIGGERED FRAME SYSTEM	-	-	-
131	CHINA ZUN TOWER	China	2018	O	528	6.77	Composite	TRUSSED TUBE SYSTEM	25.0%	4.47%	19.5
132	TIANJIN CTF FINANCE CENTER	China	2016	R, H, O	530	8.07	Composite	FRAMED TUBE SYSTEM	24.5%	1.42%	15
133	GUANGZHOU CTF FINANCE CENTER	China	2020-ATO	R, H, O	530	8.55	Composite	OUTRIGGERED FRAME SYSTEM	23.4%	4.01%	16
134	ONE WORLD TRADE CENTER	USA	2014	O	541.3	8.59	Composite	OUTRIGGERED FRAME SYSTEM	34.0%	0.82%	13.7
135	LOTTE WORLD TOWER	S.Korea	2017	H, O	554.5	7.81	Composite	OUTRIGGERED FRAME SYSTEM	25.7%	1.94%	17.5
136	GOLDIN FINANCE	China	2020-ATO	H, O	596.5	9.74	Composite	TRUSSED TUBE SYSTEM	25.8%	4.26%	12.32
137	PING AN	China	2017	O	599	9.27	Composite	OUTRIGGERED FRAME SYSTEM	35.1%	3.74%	17.05
138	SHANGHAI TOWER	China	2015	H, O	632	8.27	Composite	OUTRIGGERED FRAME SYSTEM	19.6%	4.70%	23.2
139	MERDEKA PNB 118	Malaysia	2021-UC	R, H, O	644	9.91	Composite	OUTRIGGERED FRAME SYSTEM	29.2%	3.73%	15
140	BURJ KHALIFA	Un.ArabEm.	2010	R, H, O	829.8	11.96	Concrete	BUTTRESSED CORE SYSTEM	21.5%	5.11%	10
141	JEDDAH TOWER	Saudi Arabia	2021-UC	R	1000	-	Concrete	BUTTRESSED CORE SYSTEM	-	-	-

B. Correlations Between Different Parameters

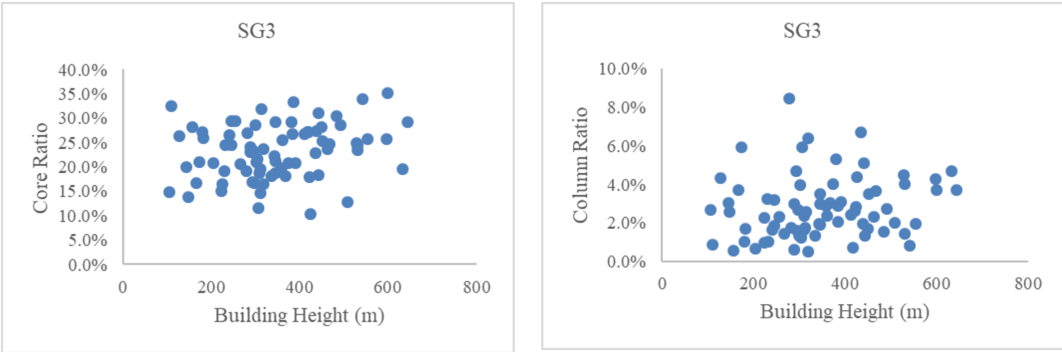

Figure B.1. Relationship between height and core and column ratio in SG3

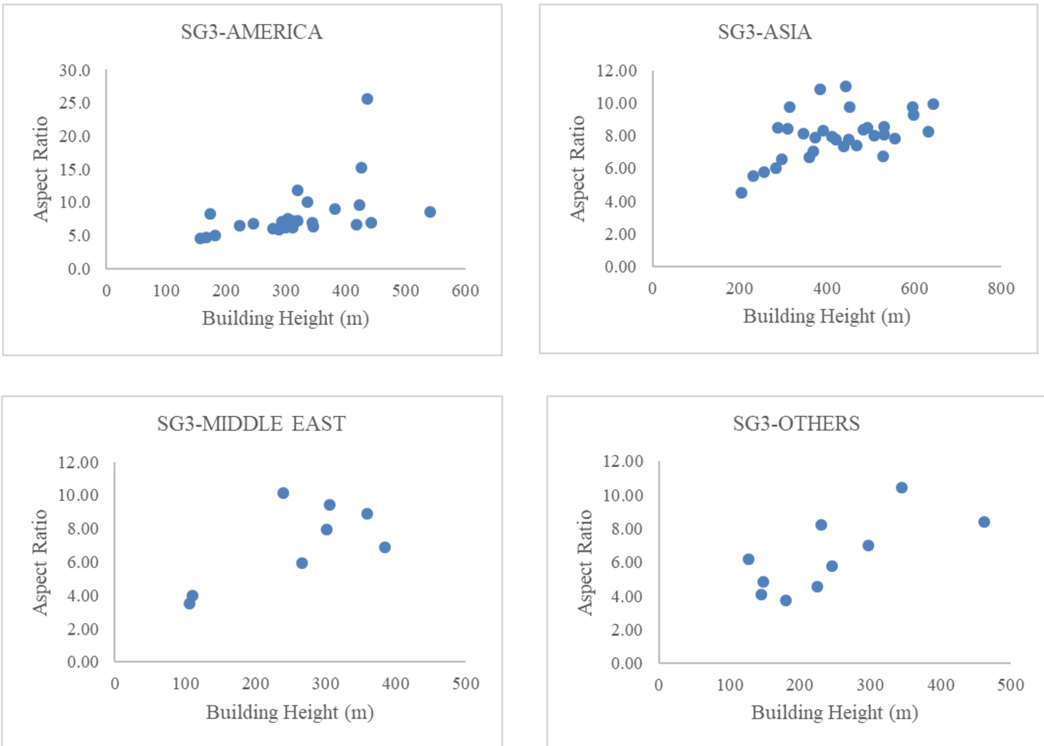

Figure B.2. Relationship between AR and building height based on locations

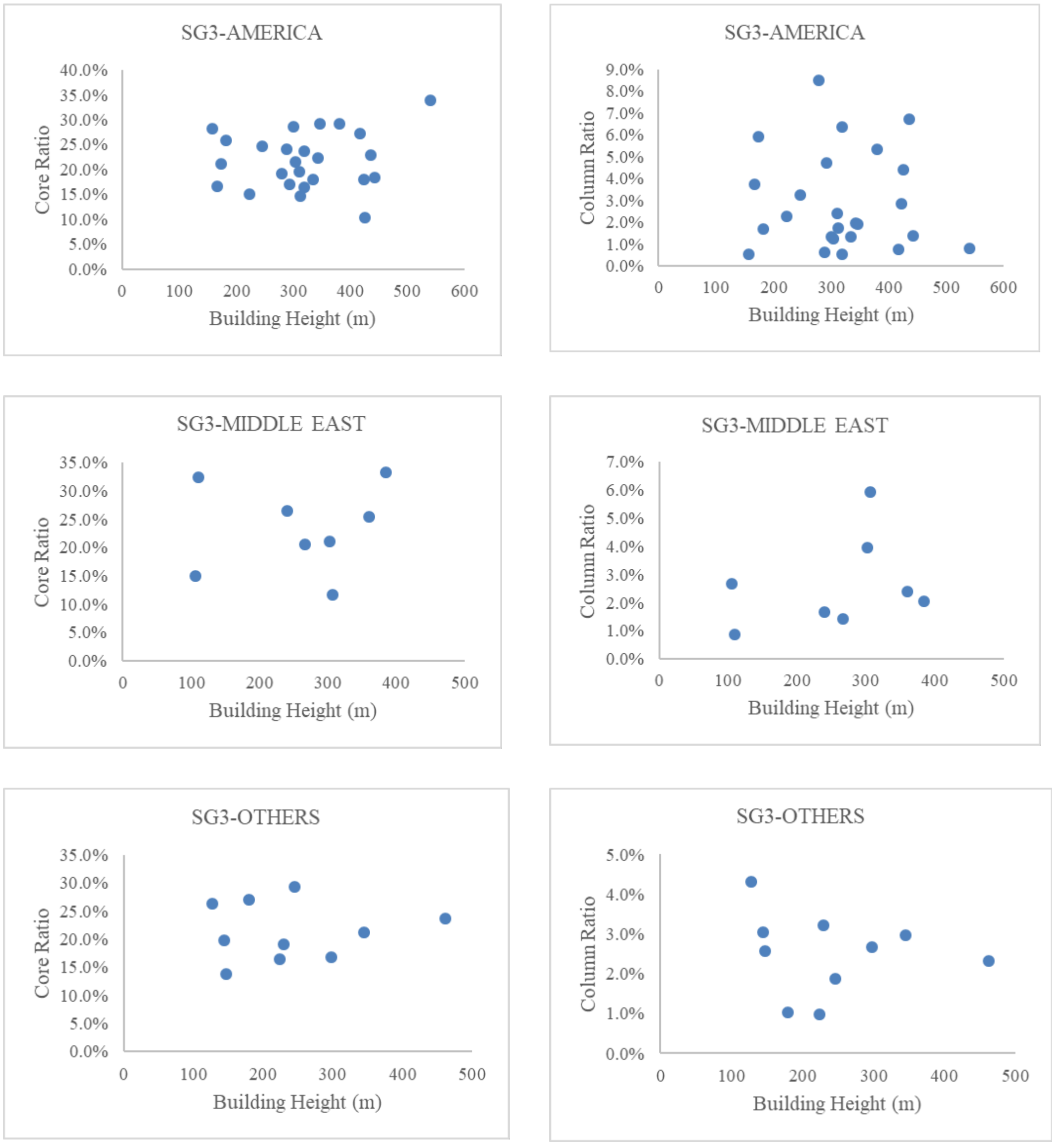

Figure B.3. Relationship between height and core and column ratio in SG3 based on location

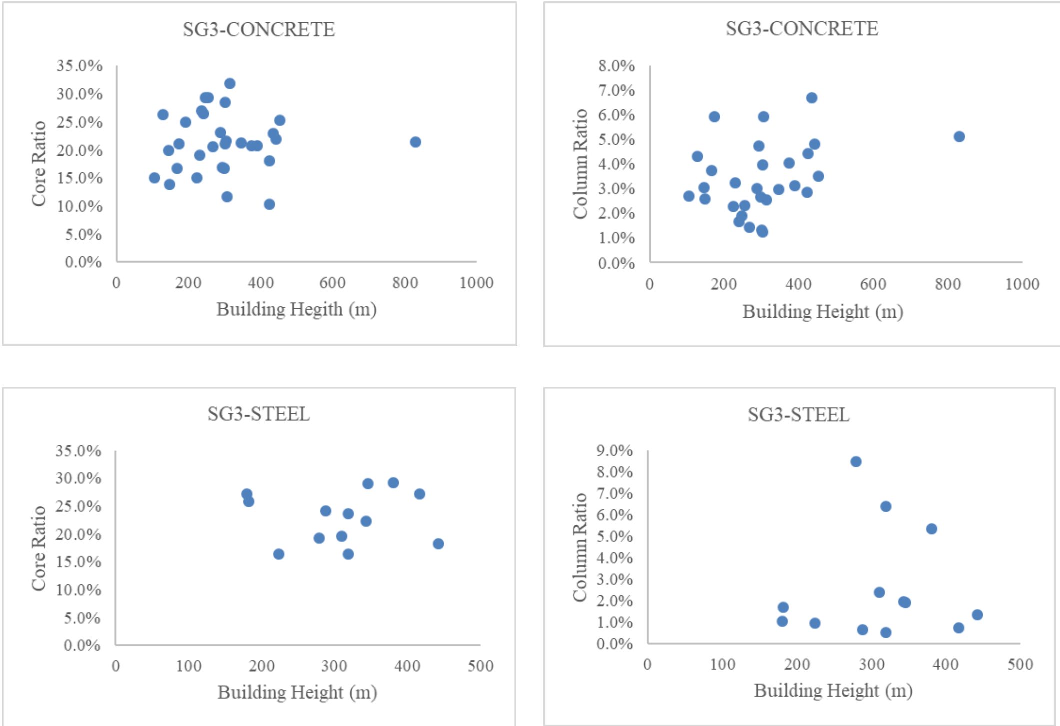

Figure B.4. Relationship between height and core and column ratio in SG3 based on structural material

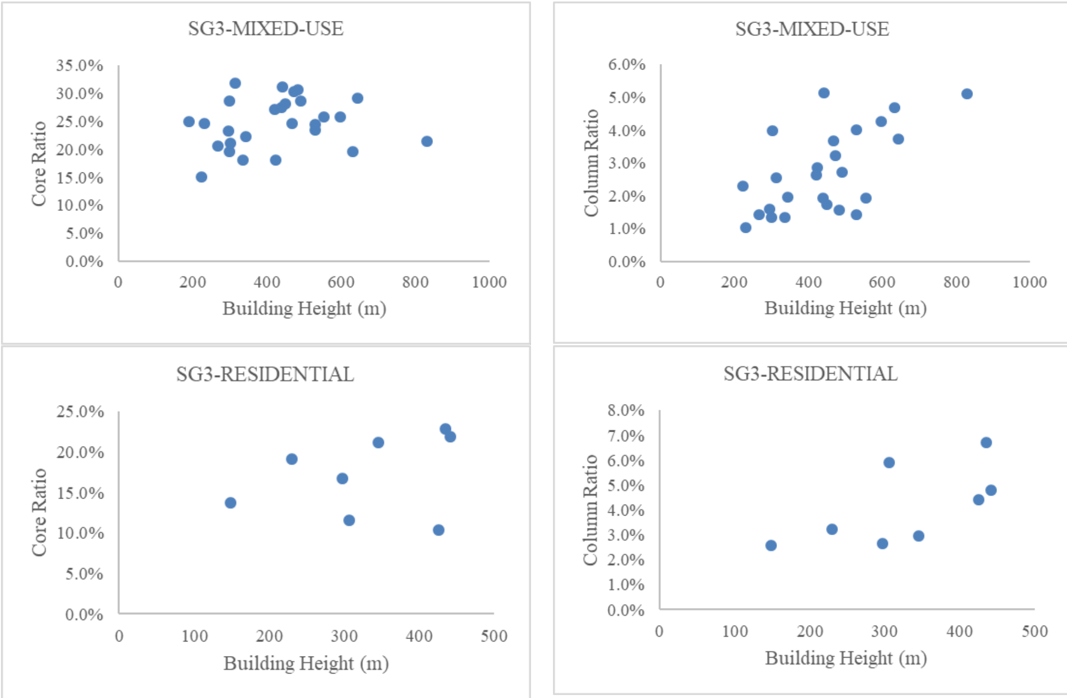

Figure B.5. Relationship between height and core and column ratio in SG3 based on function

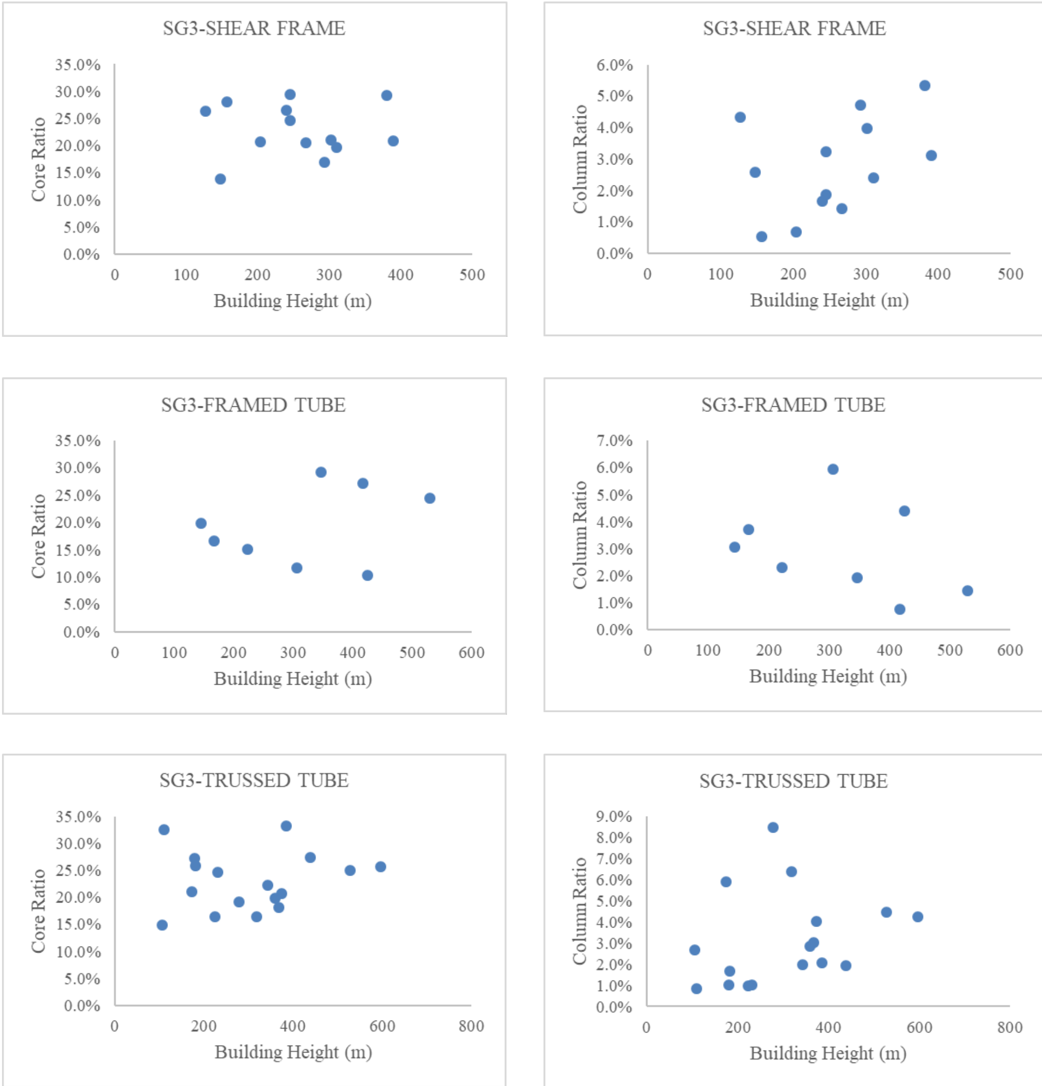

Figure B.6. Relationship between core and column ratio in SG3 according to structural systems

C. **Characterization of Outriggers**

Table *C.1. List of the buildings which are considered while evaluating outriggers*

BUILDINGS (Ascending Order ot Height)	HEIGHT	MATERIAL	Number of Outrigger	Height of Outrigger (Storey)
WORLD TOWER	230	Concrete	2	8
CHEUNG KONG CENTRE	282.8	Composite	3	1
PLAZA 66	288.2	Concrete	3	2
CHINA WORLD TRADE CENTER PHA	295.6	Composite	2	1
PEARL RIVER TOWER	309.4	Composite	2	4
KING POWER MAHANAKHON	314	Concrete	3	1
NEW YORK TIMES TOWER	318.8	Steel	2	2
WILSHIRE GRAND CENTER	335.3	Composite	3	3
NEVA TOWERS 2	345	Concrete	3	2
ALMAS TOWER	360	Composite	3	2
TWO INTERNATIONAL FINANCE CE	412	Composite	3	3
JIN MAO	420.5	Composite	3	2
TRUMP INTERNATIONAL TOWER	423.2	Concrete	3	2
111 WEST 57TH STREET	435.3	Concrete	3	2
KK100	441.8	Composite	3	2
ZIFENG TOWER	450	Composite	3	2
PETRONAS TWIN TOWERS	451.9	Concrete	1	2
LAKHTA CENTER	462	Composite	4	2
CHENGDU GREENLAND TOWER	468	Composite	3	2
INTERNATIONAL COMMERCE CENT	484	Composite	4	3
SHANGHAI WORLD FINANCIAL CEN	492	Composite	2	3
TAIPEI 101	508	Composite	10	1
GUANGZHOU CTF FINANCE CENTER	530	Composite	4	2
ONE WORLD TRADE CENTER	541.3	Composite	1	2
LOTTE WORLD TOWER	554.5	Composite	2	5
PING AN	599	Composite	4	2
MERDEKA PNB 118	644	Composite	3	3

D. **Height Distribution for Tube Systems**

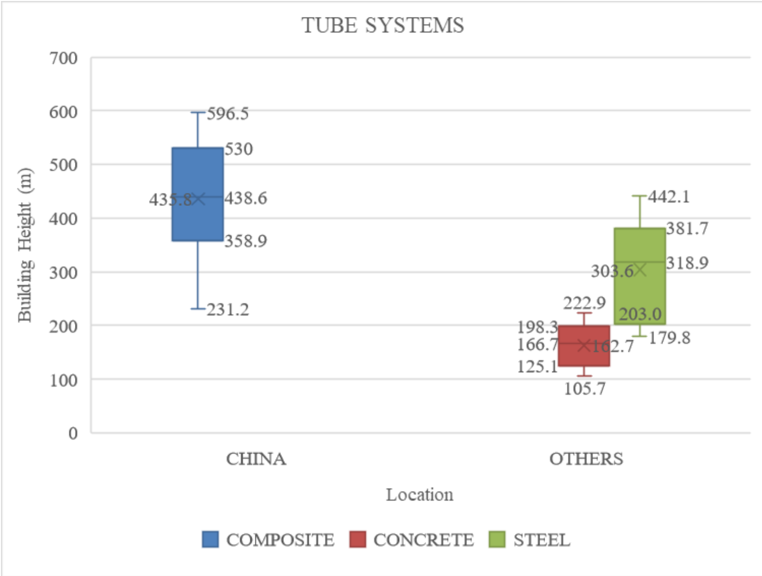

Figure D.1. Height distribution of samples based on location in tube systems

E. Comparison of Structural Systems

Figure E.1. Core and column ratio for different structural systems based on structural material

Table E.1. *Comparison of outriggered frame and tube systems in terms of core and column ratio*

CORE RATIO						
OUTRIGGERED FRAME SYSTEM			TUBE SYSTEM			
Building Height (m)	Composite (China)	Composite (Others)	Building Height (m)	Composite (China)	Concrete (Others)	Steel (Others)
250-350	21.0%	16.0%	<250	*24.60%	17.50%	25.9%
350-450	27.0%	*25.0%	250-350	-	-	20.7%
450-550	28.1%	24.0%	350-450	19.8%	-	-
>550	27.4%	27.4%	>450	25.1%	-	-
COLUMN RATIO						
OUTRIGGERED FRAME SYSTEM			TUBE SYSTEM			
Building Height (m)	Composite (China)	Composite (Others)	Building Height (m)	Composite (China)	Concrete (Others)	Steel (Others)
250-350	1.88%	1.60%	<250	*1.03%	3.06%	1.00%
350-450	2.77%	*2.38%	250-350	-	-	4.20%
450-550	2.72%	2.02%	350-450	2.87%	-	-
>550	4.22%	2.84%	>450	4.26%	-	-

* This data is obtained from only one sample, so it requires attention!

Table *E.2*. *Height, core and column ratio data of structural systems*

		HEIGHT				CORE RATIO				COLUMN RATIO			
		1ST Q.	3RD Q.	MED.	AV.	1ST Q.	3RD Q.	MED.	AV.	1ST Q.	3RD Q.	MED.	AV.
SHEAR FRAME	CONCRETE (OTHERS)	211.8	295.3	256.5	245.8	19.6%	27.2%	23.7%	23.4%	1.60%	4.41%	2.92%	2.99%
OUTRIGGERED FRAME	COMPOSITE (CHINA)	346	492	441.8	436.5	23.2%	28.6%	26.8%	26.0%	1.72%	3.74%	2.72%	2.92%
	COMPOSITE (OTHERS)	341.5	551.2	485	464.6	15.5%	28.3%	24.6%	22.9%	1.44%	2.37%	1.98%	2.04%
TUBE SYSTEM	COMPOSITE (CHINA)	358.9	530	438.6	435.8	19.8%	25.8%	24.6%	23.6%	1.42%	4.26%	2.87%	2.72%
	CONCRETE (OTHERS)	125.1	198.3	166.7	162.7	15.0%	20.5%	16.6%	17.5%	2.48%	4.82%	3.06%	3.53%
	STEEL (OTHERS)	203	381.7	318.9	303.6	17.4%	27.1%	22.2%	22.4%	1.00%	4.17%	1.68%	2.73%