EVALUATION OF THE EFFECTS OF SERVICE CORE REDUCTION ON TALL BUILDING STRUCTURES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

BESTE FAKIOĞLU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

JANUARY 2019

Approval of the thesis:

EVALUATION OF THE EFFECTS OF SERVICE CORE REDUCTION ON TALL BUILDING STRUCTURES

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ABSTRACT

EVALUATION OF THE EFFECTS OF SERVICE CORE REDUCTION ON TALL BUILDING STRUCTURES

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January 2019, 141 pages

Optimum design of the service core where the vertical circulation systems, building services, HVAC elements etc. located, is one of the major tasks in tall building design process as it directly effects the net leasable area. Among others, the elevators are one of the most area consuming elements of service core, especially valid for supertall (+300m) office buildings. By making use of developing elevator technologies, decreasing the elevator footprint area and thereby decreasing the service core area is possible, indeed. However, the core of a tall building typically serves as an important member of lateral load resisting system, namely as a structural core. The aim of this study is to investigate the effects of service core reduction due to the elevator footprint decrease. Computer models of typical outriggered frame and framed-tube office buildings with 300m height (75 story) are generated. Then, the strength and stiffness constraints of reduced core buildings have been satisfied by making several modifications such as adding outriggers, using of belt trusses, increasing the section or the number or both of perimeter columns etc. This way, the modified reduced core models having similar structural performance with standard core models in terms of strength and stiffness have been obtained. Thereafter, fundamental architectural aspects such as net leasable area, the obstruction of panoramic exterior view, the amount of structural material etc. of standard core and modified reduced core buildings are compared to investigate the trade-offs of reducing the core.

Keywords: Tall Building, High-rise Building, Service Core, Tall Building Structural Systems, Elevator Footprint

ÖZ

YÜKSEK BİNALARDA SERVİS ÇEKİRDEĞİNDEKİ KÜÇÜLMENİN DEĞERLENDİRİLMESİ

Fakıoğlu, Beste
Yüksek Lisans, Yapı Bilimleri
Tez Danışmanı: Dr. Öğr. Üyesi Bekir Özer Ay

Ocak 2019, 141 sayfa

Yüksek bina tasarımının ana hedeflerinden biri, net kullanım alanı üzerinde doğrudan etkisi bulunduğu için dikey sirkülasyon sistemleri ve ısıtma, havalandırma ve iklimlendirme (HVAC) sistemleri gibi binaya hizmet veren pek çok servis elemanını barındıran servis çekirdeğinin optimum tasarımıdır. Bunlar içinde asansörler, özellikle 300 metre üzerindeki binalar için servis çekirdeğinde en çok yer kaplayan elemanlardır. Gelişen asansör teknolojilerinin kullanımı sayesinde asansör alanının ve dolayısıyla servis çekirdeğinin alanı önemli miktarda azaltılabilir. Ancak yüksek binalarda servis çekirdeği çoğunlukla yanal yüklere dayanan taşıyıcı sistemin de bir parçası olan strüktürel bir elemandır. Bu çalışmada asansör alanındaki azalmadan kaynaklanan servis çekirdeğindeki küçülmenin etkileri araştırılmaktadır. Bunun için 300 metrelik (75 katlı) yatay perdeli çerçeve sisteme ve çerçeve-tüp sisteme sahip ofis binaları modellenmiştir. Ardından sisteme yanal perde veya kuşak eklenmesi, çevre kolonların sayısının, kesit alanının veya her ikisinin birden artırılması gibi modifikasyonlarla servis çekirdeği küçülen binaların rijitlik ve dayanım koşulları sağlanmıştır. Bu sayede servis çekirdeği küçülen modeller, standart çekirdeğe sahip modellerle rijitlik ve dayanım yönünden aynı strüktürel özelliklere sahip olmuştur. Son olarak standart ve servis çekirdeği küçülen ve modifiye edilmiş modeller, temel mimari kriterler olan kullanabilir alan, panoramik görüntünün kısıtlanması ve toplam kullanılan yapısal eleman miktarı gibi açılardan karşılaştırılmıştır. Elde edilen sonuçlarla, yüksek binalarda servis çekirdeğindeki küçülmenin mimari ve strüktürel açıdan artı ve eksi yönleri tartışılmıştır.

Anahtar Kelimeler: Yüksek Bina, Gökdelen, Servis Çekirdeği, Yüksek Binalarda Taşıyıcı Sistemler, Asansör Taban Alanı

To my beloved parents,

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Asst. Prof. Dr. Bekir Özer Ay for his kind guidance, great patience and encouragement throughout my thesis. He supported me selflessly to complete my study. I am very grateful for his advice and contributions to my thesis. Besides my advisors, I would like to thank the rest of my thesis committee for their comments and feedback to further development of research. Finally, I want to express my gratitude to my parents Emine Yücel and Osman Fakıoğlu and to my sister Buse Fakıoğlu for their moral support throughout my thesis.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

ACI	: American Concrete Institute
ASCE	: American Society of Civil Engineers
ASTM	: American Institute of Steel Construction
BIM	: Building Information Modelling
CES	: Concrete Encased Steel
CFT	: Concrete Filled Steel Tube
CIBSE	: Charted Institution of Building Services Engineers
CTBUH	: Council on Tall Buildings and Urban Habitat
DL	: Dead Load
EQx	: Earthquake Load Along X Direction
EQy	: Earthquake Load Along Y Direction
GFA	: Gross Floor Area
HVAC	: Heating, Ventilation and Air Conditioning
LL	: Live Load
NFA	: Net Floor Area
PEER	: Pacific Earthquake Engineering Research Centre
SD	: Super Dead Load
WL	: Wind Load

LIST OF SYMBOLS

SYMBOLS

H	: Building Height
R	: Response Modification Coefficient
ΔT	: Top Displacement

CHAPTER 1

INTRODUCTION

1.1 Background Information

Tall buildings are perceived as symbols of economic success in dense city areas. Demand for tall buildings still increases due to excessive population and rapid urbanization of metropolitan cities. Nevertheless, when compared to conventional buildings, tall buildings have less economic efficiency per square meter because less usable space is obtained in contrast to higher construction expenses (Özgen and Sev, 2009). As Kim and Elnimeiri (2004) states that in order to get maximum returns from the high cost of land, building space should be efficiently designed. Thus, efficient design of floor areas of tall buildings has greater significance than conventional building types.

The floor area of tall buildings can be classified into two different categories: net usable area according to purpose of the building and facilities and services area which is embodied in service core (Trabucco, 2008). Efficient design necessitates to minimize functional service area while meeting the service requirements, to obtain more leasable area in floor plans. The leasable floor area of a building depends on space efficiency which is net-to-gross floor area of a high-rise as Özgen and Sev (2009) defined. The first step to achieve efficiency can only be possible with a well-organized service core design.

Trabucco (2008) defined the service core as "an element that gathers the space necessary to provide visual, physical and functional vertical connections that work effectively to distribute services through the building". The functions of service core can be defined as a main network of utility services for building floors and contributing structural solidity of tall buildings. The elements of the service core are mainly toilets, HVAC installations, vertical transportation elements like elevators, escalators and stairs and sub-services. Elevator systems have remarkable importance among other service core elements. Fortune (1998), indicates that almost 30 percent of total floor space is occupied by elevator systems in a skyscraper with 100 floors (Auvinen, 2015). For this reason, greater attention should be directed to elevator systems among all other service core elements.

According to Mueller and Schoellkopf (2016), as the building height demand increases, the number of vertical transportation tools also increases which results in necessitating more elevators with more vertical hoist ways requiring extra footprint space. In order to optimize elevator footprint area, there are some specific methods for elevator arrangements in tall building design namely: zoning, sky lobby and call destination systems as Al-Sharif (2017) defines. Although these methods for elevator arrangements are broadly applicable, conventional elevator technologies still limits the height of the buildings (Brown, 2014).

By the progress of technological advancements, new elevator systems arise with less occupied footprint area compared to conventional ones while satisfying the same traffic needs of tall buildings. For instance, multi-car elevator systems are among the recent trends in elevator technologies which utilize multiple elevator cabins in one single shaft (Aoki, Markon, Nakagawa and Sudo, 2008). According to Liew, Lim, Tan and Tan (2015), the occupied space of elevators can be diminished by the installation of multiple elevator cabins in a same hoist way without increasing waiting times of elevator traffic. As a result, the main claim of the recently developed elevator technologies can be defined as to increase leasable floor area which is very valuable in tall buildings by reducing elevator footprint.

1.2 Argument

It can be inferred from the background information that, space efficiency in tall building design can be achieved with a rationalized service core as Özgen and Sev

(2009) states. Elevator systems are an inherent part of a service core so any change in elevator systems also transforms service core design. When the elevator footprint decreases, the service core area decreases too, and its structural walls are considerably influenced by this change. Structural walls of service core are exposed to dead loads, live loads and lateral loads and they contribute to structural stability of buildings. As a result, while the reduction of the service core area increases space efficiency of tall building design, the structural system of buildings is inevitably affected by that change. However, the amount of effects which stems from service core footprint decrease varies according to types of structural system of tall buildings.

1.3 Aim and Objectives

The aim of this research is to investigate how structural systems of tall buildings are going to be affected and evolved by the recent improvements of the elevator industry.

The objectives of this research are presented below:

- To understand the importance of service core according to different types of structural systems

- To comprehend the effects of new elevator systems on the structural system of tall buildings by producing and comparing generic computer models with current and new elevator systems

- To investigate structural, architectural and economic consequences with the application of new elevator systems

- To question exact space efficiency when the new elevator systems are used in tall buildings

1.4 Contribution

Service core is a distinctive element in tall building design, because of not only being the vertical service and transportation network of whole building but also being an inseparable part of the structural system. And since elevators are the most important vertical communication tools in tall buildings, technological improvements of elevator industry are going to shape the service core and the tall building design in near future.

As summarized in the literature review part, the amount of the contribution of service core to structural system of a tall building depends on the type of the structural system. By regarding this fact, any change in service core design resulted from the application of recently developed elevator technologies is going to affect tall buildings differently according to their structural systems. Although it was emphasized in the current literature that the improvements in elevator industry leads more efficiency in floor area of tall buildings, the relationship between the service core and the structural system of tall building is ignored. This research contributes to current literature by investigating how the reduction of footprint area of service core can shape the structural system and architectural space considering the relationship between the service core and the structural system of tall building.

1.5 Procedure and Disposition

This study comprises five chapters. In the first chapter, background information of the research, argument, aim and objectives and contribution to the current literature are presented.

The second chapter involves literature review on tall building typologies, structural systems of tall buildings and lateral loads that they are subjected to and elements, types and configurations of service core. At the end of this chapter, there is a critical review of the current literature.

The third chapter includes research materials and methodology. In materials section, the characteristics of generic building models are presented. In methodology section, a brief flowchart of the research methodology is defined in order to explain the two-step process of the methodology.

In the fourth chapter, the structural analysis results of the generic tall buildings are evaluated.

In the fifth or the last chapter, concluding remarks of the research is presented together with a brief summary of the research.

CHAPTER 2

LITERATURE REVIEW

2.1.Typological Parameters of Tall Building Design

Tall building design comprises many difficulties due to its complex necessities which can be handled with a multidisciplinary approach. Early design phase is very critical in tall building design process to interfere possible problems that can be occur in the next steps. In the conceptual design stage of tall buildings, the biggest responsibility belongs to architects. The decisions made in the early phase of design identifies the whole characteristic of a building.

There are some certain design parameters in the early design phase of tall buildings. Generic computer tall building models are built accordingly in this research. These parameters are, planning modulation, lease span, floor to floor heights and floor plate sizes.

2.1.1. Planning Modulation

In the early phase of tall building design, well-arranged floor plan organization enables more space efficiency for built projects. Organization of floor plans can be designed with utilization of planner modulation. Modulation is very critical in tall building design, since it constitutes a basis of dimensions and proportions for both architectural, structural and mechanical systems. Modular grid provides structural bays, curtain wall panels, ceiling grids and cellular subdivisions to exist in harmony. Marfella (2010) states that standard metric units are 1200 mm, 1350 mm, 1500 mm and 1800 mm which are currently used. Besides, he contributes that the 1500 mm module can be divided into 3m wide rooms for integration of structural bays of 6 m by 12 m and 1500 curtain wall panels, so it is exclusively profitable.

An exemplar planning modulation is illustrated in Figure 2.1 to indicate lease span measurements, structural bays on a repetitive floor plan (Katz and Kohn, 2002).

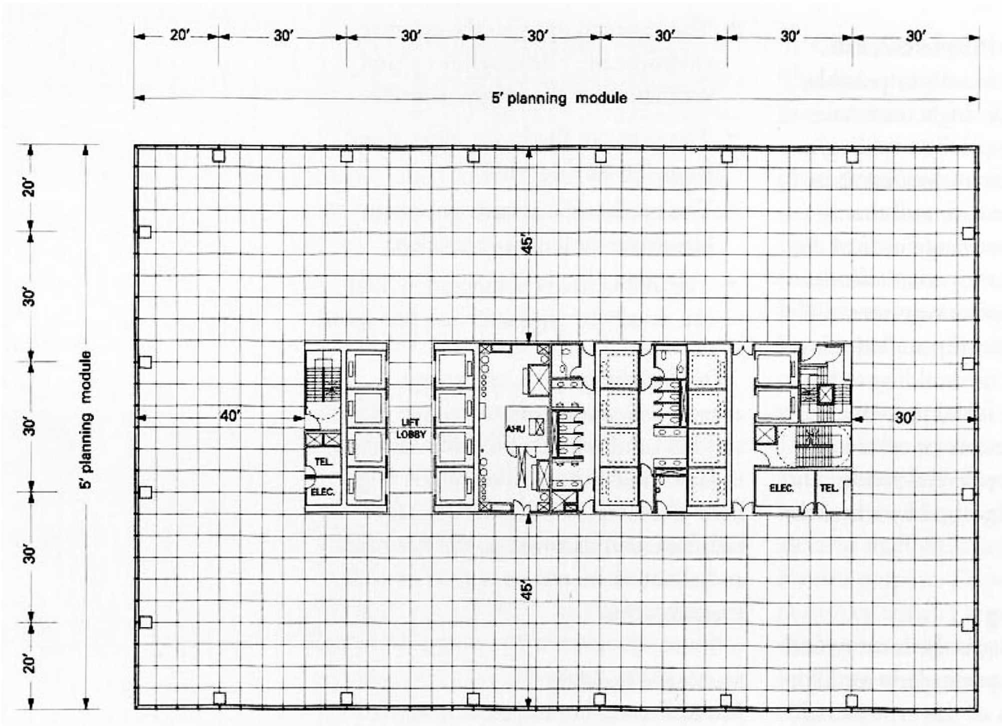


Figure 2.1. Planning modules illustrated on a repetitive floor (Kohn and Kanz, 2002)

2.1.2. Lease Span

Lease span or leasing depth is defined as the distance between the core and the exterior wall. It is assumed that increase of lease span also increases the floor plate efficiency (Chandwani, Agrawal and Gupta, 2012). However, there are multitude of constraints for maximum allowable lease span in terms of structural considerations, natural light penetration and fire escape distances. All these restrictions differ from one country to another (such as local climate, zoning regulations, cultural conditions, technological opportunities, and etc. as Özgen and Sev stated in 2009) and, there is no international standard for lease span. As an example, maximum leasing span in Germany is 8.0 meters according to the building codes while the lease span of Canary Wharf Tower in London is 11.0 m. The reason of this restriction in Germany is mostly based on allowing building users to benefit from the natural light (Özgen and Sev, 2009).

In addition, the functional use of a building also affects lease span dimensions. For commercial buildings, it is essential to obtain column free area within the lease span area for flexibility in office planning. On the other hand, for residential and hotel functions, lease span depends on the ratio of the room divisions.

In the Table 2.1, the lease spans of the ten tallest buildings according to year 2000 is presented and the leasing depth changes between 8.3 m and 23.9 m with an average depth of 12.1 m (Özgen and Sev, 2009).

Table 2.1. Leasing depths, floor-to-floor heights, floor-to-ceiling heights and structural floor materials from the world (Özgen and Sev, 2009

	Name of Building	**Leasing Depth (m)**	**Floor-to-floor height (m)**	**Floor-to-ceiling height (m)**	**Structural floor material**
WORLD	Taipei 101 T.	13.9 – 9.8	4.20	2.80	Composite
	Shanghai WFC	12.5	4.20	2.75	Composite
	Petronas T. 1-2	13.0 – 8.3	4.00	2.65	Composite
	Sears Tower	22.9	3.92	2.70	Composite
	Jin Mao Tower	14.8 – 11.8	4.00	2.79	Composite
	Two International Finance Center	14.5	4.00	2.70	Composite
	CITIC Plaza	11.3	3.90	2.70	Composite
	Shun Hing Square	12.5 – 12.0	3.75	2.65	Composite
	Central Plaza	13.5 – 9.4	3.90	2.60	Reinforced concrete
	Bank of China	17.6	4.0	2.80	Composite
	Average	**12.1**	**3.98**	**2.7**	

As a result, while there is no international standard for lease span, parties can reach an agreement on an optimum lease span dimension by considering all these structural, architectural and mechanical factors. According to Ho (2016), typical span between the core and the building perimeter ranges 9 meters to 15 meters.

2.1.3. Floor to floor heights

The space between two floors is composed of three layers: structural floor, all kinds of mechanical and lighting installations and the usable floor to ceiling space. Minimum thickness of a floor plate is mainly specified regards to structural considerations. In addition, there should be a delicate balance between creating an architecturally spacious space and leaving enough room for mechanical installations while deciding floor heights of a tall building. Baum (1994) indicated in his book "Quality and Property Performance" that the importance of the plan layout and ceiling height is superior than these three elements: services and finishes, external appearance and durability of materials.

Floor to floor height varies according to building functions. For example, for commercial buildings, the same height continues along the typical floors except the lobby and floors with special functions. Little changes in floor to floor heights in tall buildings causes tremendous changes in terms of the amount and the cost of structural elements, cladding materials, mechanical risers and vertical transportation systems (Özgen and Sev, 2009).

Although there are variations on tall building features according to needs of the clients or local impacts, for office buildings the fundamental design considerations are almost identical (Kohn and Katz, 2002; Strelitz, 2005). Council of Tall Buildings and Urban Habitat (CTBUH) developed a height calculator according to three main functional categories of tall buildings: office, residential/hotel and mixed-used or unknown functions (Table 2.2). The calculator gives an approximate idea for height of a single tall building based on a known number of stories. Because there can be variations of estimates due to different tall building features, the calculator works best for statistical studies. Özgen and Sev (2009), calculated the average building height as 3.98 (which ranges from 3.73 m to 4.20 m) of ten tallest office buildings of the world in year 2000 (Table 2.1). This average height is almost the same with CTBUH's height calculator.

Table 2.2. Floor to floor heights for tall buildings according to their functions (CTBUH Tall Building Height Calculator, n,d.)

Height Calculator Assumptions	Office	Residential/Hotel	Function Unknown or Mixed-Use[1]
Floor-to-floor height (*f*)	3.9m	3.1m	3.5m
Entrance lobby level floor-to-floor height	2.0*f* = 7.8m	1.5*f* = 4.65m	1.75*f* = 6.125m
Number of mechanical floors above ground, excluding those on the roof	*s*/20 = One mechanical floor every 20 stories	*s*/30 = One mechanical floor every 30 stories	*s*/25 = One mechanical floor every 25 stories
Height of mechanical floors	2.0*f* = 7.8m	1.5*f* = 4.65m	1.75*f* = 6.125m
Height of roof-level mechanical areas / parapets / screen walls[2]	2.0*f* = 7.8m	2.0*f* = 6.2m	2.0*f* = 7.0m
Key H = Building Height *f* = Typical occupied floor-to-floor height *s* = Total number of stories[3] Useable floors Entrance lobby Mechanical floors Roof	[1]Mixed-use assumptions derived from the average values between office and residential/hotel figures. [2]Figures do not assume spires or other major projections at the roof plane. [3]The number of stories should include the ground floor level and be the number of main floors above ground, including any significant mezzanine floors and major mechanical plant floors. Mechanical mezzanines or penthouses should not be included if they have a significantly smaller floor area than the major floors below. CTBUH floor counts may differ from published accounts, as it is common in some regions of the world for certain floor levels not to be included (for example, the level 4, 14, 24, etc in Hong Kong).		

2.1.4. Floor Plate Sizes / Efficiency

Since space efficiency is the fundamental goal of tall building design, the design process starts with clarifying the floor shape and total area of the floor. Space efficiency is defined by the ratio of leasable to gross floor area. It can be increased by maximizing the floor plate size while minimizing the service core size. However, there are some statutory constraints depending on local building codes and regulations. For instance, the ratio of a floor plate size to its site area can be restricted constitutionally (Ho, 2007).

There are two basic terms when considering the space efficiency: Gross Floor Area (GFA) and Net Floor Area (NFA). These terms are very important in order to get maximum returns from the high cost of land. Özgen and Sev states that the ratio of net to gross floor area of a typical floor is economically very critical for a developer because of the excessive number of floors of a tall building (2009). The importance of the efficiency of a typical floor of a tall building can be clearly understood if floor area efficiency of high-rises is compared to low-rises'. According to Langdon and Watts, typical floor area efficiency, which corresponds to NFA/GFA, is between 68%–75% for low-rises while it is between only 60%-70% for high-rises (2010).

Although there is a current trend of challenging the height limits of tall buildings, Kalita, Maclean and Watts (2007) indicate that as the building height increases the core and the structural elements also increases in order to resist increased lateral-loads and to meet vertical circulation requirements. It means that slender tall buildings have less floor space efficiency and more expensive to build. A building's slenderness ratio which is the ratio of a building's height to its smallest structural width has a major influence on its structural efficiency. In this sense, the slenderness ratio (height to least width) has a great impact on a tall building's structural and space efficiency (Ali and Kodmany, 2012). As the slenderness increases, the economics of the building is adversely affected.

Another factor which affects the floor plate sizes is the building function. When office and residential buildings are compared according to their floor plate sizes, there is a big difference. Watts and Langdon (2010), calculated the average floor plate sizes of office and residential tall buildings for UK. For office buildings floor plate sizes ranges from 1500 m^2 to 3000 m^2, while it is between 560 m^2 and 790 m^2 for residential buildings.

In 2000, the average space efficiency of top ten tallest office buildings is specified as 68.5%. The detailed information of net and gross floor areas and space efficiencies are indicated in Table 2.3.

Table 2.3. GFA, NFA and space efficiency of the ten tallest office buildings of the world (Özgen and Sev, 2009)

	Name of Building	GFA (m^2)	NFA (m^2)	Space Efficiency (%)
WORLD	Taipei 101 Tower	2650	1920	72
	Shanghai WFC	2500	1750	70
	Petronas T. 1-2	2150	1290	60
	Sears Tower	4900	3780	77
	Jin Mao Tower	2800	1940	69
	Two International Finance Center	2800	1904	68
	CITIC Plaza	2230	1500	67
	Shun Hing Square	2160	1450	67
	Central Plaza	2210	1460	66
	Bank of China	2704	1865	69
	Average			**68.5**

2.2. Structural Systems of Tall Buildings

Buildings are subjected to variety of loads and the main function of a structural system of a building is to carry all these loads and then to transmit them to the foundations. As the building height increases in conjunction with the increased loads affecting on a building, the structural system gets more complicated and a need for special structural systems arises (Khajehpour, 2001). There are so many complicated factors in the design and selection process of a structural system. Khajehpour (2001) defines these factors as vertical loads affecting on structural system, wind and earthquake forces depending on the geographical and climatic conditions of the site, local foundation characteristics and the cost of diverse construction systems.

2.2.1. Lateral Loads on Tall Buildings

When it comes to high-rise buildings, lateral loads are more decisive in the selection and design of the structural system than low-rise buildings because high-rises are subjected to excessive wind and in some cases earthquake loads. As the building height increases, the effect of the wind loads increases, and as the building weight increases, the effect of earthquake loads increases correspondingly. Both these lateral loads cause a considerable amount of lateral drift over the building. Therefore, there should be a limitation on lateral drift in order to provide occupant comfort. There are two main definitions in order to calculate these limitations namely, drift index and inter-story drift index. Drift index is the ratio of the maximum lateral top displacement of the building to the building height. Bennett (1995) and Taranath (1998) claims that drift index should be around 1/500. And inter-story index is the ratio of the lateral displacement of the floor relative to the floor below. According to Günel and Ilgın (2014), the commonly accepted drift index and inter-story drift index is between 1/400 to 1/500.

2.2.1.1. Wind Loads

As the height of the building increases, the wind speed and the wind pressure over the building increases parabolically (Günel and Ilgın, 2014). Especially flexible slender structural elements are subjected to two kinds of wind forces: along wind which is originated from buffeting effects of turbulence and across wind which is almost perpendicular to the wind flow and caused by vortex shedding. Both along and across wind gusts should be taken into account when considering wind-induced dynamic responses of buildings which are indicated in Figure 2.2. Besides, if a building is slender at both axes, across wind responses dominates the structural design more than along wind responses since it exceeds along wind accelerations (Aiswaria and Jisha, 2015).

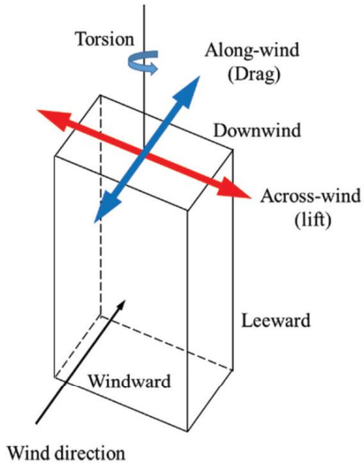


Figure 2.2. Illustration of along and across wind (Allsop, Sien, To and Zhang, 2017)

That leads the concerns of wind-induced dynamic response of the building. Thus, the sway of the building increases at higher floors of the building, which damages serviceability and occupant comfort.

At the upper floors of a tall building, wind induced dynamic responses increases. This leads to lateral drift and vibration of structure of the building which has an adverse effect on serviceability and occupant comfort. According to Günel and Ilgın (2014), specifically for buildings of more than 40 stories, or for buildings with an aspect ratio of 6 or higher, or for buildings having unusual forms dynamic calculation methods or wind tunnel tests should be used due to more effective dynamic building response to wind. Because different from dead or live loads, the speed and the direction of the wind can change quickly. In addition, all major structural design codes and standards worldwide which are applied by structural engineers to design wind loads on tall buildings, rely on the gust factor approach which is developed by Davenport (1967).

2.2.1.2. Earthquake Loads

Buildings are subjected to variety of earthquakes with different magnitudes and intensities during their life time. These are grouped as frequent small and moderate earthquakes, large ones which happens once or more and possibly a very severe one.

There are two main aspects of earthquake resistant design: properties of the structure (building massing, shape and proportion) and characteristics of earlier earthquakes of a region. The buildings with unsymmetrical plan are more vulnerable to earthquake damages than symmetrical ones. Thus, symmetrical arrangement of wall openings, columns and shear walls is very critical for earthquake resistant design.

Another factor that affects the earthquake resistant design is the characteristics of soil type of the site and the risk category of the structure. The types of the site classification according to ASCE 7-10 is demonstrated in Table A.1 in appendix. Risk category of the structures for wind and earthquake loads are also indicated in ASCE 7-10. Risk category is based on the use or occupancy of a structure and the types of risk categories are indicated in Table A.2 in Appendix.

In order to specify characteristics of earlier earthquakes, hazard maps are prepared. Hazard maps indicate expected shaking at a given region and examines the earthquake history of the region to estimate probability of an earthquake, peak acceleration, the frequency of shaking and the distance from the fault and site conditions (Aly, 2014).

2.2.1.3. Wind Versus Earthquake

The structural design principles against wind and earthquake loads are fundamentally different because the wind forces are consistent and affects a portion of a surface area while during earthquakes random motion of the ground affects the building from its base (Aly, 2014). In addition, earthquake loads are more intense and have shorter durations when compared to wind loads (Guha and Rajmani, 2015).

According to the regional conditions, either earthquake or wind loads dominates the characteristics of the structural design. For wind dominant design the rigidity of the structure is more important while for earthquake dominant design ductility of the structure is the main concern.

2.2.2. Classification of Structural Systems of Tall Buildings

Tall buildings require more complicated structural systems than low rises due to the excessive wind and earthquake induced lateral loads which they are subjected to. Therefore, special structural systems for tall buildings which can be envisioned as "vertical cantilever beams", are developed in progress of time (Günel and Ilgın, 2014).

The first systematic classification of tall buildings is made by Fazlur Khan which is indicated in the diagram of "Heights for Structural Systems" in 1969. This was a revolutionary breakthrough which initiates a new era in tall buildings regards to multiple structural systems. Khan developed a holistic approach towards tall building structures. In 1972 and 1973, he made some modifications on these diagrams both for steel and concrete buildings as shown in Figure 2.3 (Ali and Moon, 2007).

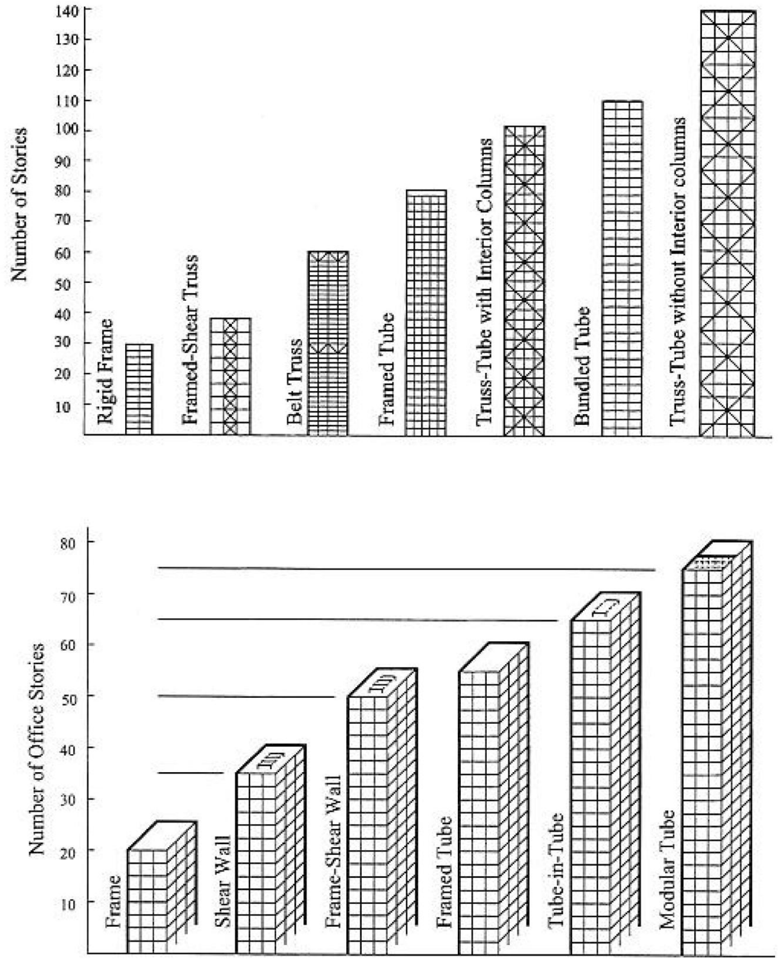


Figure 2.3. Classification of tall buildings structural systems by Fazlur Khan, above: steel and below: concrete (Ali and Moon, 2007)

In conjunction with the rise of new developments in structural systems of tall buildings, a new proposal for classification of tall building structural systems are generated by Ali and Moon in 2007. They proposed two main categories based on the distribution of primary structural elements resisting to lateral loads. These are namely interior and exterior structures. If majority of the structural elements take place within the interior building part, the system is categorized as interior structure. On the other hand, if major part of the structural elements is located at the perimeter of the building, the system is defined as exterior structure. However, all the components of a structural system are subjected to some portion of lateral loads, either it is interior or exterior structural system (Ali and Moon, 2007). In addition, Ali and Moon separated the interior and exterior structural systems into sub-categories. These sub-categories are demonstrated in Figure 2.4 and 2.5.

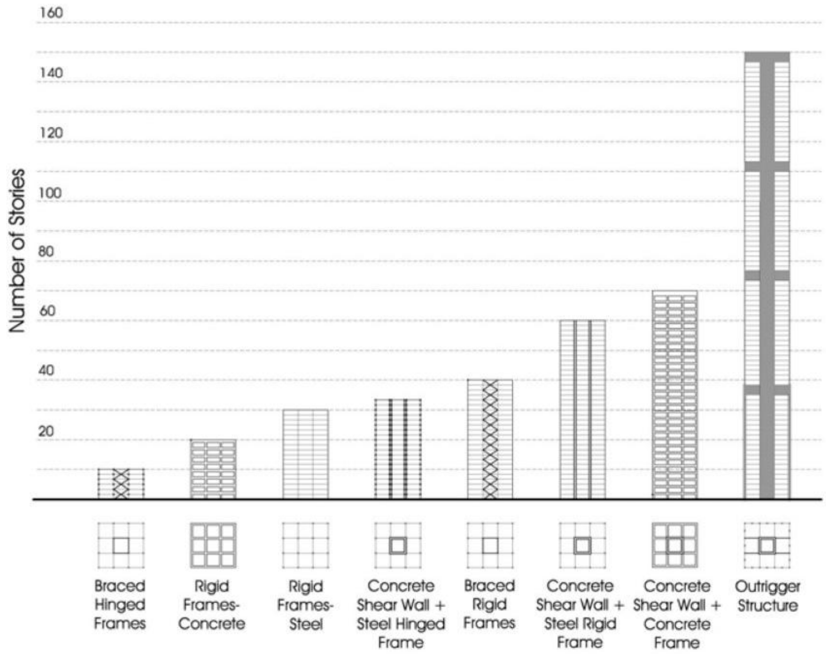


Figure 2.4. Interior Structures (Ali and Moon, 2007)

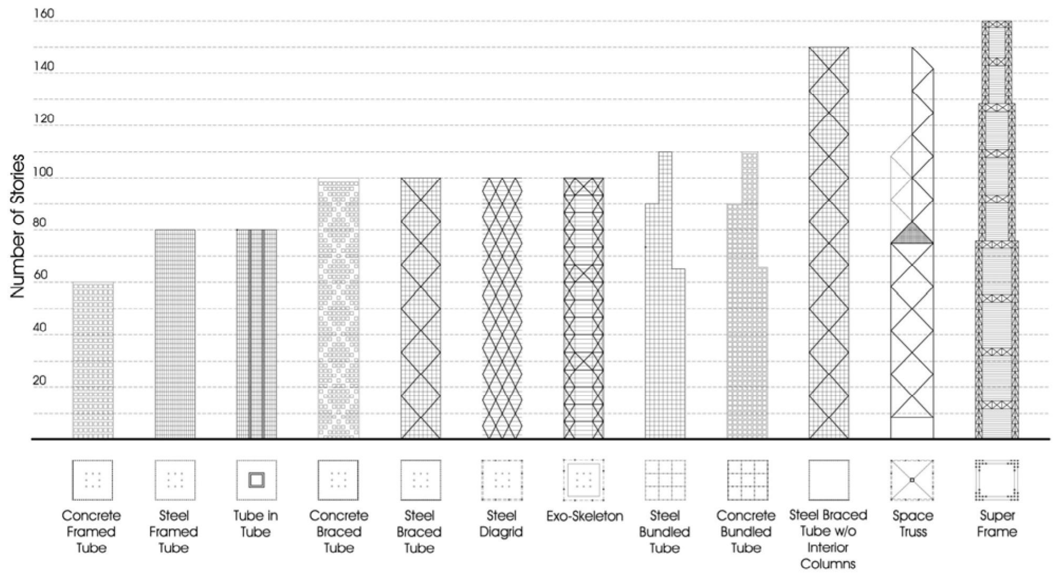


Figure 2.5. Exterior Structures (Ali and Moon, 2007)

All in all, lots of classification system proposals are discussed in literature and in practice: Khan, 1969; Khan, 1973; Schueller, 1977; Smith and Coull, 1991; Taranath, 1998 (Günel and Ilgın, 2014). Another up-to-date classification is prepared by Günel and Ilgın (2014), according to the behavior of tall buildings structures under lateral loads as indicated below:

- rigid frame systems
- flat plate/slab systems
- core systems
- shear wall systems
- shear-frame systems
    - shear trussed frame (braced frame) systems
    - shear walled frame systems
- mega column (mega frame, space truss) systems
- mega core systems
- outriggered frame systems
- tube systems

- framed-tube systems
- trussed-tube systems
- bundled-tube systems

As the height of tall buildings increases, the number of convenient types of structural systems decreases in order to satisfy structural safety and occupant comfort caused by lateral drift. Rigid frame systems, flat plate/slab systems, core systems and shear wall systems are preferable for buildings with 40 stories and below. For buildings over 40 stories previous systems are not feasible. Therefore, they utilize shear-frame systems, mega column systems, mega core systems, outriggered frame systems and tube systems which is indicated in Table 2.4 (Günel and Ilgın, 2014).

Table 2.4. Tall building structural systems and number of floors they can reach (Günel and Ilgın, 2014)

Tall building structural systems, and tentatively the number of floors they can reach efficiently and economically	*10*	*20*	*30*	*40*	*>40*
Rigid frame systems	■	■	■		
Flat plate/slab systems with columns and/or shear walls	■	■	■		
Core systems	■	■			
Shear wall systems	■	■	■	■	
Shear-frame systems (shear trussed / braced frame and shear walled frame systems)	■	■	■	■	■
Mega column (mega frame, space truss) systems	■	■	■	■	■
Mega core systems	■	■	■	■	■
Outriggered frame systems	■	■	■	■	■
Tube systems	■	■	■	■	■

In the scope of this research, only outriggered frame system and framed-tube system are investigated as an example sequentially to interior and exterior structures.

2.2.2.1. Outriggered Frame Systems

Outriggers are steel braces or concrete structural walls which connects the core of the building to the perimeter columns. The concept of the utilization of outriggers is stiffening the structural system as whole by combining the perimeter columns with the structural core (Ho, 2016).

Efficiency of outriggered frame systems can be increased with the use of belt trusses. Belt trusses, connects the perimeter columns to each other in order to equalize axial column loads. They can be conceptualized as very stiff beams that are having the same depth with outriggers. In addition to conventional outrigger systems, belt trusses are also used in virtual outrigger systems (Günel and Ilgın).

In virtual outrigger systems, there is no element to connect perimeter columns to the core rather than stiff floor slabs. The advantage of this system is the elimination of complex construction and core connections of the outrigger and belt trusses and thus being more economical (Sitapara and Gore, 2016).

The number and the location of outriggers changes the amount of bending moments of the structural core. In Figure 2.6, core moments of the three structural systems are compared to each other (a: no outrigger, b: one outrigger at the top, c: one outrigger at the top and one outrigger in the middle). Version "a", the core acts like a cantilever from its base and the top of the structure rotates freely. Version "b", demonstrates that when the core is connected to the perimeter columns with a hinge connection (no transfer of bending moments of the core to the perimeter columns) at the top of the building. Thus, the base bending moment of this system is less than the structural system illustrated in version a. By adding one more level of outriggers to the system as indicated in Figure 2.6,"c" the strength and stiffness of the system increase and the bending moments at the base level decrease (Bayati, Mahdikhani and Rahaei, 2008).

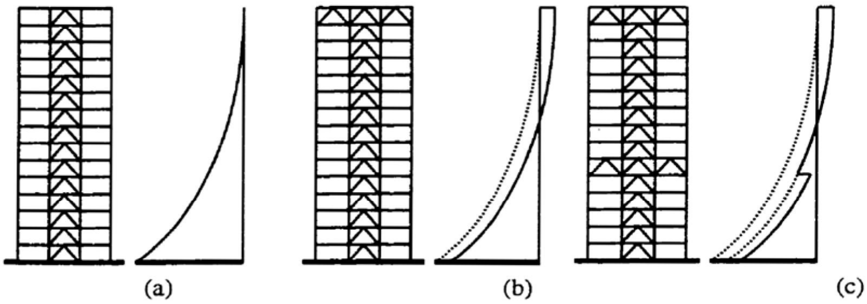


Figure 2.6. The effect of outriggers on core moment (Bayati, Mahdikhani and Rahaei, 2008)

Optimum Location of Outriggers

In order to give an idea at preliminary design stage of tall buildings, there are many researches in the literature to estimate the optimum location of outriggers in a structural system. A priori research is made by Smith and Coull (1991), by considering hypothetical structures with use of outriggers with flexural rigidity. They formulated their findings for optimum location of outriggers as a structure with number of "n" outriggers, the placement of outriggers should be at the 1/(n+1), 2/(n+1), up to the n/(n+1) height locations (Bayati, Mahdikhani and Rahaei, 2008). In addition, with each outrigger addition to the structural system, base moments of the core decreases. However, the amount of the decrease is not linear. According to Smith and Coull (1991), for one outrigger, two outriggers, three outriggers and four outriggers, respectively the bending moments of the core is approximately 58%, 70%, 77% and 81%.

Another research is conducted by Günel and Ilgın (2014) to specify optimum outrigger locations. This research is based on the decrease of maximum lateral top drift. Three cases are illustrated in Figure 2.7, "a" as one outrigger at optimum location, "b" as one outrigger at the top, another at optimum location and "c" as two outriggers at their optimum locations. "L" symbolizes the building height and "x, x_1 and x_2" symbolizes distances of the outriggers from the top point of the structure. When considering optimum locations: for case "a", x=0.455 L, for case "b", x=0.5774 L and for case "c", x_1=0.31 L and x_2=0.69 L.

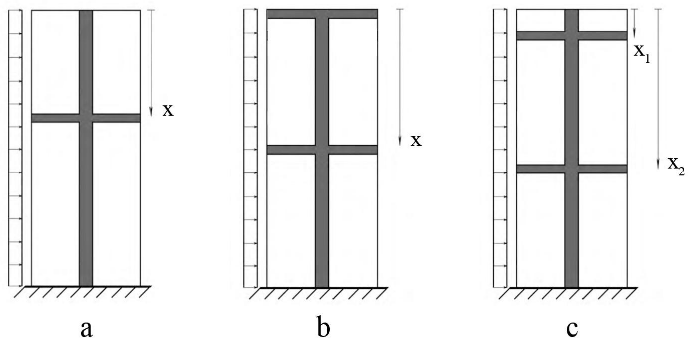


Figure 2.7. Location of outriggers (Günel and Ilgın, 2014)

As Günel and Ilgın (2014) state, if the outriggers are placed at their optimum locations, the lateral top drift at the top of the structure decreases as:

- 88% for case "a",
- 92% for case "b",
- 96% for case "c".

With its 492 meters architectural height, Shanghai World Trade Centre is an example to outriggered frame systems. It was completed in 2008 as a mixed-use building with office and hotel functions. In Figure 2.8, the tower and the outriggers of the structure is illustrated.

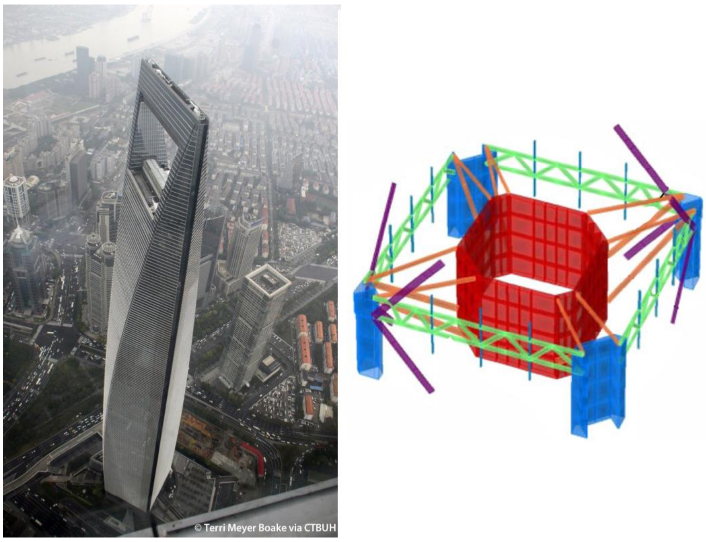


Figure 2.8. Shanghai Tower (Boake, "Shanghai World Financial Center") and its structural system (Lu, Zou, Lu and Zhao, 2007)

2.2.2.2. Tube Systems

Fazlur Rahman Khan who is commemorated as the founder of most of the innovations in structural systems of tall buildings, is also the inventor of the tube system (Günel and Ilgın, 2014). He understood the boundaries of imagining a tall building as a tube with solid walls. Since it is inevitable creating openings for windows, he comprehended that with the application for openings for windows, the structural system can be still efficient. Then, he transformed this conceptual system to an erectable and applicable system: the tube system (Sarkisian, 2012). In Figure 2.9, the evolution of this idealistic concept to tube systems is illustrated.

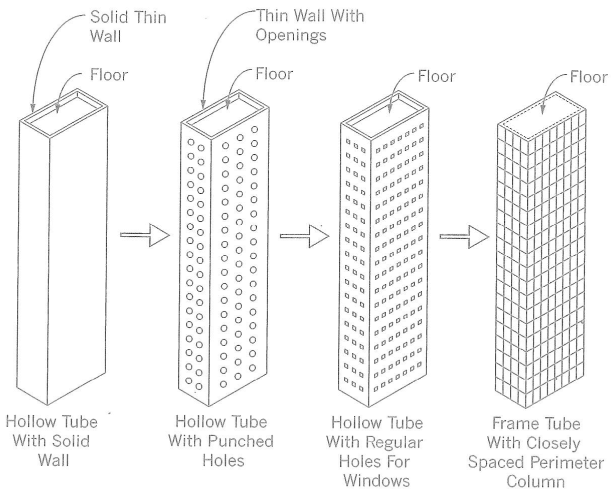


Figure 2.9. Dr. Fazlur Khan's conceptual tube systems (Sarkisian, 2012)

Buildings with tube systems act like a three-dimensional hollow box, cantilevered from the ground as Varghese and Vikram (2015). There are some methods defined by Günel and Ilgın (2014) in order to increase rigidity of the structural systems against lateral loads as:

• increasing the number of columns by reducing the spaces in between
• increasing the spandrel beam depth which connects the perimeter columns
• strengthening the structural core by adding shear walls or braces
• an inner tube addition to the system (tube-in-tube)
• adding braces to the exterior facade of the building (trussed-tube)
• combination of multiple tube structures in one building (bundled-tube)

The first application of tube systems is in 1966 with the 120 meters high The Plaza on Dewitt building in Chicago as "framed-tube system". With the intent of increasing structural efficiency, new developments are introduced in tube systems. These developments evolved with new architectural forms into new branches in tube systems namely, "braced tube systems" and "bundled tube systems" (Sev and Tuğrul, 2014).

Framed-tube Systems

Framed-tube systems are composed of closely spaced perimeter columns (approximately 1.5 to 4.5 meters) tied to each other with deep spandrel beams. As the building height increases, the deeper cross-sectionals for columns and beams becomes necessary to resist bending moments (Sarkisian, 2012). However, this results in obstructing the panoramic exterior view from inside the building (Günel and Ilgın, 2014).

First Canadian Place (in Figure 2.10) is constructed in 1975 as a 298.1 meters high office building as stated in the database of The Skyscraper Center (www.skyscrapercenter.com). The structural system of the tower is framed-tube according to the database of Emporis (www.emporis.com).

Figure 2.10. First Canadian Place (Bregman+Hamann Architects, n.d.)

2.3. Service Core in Tall Building Design

Service core design is a fundamental element in tall building design. It is defined as "An element that gathers the space necessary to provide visual, physical and functional vertical connections that work effectively to distribute services through the building" by Trabucco in 2008. Because of its importance, planning of the service core starts at the very early stages of the design process. According to Ali and Armstrong (2008), the service core is a specific feature of a tall building and for success and sustainability of the whole structure, it should be designed carefully. Functions of the service core is classified by Trabucco in 2008 as three main headings:

1- Services: the main servant facilities of the building necessary to its existence and operation, such as elevators, their shafts and corridors, egress stairs and secure spaces, machine and electrical/ communication rooms, toilets and storage rooms.
2- Subservices: vertical risers, ducts, pipes and chutes, whose sub servant role derives from being necessary to the operation of the main services. They are generally placed in the residual areas left free by the design of the main utilities.
3- Core: the structural shell that often encircles the services. The core exists when the structural scheme of the building requires shear walls/trusses or moment-resisting frames to withstand the horizontal forces; otherwise, it is omitted.

2.3.1. Types and Configurations of Service Core

There have been many classifications of service core configurations which are available in the literature. Some of them are discussed by Yeang, in 1996 and 2000; Kohn and Katz, 2002; Trabucco, in 2008 and in 2010; Grondzik, Kwok, Stein and Reynolds in 2010; Ali and Al-Kodmany in 2012 (Ali and Al-Kodmany, 2013). Grondzik et.al. (2010) defined six alternative configurations of service core in "Mechanical and Electrical Equipment for Tall Buildings" as:

• edge core
• detached core
• central core
• two cores
• corner cores
• random cores

Selection of the suitable service core configuration depends on many factors as, function of the building, building users and building codes and legislations (Yeang, 2000). The detailed comparison of these six alternatives are indicated in Figure 2.11.

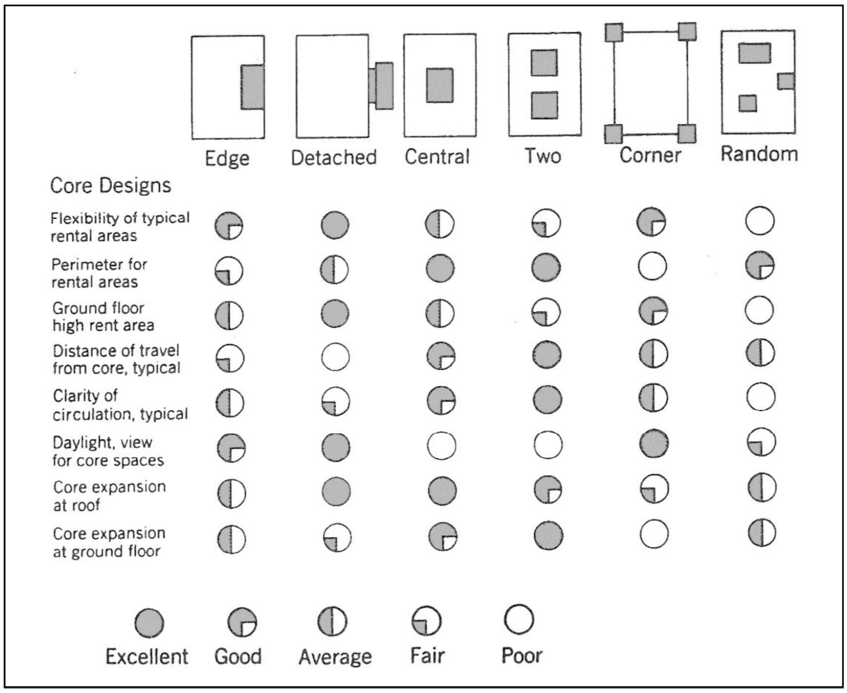


Figure 2.11. Service core configurations and their comparison (Grondzik et.al., 2010)

Central core is the most commonly used configuration type among structural systems of tall buildings. Especially for the interior structural systems, central core application is more suitable due to its contribution to resist lateral loads. By placing the structural service core at the center of the building, the torsional deformation can be prevented. In architectural point of view, the central core facilitates the subdivision of floor plans according to different functions with a minimum circulation area when compared to other core arrangements. With minimum distances to reach service core from any locations in floor plans, it is easy to access fire escapes. The central core configuration is also advantageous in terms of easiness of distribution of mechanical services since the leasable span is almost equal around the core. However, the central core requires an access corridor in its perimeter (Figure 2.12).

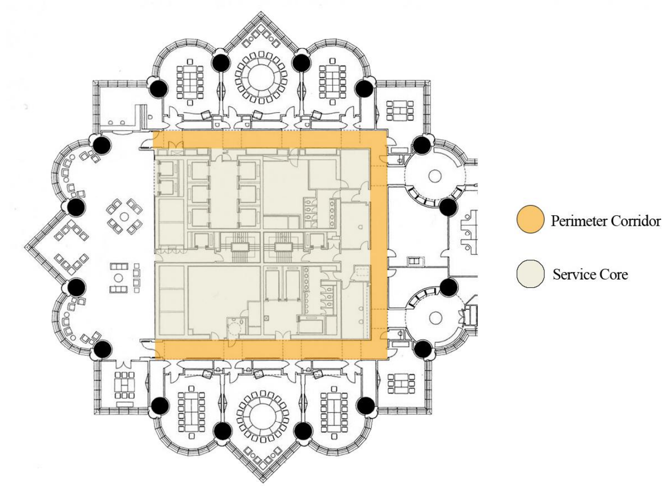


Figure 2.12. Petronas Tower 40th floor plan (Pelli and Crosbi, 2001)

Two cores and random cores are generally used when there is variety in tenant sizes and accommodations with the division of the central core. By dividing the central core, the central area is utilized as a wide circulation corridor which results in the elimination of peripheral corridors around the core. This increases the efficiency of functional floor space by providing larger functional floor spaces. The number and form of the divisions depend on individual needs of the building. Bank of China

(Figure 2.13), is an example to two cores configuration with its service core arrangement besides being an example to non-structural service core.

Figure 2.13. Bank of China, floor plan (Blake, 1991)

Edge core configurations can be applied to floor plans considering the site conditions, floor plate sizes and sustainability issues. This type of configuration is mostly preferred in smaller site areas which requires smaller floor plates in case of central core configuration is not applicable due to inadequate floor space around the service core. The sustainability criterias can be assessed with accessibility of service core to daylight and natural ventilation in edge core. Besides, edge core can be located according to the hottest side of the facade to be used as a thermal buffer. In Figure 2.14, Menara Mesiniaga building is illustrated as an example to edge core configuration.

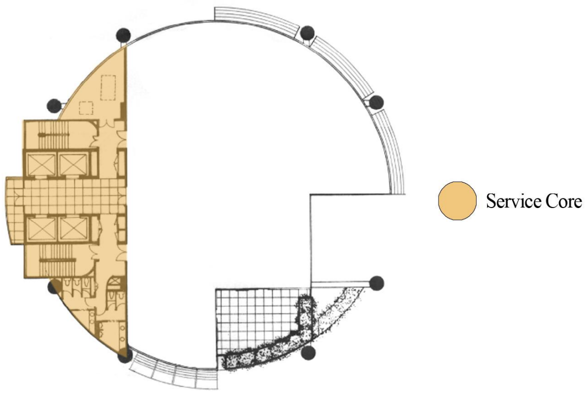


Figure 2.14. Menara Mesiniaga, floor plan (Hamzah & Yeang, 2015)

Detached core is separated from the building and it can be reached by sky bridges. Since it is isolated from the building, the structural system of the service core should be independently designed in order to resist vertical and lateral loads which it is subjected to. While it is advantageous in terms of energy efficiency considerations of the building as in the edge core configuration, because of the long distances to reach service core from the opposite side of the building in case of emergency situations, it is disadvantageous. Besides, the cladding expenses increase due to larger surface area resulted from the separation of the service core. In Leadenhall Building, the service core is separated from the building as illustrated in Figure 2.15.

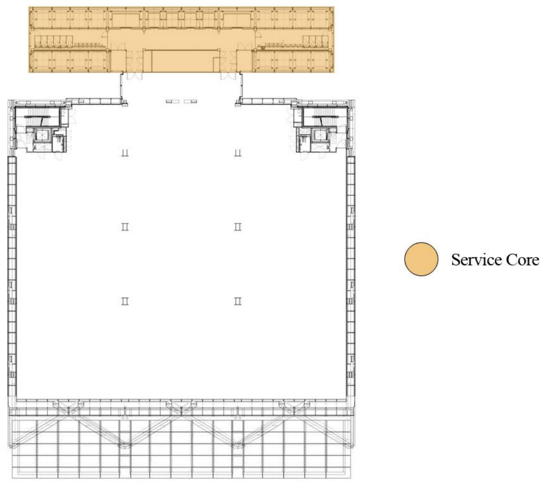


Figure 2.15. Leadenhall Building, floor plan (Roger & Stirk, 2014)

Corner cores are generally used when a single core is insufficient for large floor plates. The number of cores can change according to occupants' needs. The circulation area is larger than central core configuration but there are multiple options for escape routes in case of emergency. In addition, as the number of service core increases, the design and distribution of mechanical services are getting more complex. With its three corners service core configuration, Commerzbank Tower is a good example to corner core configurations (Figure 2.16).

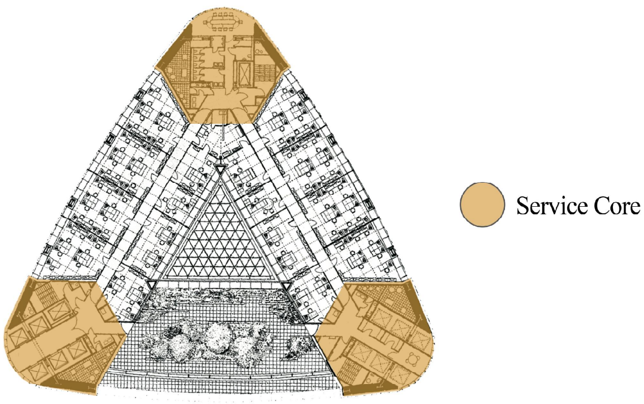


Figure 2.16. Commerzbank Tower, floor plan (Foster+Partners, 1997)

2.3.2. Functional Elements of Service Core

The service core arrangement should be completed in preliminary design stage of the building. Architect is the first person who decides the core configuration. Nonetheless, since the service core is multi-functional, the optimization of the core should be resolved with experts of related disciplines (Yeang, 2000).

Yeang (2000) indicates that the whole list of elements which a service core contains are:

• elevator shafts and lobby
• main staircases and fire escape staircases
• fire-protected lobbies
• toilets
• mechanical installations (both for riser-ducts and for fire protection risers)
• electrical installations (risers for power, telecommunication and data systems)
• mechanical and electrical services plant rooms
• ancillary rooms
• structural walls

2.3.3. Vertical Communication Systems

As the building height increases, large number of elevators are necessary which results in the decrease of NFA/GFA as the indication of floor area efficiency (Trabucco, 2008). Therefore, optimization of vertical communication systems is a key point in tall building design. There are lots of methods for the efficient arrangement of elevators both in the literature and in the practice. Besides, new technologies in elevator systems continue to develop by aiming the minimization of footprint area of elevator shafts in order to provide more leasable area which is very valuable in tall buildings.

The following sections respectively presents elevator arrangement strategies and elevator types with current technological advances.

2.3.3.1. Elevator Arrangement Strategies

At the beginning of selection and design of elevator systems, objectives should be clearly determined. Parker and Wood (2013) defines the goals of vertical traffic design as; effective circulation, minimum cost, life safety, security and energy efficiency. In order to achieve these objectives, the number, speed and capacity of the lifts required should be carefully selected. Besides, the most suitable arrangement in terms of zoning, group control algorithm and the use of special elevator technologies should be identified (Al-Sharif and Seeley, 2010).

One of the main factors which enormously affects the elevator system design is the functional use of a building. For office building, there are two main daily users as employees and visitors. Since the working hours is generally fixed in office buildings, these rush hours lead to an enormous elevator traffic need (Loon, 2004). As indicated in Table 2.5, the amount of population, traffic conditions in terms of rush hours and the need for quality and quantity of services changes according to functional use of buildings. The handling capacity which is indicated in quantity of services part is defined as; "the percentage of the population on the floors served by the elevator group that is transported on average within 5 minutes" by Schindler, elevator brand.

Table 2.5. Example of design factors according to building type (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

In Table 2.6, the estimated population amounts are indicated depending on the functional use of building types. When both tables are considered, it could be concluded that the demand for vertical communication elements are maximum in office buildings.

Table 2.6. Estimated populations according to building functions (CIBSE Guide D, 2016)

Building type	**Estimated population**
Hotel	1.5-1.9 persons/room
Flats	1.5-1.9 persons/bedroom
Hospital	3.0 persons/bedspace*
School	0.8-1.2 m^2 net area/pupil
Office (multiple tenancy): - Regular - Prestige	 10-12 m^2 net area/person 15-18 m^2 net area/person
Office (single tenancy): - Regular - Prestige	 8-10 m^2 net area/person 12-20 m^2 net area/person

* excluding patient

The terms of zone, stack and transfer floors in elevator arrangement strategies are defined by Al-Sharif (2017) while before him there was no clear definition in literature.

Zone is a group of contiguous floors which are served specially by a number of elevators.

Stack is a contiguous group of floors but served by a sky lobby and away from the main lobby of the building. A stack can include multiple zones.

Transfer floors allow passengers to move between different zones without the need to travel to the main lobby. Transfer floors are shared by both users of two adjacent floors.

Elevator zoning is a widely used system for very tall buildings. The aim of zoning is to reduce footprint of the total elevator shaft area by stacking elevator shafts on top of each other and each group of elevators serves to their own zones. These zones are connected to each other by sky lobbies and transfer floors.

According to Al-Sharif (2017), as a rule of thumb, the number of floors in a single zone should not exceed 18 to 20 floors. Furthermore, for buildings with more than 50 to 60 floors utilizes sky lobbies for efficient elevator traffic design. Sky lobby is an interchange floor which are served by shuttle elevators. They are mostly preferable in mixed use building types. Barney (2002), defined shuttle elevators as specialized large and fast elevators which are generally used only to serve sky lobbies without stopping at interval floors.

2.3.3.2. Developments in Elevator Technologies

Gerstenmeyer and Jetter (2015) identified the elevator systems mainly based on the number of elevator cars as single car elevators, paternosters, double-deck elevators and multi-car elevators.

Single car elevator is the most commonly used elevator type. It is an inefficient vertical transportation tool since a long single elevator shaft is used only for one elevator car. They are composed of a hoisting machine, a car, a counterweight, and a rope that connects other parts.

The paternoster elevator is the world's first multicar elevator having a constant motion along a circular track in two parallel hoist ways (Caporale and Strakosch, 2010). One hoist way is dedicated for upward and the other for downward transportation. The travel speed is slow because of the constant motion of the elevator cars. Even if the idea of continuous circulation of elevator cars is appealing for high transportation capacity with no waiting time, many countries prohibited the use of paternosters due to the system's being dangerous as understood from experiences (Markon, Kita, Kise, and Bartz-Beielstein, 2010).

Double deck elevators are composed of a lifting device with two cars attached together in a single hoist way. The disadvantages of double-deck elevators are the challenges in passenger flow and a weak power efficiency. The reason of the weak power efficiency is that the entire double-deck car has to be transported even in situations where only a small amount of conveying capacity is required (Tschuppert, 2013).

The multi car elevator concepts are the most recent elevator technologies which can be classified mainly as roped and self-propelled elevator systems (Caporale and Strakosch, 2010). The elevator systems had been benefited from ropes for a very long time. However, due to some limitations of the roped elevator systems in tall buildings, new rope-less elevator systems also started to be popular. Ali and Al-Kodmany (2012) state that almost 70% of the elevator's weight is loaded to the cable itself and if the rope gets too long it cannot support its own weight in very tall buildings. On the other hand, as Strakosch and Caporale (2010) indicates that the conventional rope materials limit the maximum travel height to about 500 meters. In 1999, Koseki and Miyatake claimed that rope-less lifts will be necessary for future skyscrapers whose height will exceed 800 meters, due to limited handling capacity of roped elevator systems.

Because of the limitations of roped elevator systems, recent technologies are mainly focused on rope-less elevator systems. The advantages of the rope-less lifts are the ability to operate multiple elevator cars in a single hoist way and transferability between shafts (Koseki and Miyatake, 1999). These advantages paved the way for most recent multi car elevator technologies which enables considerable amount of the elevator footprint decrease. The development of multi-car elevator systems is very new by considering the first multicar elevator which is known as twin elevator was built by ThyssenKrupp Group in 2002 (Liew et. al., 2015). Twin elevators run with two cars independently within one shaft. Mueller (2016) state that the number of elevator shafts reduce by up to 30% by the utilization of twin elevators.

Elevator firms produced many innovative elevator systems by utilizing multi-car elevator design concept. One of the latest technologies of vertical transportation is MULTI by ThyssenKrupp. This elevator system had received gold medal in Edison Awards in 2017 which is a prominent prize rewarding the most innovative technologies in engineering around the world. Gerstenmeyer and Jetter (2015) states that MULTI represents a landmark revolution in the elevator industry which is a new system operating multiple cabins in the same shaft moving both vertically and horizontally by allowing buildings to adopt various heights, shapes and purposes. It utilizes transrapid technology and it was unveiled in 2014 (Gerstenmeyer and Jetter, 2015). It is also claimed by Mueller that MULTI can reduce the elevator footprint up to 50 percent (2016). In Figure 2.17, elevator shaft footprints of double decks and multi elevator systems are compared based on a real project. In that graphic, it is understood that both local and shuttle elevators are more efficient in terms of space occupation when they are compared to local and shuttle double deck elevators.

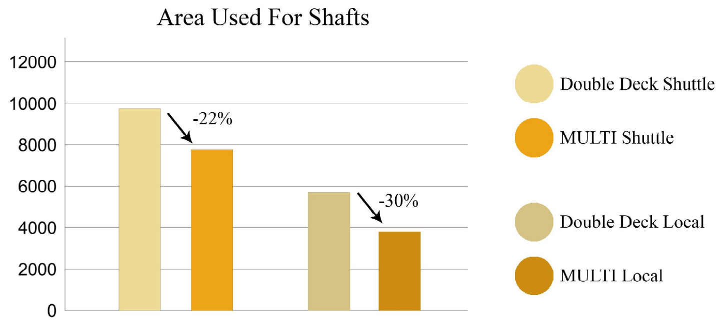


Figure 2.17. Footprint comparison: double deck and multi on a real project (Schoellkopf and Mueller, 2016)

Gerstenmeyer and Jetter (2015) also compared the efficiency of double deck elevators with multi car elevators depending on travel height according to some aspects such as handling capacities and number of cabins as in Figure 2.18. In this research, comparisons are based on four different travel times (100m, 200m, 300m and 400m). As it is shown in the first graphic, the handling capacity of multicar elevators are constant independent from travel height. Choi (2000), states that the certain number of elevators is specified according to population density and the handling capacity during the peak periods. Furthermore, the number of cabins per an elevator shaft can increase for multi car elevators if the travel height increases unlike double decks as indicated in the second graphic. It is inferred from this study that, multi car elevator systems provide not only better space efficiency but also better values in terms of destination time.

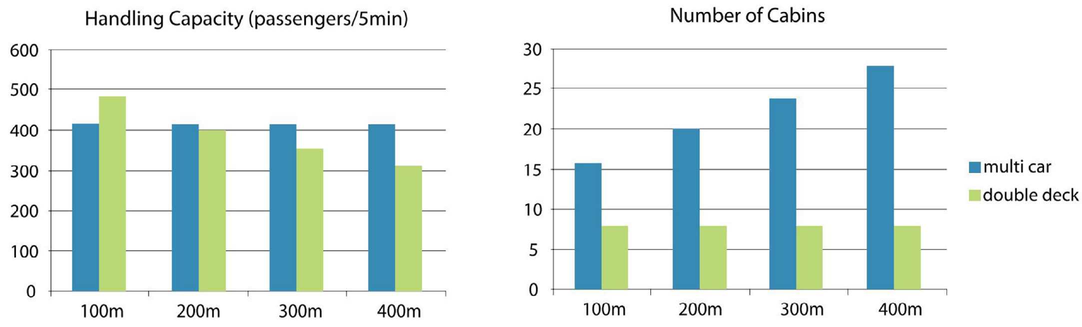


Figure 2.18. Comparison of multicar vs. double deck in terms of travel height: handling capacity and number of cabins (Gerstenmeyer and Jetter, 2015)

As the building height increases, multi car elevator systems enable more efficiency. Especially for mega tall buildings which are defined as the buildings higher than 600 meters, excessive number of elevators are necessary. That leads to a tremendous increase in elevator shafts with mostly unused and inefficient space. According to Mueller (2016), “MULTI” is ideal in one loop for 600 meters driveway or 300 meters height, yet without a height limitation.

In office buildings, elevator capacity varies during the day since people arrive to the building about at the same time. Thus, multi car elevators are ideal for tall office buildings. Many multi-car elevator concepts are adaptable to the necessities of rush-hour transportation flow as it is indicated previously (Loon, 2004).

2.4. Critical Review of the Literature

The primary aim of tall building design is obtaining maximum leasable area by optimizing service areas and structural systems as mentioned before. When the current literature is examined, there are lots of methods are being developed to minimize service areas and structural systems while meeting the mechanical and structural needs of the building. The optimization process contains every element of service core which are defined in the current literature. Elevators are particularly important especially in tall building design and thus, new technologies and innovations in elevator systems continue to develop. One of the main goals of these new systems is to minimizing elevator footprint in order to increase net usable area. Besides unlike conventional elevators, by the utilization of the developing elevator systems, the need for transfer floors and sky lobbies can be eliminated for very tall buildings. In the current literature, above mentioned advantages of new elevator systems in terms of space efficiency are summarized. It is also claimed that with the application of these new elevator technologies, the service core gets smaller based on the reduction of elevator footprint that leads to increase in net usable area as indicated in Figure 2.19. In the schematic illustration, “primary core” represents a generic building with conventional elevators and “reduced core” represents the previous building with the new core which is reduced by the utilization of the new elevator system (Figure 2.19).

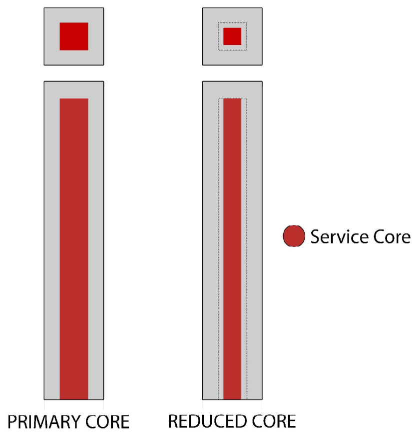


Figure 2.19. The reduction of the service core with the application of new elevator systems

The current literature disregarded even if it is claimed that the net usable area will increase with the reduction of the core area in tall buildings, the fact is that the service core is also backbone of a building for structural strength (Trabucco, 2008). When the service core area decreases due to the application of recently developed elevator technologies, it will affect the whole structural system accordingly architectural features of a building. It could be inferred that the amount of contribution of service core to total structural system in order to resist lateral loads of the building depends on the type of structural system which is discussed in the literature currently. When the service core gets smaller, it is explicit that the extra structural support is necessary for the building in order to resist vertical and lateral loads. There are two strategies in order to strength the existing structure as, increasing the dimensions of the present structural elements or adding new structural elements. While applying these strategies, the factors which is explained in detail in "typological parameters of tall buildings" section are taken into consideration. The aim of this research is to investigate the structural and the architectural effects of the reduction of the service core caused by the application of new elevator systems regards to different structural typologies of tall buildings.

CHAPTER 3

RESEARCH MATERIAL AND METHODOLOGY

The aim of this study is to investigate the effects of the potential reduction of service core on structural and architectural features of tall buildings. In order to achieve this aim, various hypothetical computer models are produced and potential lateral loads are applied to those buildings by the utilization of "ETABS" structural analysis software. In the determination procedure of characteristics and basic structural components of generic tall buildings, actual tall building cases are investigated.

The effects of the service core reduction on tall buildings differentiate according to the type of its structural system because the contribution of the service core to resist lateral loads changes based on the structural system type of a tall building. For this study, outriggered frame system for interior structures and framed-tube systems for exterior structures are selected according to the classification of tall building structural systems by Ali and Moon in 2007. In methodology section, structural analysis of these models has been performed and the analysis stages are explained step by step.

3.1. Research Material

The building height for generic building models is determined as "300 meter" which is defined as the lower limit of supertall buildings according to "CTBUH Height Criteria". As it was previously mentioned in "Literature Review" chapter, the recent multi car elevator technology, Multi, is ideal in one loop for 600 meters, which corresponds to 300 meters building height (300 meters for upward and downward direction). It is also indicated that there is no limitation on its use in higher buildings (Mueller, 2016). Thus, the height of the generic buildings is adjusted as 300 meters.

For both outriggered frame and framed-tube building models, there are two main groups as indicated in Figure 3.1. The first group is named as "buildings with primary core" which is assumed as utilizing conventional elevator systems. The buildings in the first group are generated based on the actual building case studies. The second group of buildings are assumed as utilizing developing elevator technologies which claims 50% reduction in elevator footprint when compared to the conventional elevator systems (Mueller, 2016). They are named as "buildings with reduced core" which are generated by the reduction of the service core of primary models due to 50% elevator footprint decrease.

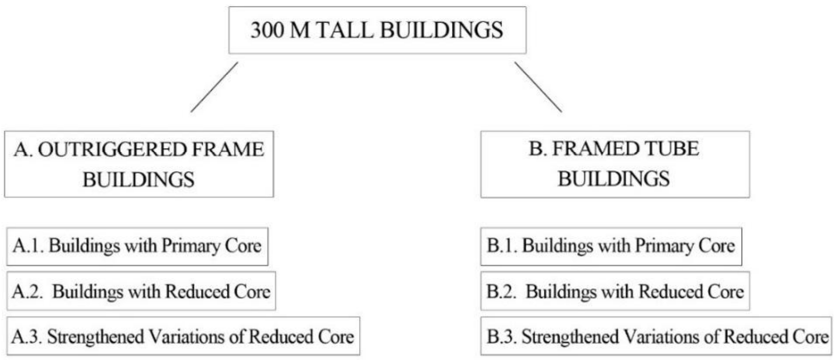


Figure 3.1. Categorisation of generic 3D building models

3.1.1. Parameters of Generic Tall Buildings

Every generic building model in this study have common features. The number of floors for both outriggered frame and framed-tube buildings are 75 and the floor to floor heights are identically 4 meters for each floor (300 meter in total). It is coherent with the approximate floor height value of 3.9 meter as indicated previously in CTBUH Tall Building Height Calculator. The slab thickness is determined as 30 cm according to the empirical formula for flat plate depth, “l/30”, where “l” corresponds to the clear span in Section 9.5.3.3 of ACI 318-08 (2008) which is given in Table A.3

in Appendix. The structural floor plans are identical in each floor and every building model is symmetric both in “x” and “y” axes.

Aspect ratio is defined as the ratio of the structural height of a building to its narrowest structural width by Günel and Ilgın (2014). The aspect ratio is determined according to the sample buildings in Table 3.1 and Table 3.3. The median aspect ratio of all buildings has been found as 7.4. On the other hand, the median aspect ratio of buildings with office function, framed-tube or outriggered-frame structural system and concrete or composite structural material have been found as 8.4. Thus, an aspect ratio of 8 which yields 37,5 meters plan width in both directions have been used in this study. In this case, the floor plate area is equal to 1406,25 m² which acceptable for an office floor.

The building typology, type of the structural system, structural material of the building and the estimated elevator footprint area of generic building models are given below in detail.

Building Typology

There are some common features of alternative building models within the scope of this research. At first, every building model is regarded as office building because the up peak and down peak of elevator traffic are enormous in office buildings when compared to other building typologies as indicated previously in "Table 2.5" and "Table 2.6" in the literature review chapter.

In office buildings, generally a column free area from service core to exterior facade of the building is more preferred. In architectural perspective, it gives an opportunity in flexible floor plan design for alternative user needs. In that manner, column-free space between the service core and the building perimeter is provided for each building alternatives.

Type of the Structural System

The reduction of the service core differently effects the structural behavior depending on the structural system of a building. There are mainly two types of structures according to distribution of structural members in resisting lateral loads: exterior and interior structures as defined previously. For this study, outriggered frame system representing interior structures and framed-tube systems as an example of exterior structures are selected according to the classification of tall building structural systems by Ali and Moon (2007). The structural systems of completed tall buildings which are built from 1961 to 2010 are categorized in a study of CTBUH in 2010. In this study, the tube systems are classified according to four main headings namely framed-tube (including diagonal framed-tube), tube in tube, braced-tube and bundled tube.

In CTBUH (2010) study, the tube systems are classified according to four main headings namely framed-tube, bundled tube, tube in tube and diagonalized. When the buildings around 300 meters height are examined, the number of completed framed-tube systems are highest among all the tube systems (in Figure 3.2, yellow area indicates the buildings around 300 meters). Since tube-in-tube and diagrid-framed-tube systems are considered as a sub branch of framed-tube systems based on Günel's structural system classification (2014), tube-in-tube buildings are also classified as framed-tube buildings.

Structural Building Material

According to the graphic illustrated in Figure 3.2, steel is dominantly used as a structural material for buildings built especially before 1990's. After the September 11 attacks, the fire resistance of standalone use of steel material for the whole structural system is widely questioned.

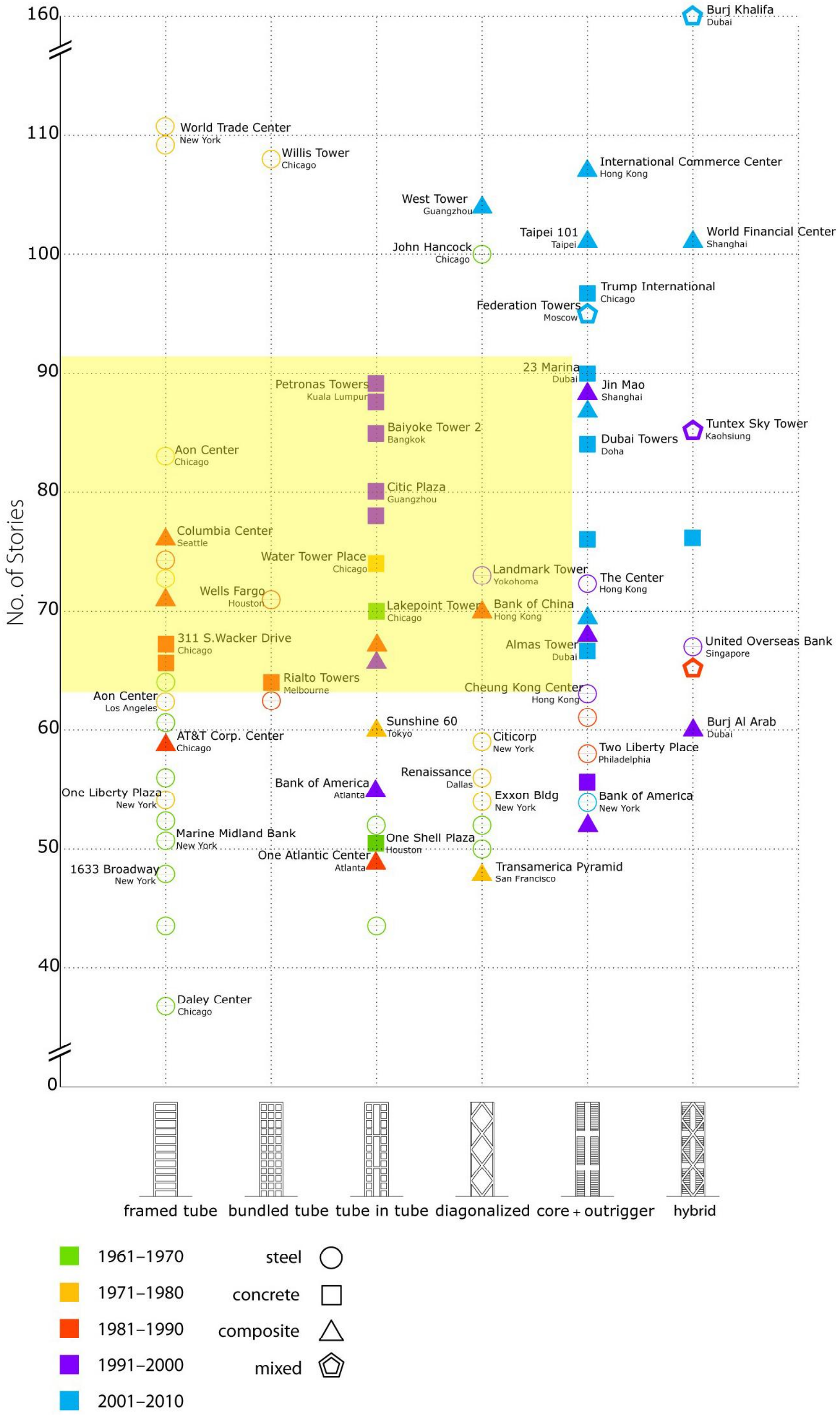


Figure 3.2. Structural System Categorization for Tall Buildings completed 1961-2010 (Langdon and Watts, 2010)

The use of reinforced concrete and composite structural materials in tall buildings accelerated after the attacks together with the technological advances in concrete pumping to higher floors. Thus, the material of columns and shear walls on outriggered and framed-tube buildings are selected as reinforced concrete whereas, steel is used for outrigger members. The concrete type is specified as “C90/105” and the steel is specified as “A992Fy50”. ASTM (American Institute of Steel Construction) A992 (Fy=50 ksi which is equal to 344737,86 kN/m^2) is the material specification which is widely used in USA for steel wide-flange beams.

Approximate Elevator Footprint Area for Generic Building Models

In order to determine the approximate elevator footprint area in generic building models which utilizes current elevator systems, the study of Beedle (2012) is used as a guideline. In that study, the ratio of the elevator footprint area to served office space is calculated and plotted as a percentage over the building height which is demonstrated as number of floors (Figure 3.3). All these calculations are based on some assumptions as:

• population, as 100 passengers per floor

• handling capacity, as 15% of population per 5 minutes

• office space, as 15 m^2 for one passenger

Since the focus of this research is 300 meters high buildings, in the graphic only 60 to 70 story tall buildings are evaluated. It is inferred from the figure that only the elevator configurations of “A (single-deck, no sky lobbies)”, “B (single-deck one level sky lobby)”, ”C (double-deck, no sky lobbies)” and “D (double-deck, a two level sky lobby)” are in used in the buildings with 60 to 70 story heights. The elevator footprint area of the buildings with 60 to 70 story heights ranges between 11 to 23 percent. However, in order to validate this information and reflect the existing buildings with a specific value rather than a relatively wide range, tall building case studies are also evaluated.

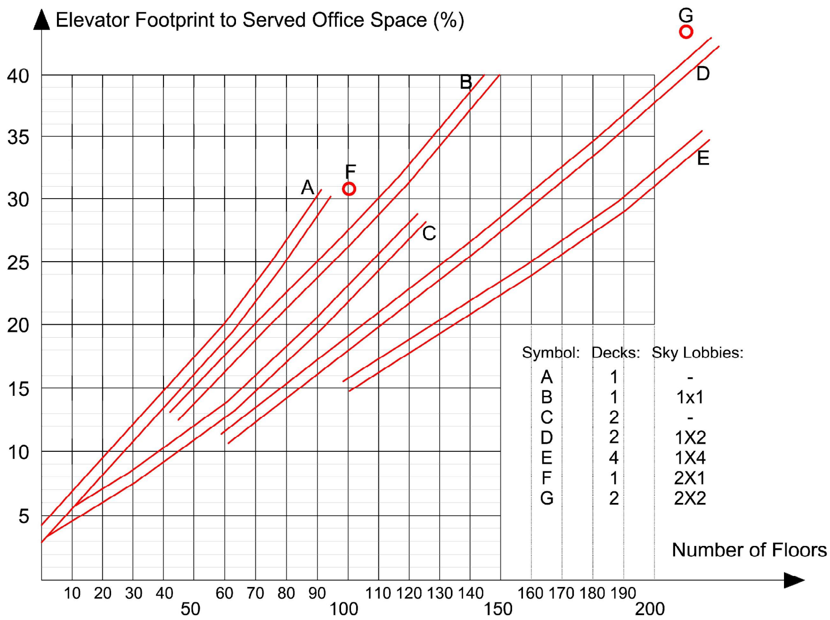


Figure 3.3. Elevator footprint to served office space ratio of different elevator configurations (Beedle, 2012)

3.1.2. Sample Buildings

Real building cases are investigated, in order to determine typical gross floor area, service core area, total column area per floor, total elevator footprint area and the exterior wall thickness of service core of the generic tall buildings. The building cases which are completed are examined mainly in two groups in terms of structural systems as outriggered frame buildings and framed-tube buildings. In the selection of tall buildings, the buildings with an architectural height around 300 meters are examined (which ranges from 222 meters to 373.9 meters). The information on floor plans, particularly ground floor plans if possible, of thirteen examples for outriggered frame and framed-tube buildings have been found and selected for detailed investigations.

The building parameters of location, date of completion, building function, architectural height, number of floors, structural material and structural material of columns are obtained from the database of The Skyscraper Center (www.skyscrapercenter.com). The rest of the building parameters like number of columns, gross floor area of typical floor (T), service core area (C), total column area per floor (TC), elevator footprint area (E) and the shear wall thickness of service core (SW) are obtained from typical floor plans of the sample buildings investigated in this study. While calculating the building parameters, the floor plans are scaled proportionally based on the dimensions indicated in floor plans, the area information of building parts or demonstration of linear scale.

The general characteristics of exemplar outriggered frame and framed-tube buildings are given in Tables 3.1 and 3.2. Besides the schematic floor plans of buildings with both structural systems are demonstrated in Figures 3.5 and 3.6. In Figure 3.5, schematic drawings of outrigger floors are also demonstrated. Average values of building parameters for each case are calculated to establish a framework for generic computer building models. The formulations of these parameters are:

- C/T: (the ratio of the service core area to the typical floor area),
- TC/T: the ratio of total column area to typical floor area,
- E/(T-C): the ratio of elevator footprint area to net floor area,
- SW: thickness of the service core wall.

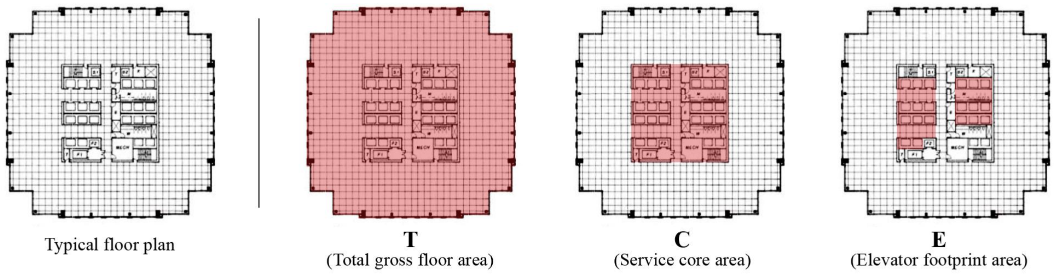


Figure 3.4. Demonstration of “T, C and E” on typical floor plan of One Liberty Place

The average value of the service core area to the typical floor area ratio (C/T) and the ratio of elevator footprint area to net floor area (E/(T-C)) are calculated according to,

• the buildings with office function,

• the buildings with framed-tube or outriggered frame systems,

• and the concrete or composite buildings with concrete or composite (CFT or CES) columns,

which are demonstrated in Table 3.1 and Table 3.2. The highlighted buildings in Tables 3.1 and 3.2 have been used for calculating the average values of member dimensions of generic models with buildings with outriggered frame and framed-tube systems (Tables 3.3 and 3.4).

Table 3.1. Characteristics of outriggered frame buildings

BUILDING NAMES	CITY	COMPLETION	FUNCTION	ARCH. HEIGHT (m)	N. OF FLOORS	STRUC. MATERIAL	STRUC. SYSTEM	COLUMN TYPE	OUTRIGGER FLOORS	REFERENCES
1. ALMAS TOWER	Dubai	2008	office	360	68	concrete	outriggered framed[6]	concrete	-	Kilmister, 1995
2. WILSHIRE GRAND CENTER	Los Angeles	2017	office/hotel	335.3	73	composite	outriggered framed[7]	*CFS	28-31, 53-59, 70-73[20]	Joseph, Gulec and Schwaiger, 2016 Wong, Gulec and Schwaiger, 2016
3. NEW YORK TIMES TOWER	New York	2007	office	318.8	52	steel	outriggered framed[5]	steel	28-51[18]	Wong and Ho, 2004 Barben, Bonfanti and Perez, 2009
4. MAHANAKHON TOWER	Bangkok	2016	hotel/resid.	314.2	78	concrete	outriggered framed[8]	concrete	19-20, 35-36, 51-52[19]	Talas, 2017 Chanvaivit, Ly and Clair, 2015
5. PEARL RIVER TOWER	Guangzhou	2013	office	309.4	71	composite	outriggered framed[9]	*CES	23-27 and 49-53[16]	Tumbas, 2015 Tomlinson, Baker, Leung, Chien and Zhu, 2014
6. TWO PRUDENTIAL PLAZA	Chicago	1990	office	303.3	64	concrete	outriggered framed[6]	concrete	40 and 59[21]	Kilmister, 1995 Choi, Joseph and Mathias 2014
7. TORRE COSTANERA	Santiago	2014	office	300	62	concrete	outriggered framed[10]	concrete	-	The Skyscrapercenter, n.d.
8. EUREKA TOWER	Melbourne	2006	residential	297.3	91	concrete	outriggered framed[5]	concrete	11-65, 11-89[5]	Günel and Ilgın, 2014
9. CHINA WORLD TRADE CENTER PHASE 3	Beijing	2017	office/hotel	295.6	59	composite	outriggered framed[11]	*CES	28-29 and 56-57[11]	Kwok. Gibbons, Tsui, Liu, Wang and Ho, 2005
10. PLAZA 66 (TOWER-2)	Shanghai	2001	office	288.2	66	concrete	outriggered framed[5]	concrete	24-26, 39-41, 54-56[17]	Günel and Ilgın, 2014 Tomasetti, Poon and Hsaio, 2001
11. ONE LIBERTY PLACE	Philadelphia	1987	office	288	61	steel	outriggered framed[15]	steel	-	Choi and Joseph, 2012
12. CHEUNG KONG CENTER	Hong Kong	1999	office	282.8	63	steel	outriggered framed[5]	steel	22-23, 41-42, 61-62[12,13]	Günel and Ilgın, 2014 Wong and Ho, 2004 Ho, 2016
13. LANGHAM PLACE OFFICE TOWER	Hong Kong	2004	office	255.1	59	concrete	outriggered framed[5,14]	concrete	26 and 44[14]	Günel and Ilgın, 2014 City University of Hong Kong, n.d.

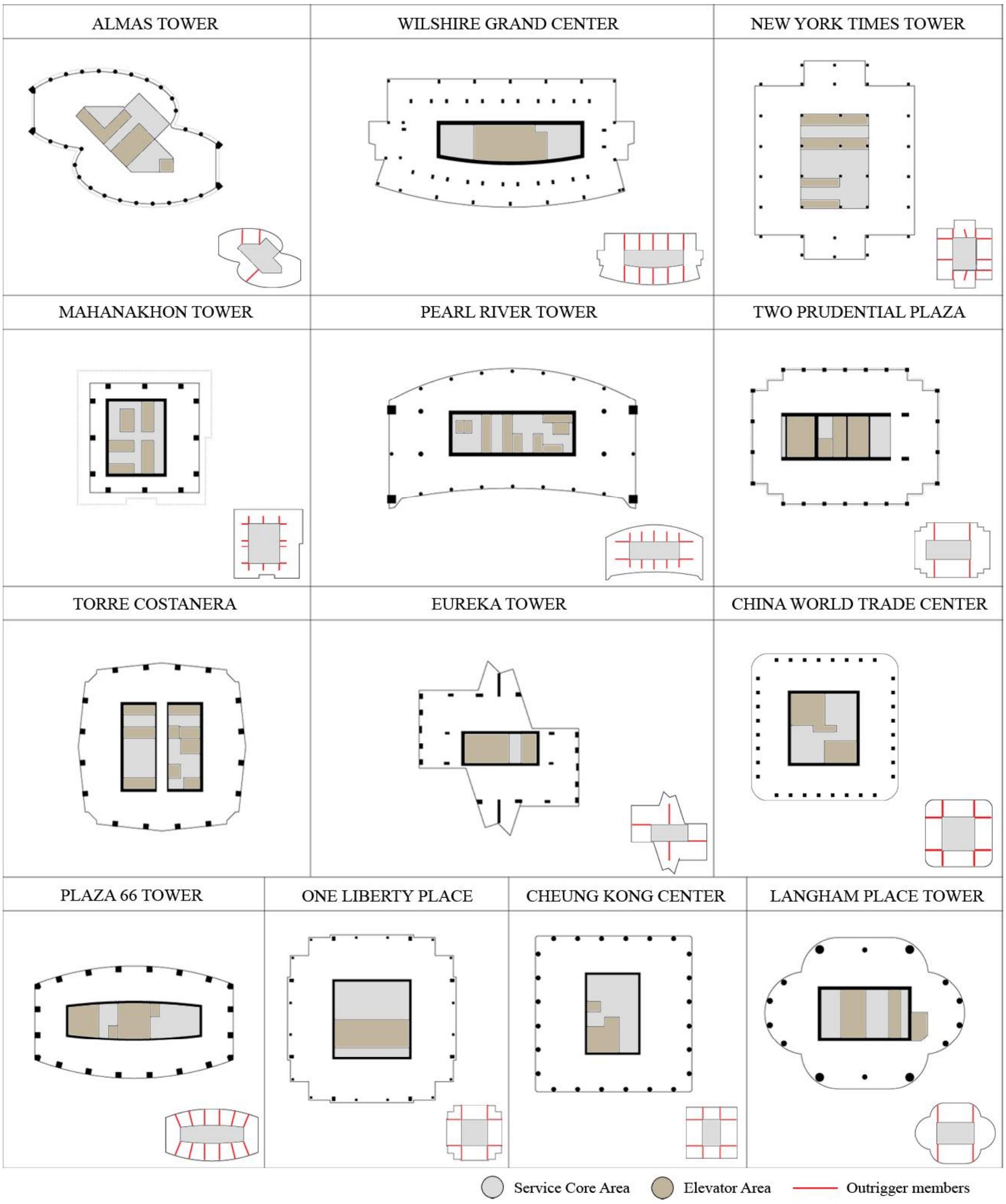


Figure 3.5. outriggered frame buildings, schematic plans (top left) and outrigger application (bottom right)

Table 3.2. Characteristics of framed-tube buildings

BUILDING NAMES	CITY	COMPLETION	FUNCTION	ARCH. HEIGHT (m)	N. OF FLOORS	STRUC. MATERIAL	STRUC. SYSTEM	COLUMN TYPE	REFERENCES
1. CENTERAL PLAZA	Hong Kong	1992	office	373.9	78	concrete	trussed tube[22]	concrete	Ayres and MacArthur, 1993
2. AON CENTER	Chicago	1973	office	346.3	83	steel	framed tube[1, 3]	steel	Smith and Coull, 1991 Al-Kodmany and Ali, 2013
3. THE FRANKLIN-NORTH TOWER	Chicago	1989	office	306.9	60	composite	framed tube[1]	concrete	Smith and Coull, 1991
4. CAYAN TOWER	Dubai	2013	residential	306.4	73	concrete	framed tube[2]	concrete	Topak, 2014
5. WELLS FARGO PLAZA	Houston	1983	office	302.4	71	steel	bundled tube[1]	steel	Smith and Coull, 1991
6. FIRST CANADIAN PLACE	Toronto	1975	office	298.1	72	steel	framed tube[4]	steel	Emporis, n.d.
7. COLUMBIA CENTER	Seattle	1984	office	284.4	76	composite	framed tube[1]	*CFS	Smith and Coull 1991
8. WATER TOWER PLACE	Chicago	1976	hotel/resid.	261.9	74	concrete	framed tube[3]	concrete	Al-Kodmany and Ali, 2013
9. RIALTO TOWERS	Melbourne	1986	office	251.1	63	concrete	bundled tube[2]	concrete	Topak, 2014
10. SOUTHEAST FINANCIAL CENTER	Miami	1983	office	232.8	55	composite	bundled tube[5]	*CES	Günel and Ilgın, 2014
11. ONE LIBERTY PLAZA	New York	1972	office	226.5	54	steel	framed tube[1]	steel	Smith and Coull, 1991
12. OLYMPIA CENTER	Chicago	1986	ofice/resid.	222.9	63	concrete	framed tube[5]	concrete	Günel and Ilgın, 2014
13. HOPEWELL CENTER	Hong Kong	1981	office	222	64	concrete	framed tube[6]	concrete	Kilmister, 1995

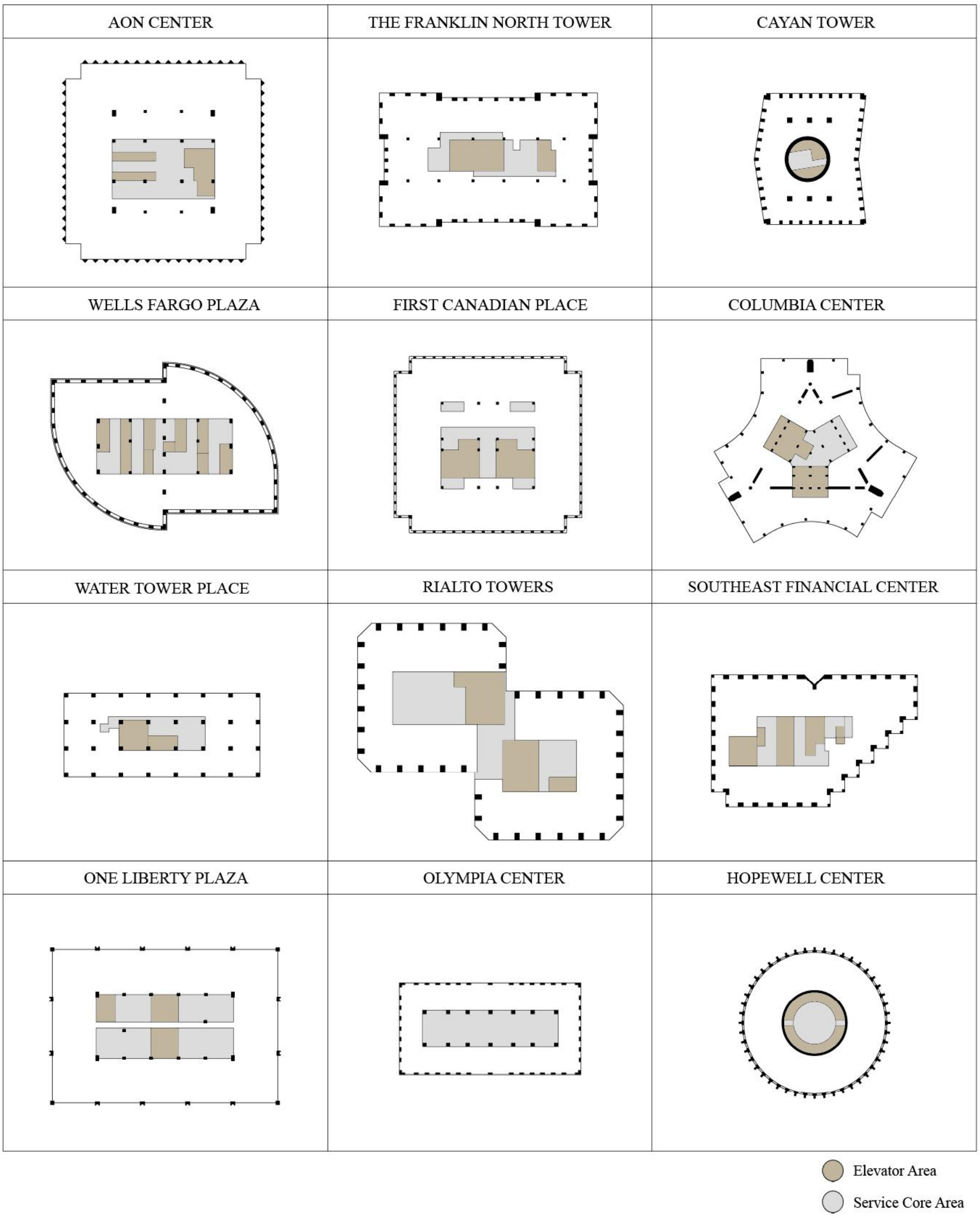


Figure 3.6. Framed-tube buildings, schematic plans

Table 3.3. Calculations for outriggered frame buildings

BUILDING NAMES	STRUC. SYSTEM	ASPECT RATIO	N. OF COLUMNS	T (m^2)	C (m^2)	TC (m^2)	E (m^2)	SW (cm)	C/T	E/(T-C)	TC/T
ALMAS TOWER	outriggered framed	9	30	1622.00	413.00	38.70	155.83	70	0.25	0.13	0.02
WILSHIRE GRAND CENTER	outriggered framed	10.5	19	1837.70	377.51	30.91	188.14	100	0.21	0.13	0.02
PEARL RIVER TOWER	outriggered framed	8.4	20	2440.47	501.16	40.49	185.78	100	0.21	0.10	0.02
TWO PRUDENTIAL PLAZA	outriggered framed	7.5	22	2083.65	450.00	26.00	224.76	100	0.22	0.14	0.01
TORRE COSTANERA	outriggered framed	6	16	2235.12	637.67	36.00	264.29	110	0.29	0.17	0.02
CHINA WORLD TRADE CENTER PHASE 3	outriggered framed	6.6	32	2003.54	451.00	32.00	200.68	90	0.23	0.13	0.02
PLAZA 66 (TOWER-2)	outriggered framed	9	20	1732.59	400.00	51.52	212.28	80	0.23	0.16	0.03
LANGHAM PLACE OFFICE TOWER	outriggered framed	7.5	20	2358.73	490.10	56.63	321.45	100	0.21	0.17	0.02
						Average Value:		94	0.23	0.14	0.02
						Used Value:		100	0.23	0.14	0.02

Table 3.4. Calculations for framed-tube buildings

BUILDING NAMES	STRUC. SYSTEM	ASPECT RATIO	N. OF COLUMNS	T (m^2)	C (m^2)	TC (m^2)	E (m^2)	SW (cm)	C/T	E/(T-C)	TC/T
THE FRANKLIN-NORTH TOWER	framed tube	7.7	46	2552.16	427.06	73.48	200.07	-	0.17	0.09	0.03
COLUMBIA CENTER	framed tube	9.5	26	2171.57	381.30	55.27	220.65	70	0.18	0.12	0.03
WATER TOWER PLACE	framed tube	10.2	20	1499.03	285.15	26.45	-	-	-	-	0.02
OLYMPIA CENTER	framed tube	12.1	44	1391.25	408.45	28.46	-	-	0.29	-	0.02
HOPEWELL CENTER	framed tube	5.2	48	1506.74	307.91	55.31	168.00	60	0.20	0.14	0.04
						Average Value:		65	0.21	0.12	0.03
						Used Value:		65	0.22	0.14	0.03

3.1.3. Characteristics of Generic Tall Buildings

As mentioned before, there are two variations of outriggered frame and framed-tube generic building models namely, "buildings with primary core" and "buildings with reduced core". In total, there are four generic building cases. The characteristics of each building model, except building height, number of floors, aspect ratio and structural material, are determined according to the average values derived from sample buildings (in Table 3.1 and Table 3.2).

The average values of existing building cases are used as a guideline in the preliminary dimensioning process of generic computer models which are presented comparatively in Table 3.5. Although the average value of the ratio of elevator footprint area (E) to net floor area (T-C) is calculated for outriggered frame and framed-tube systems separately (Table 3.5), but a single value for both structural systems (the first row third column in Table 3.5) is used in the production of generic building models (which is equal to 0.14).

Table 3.5. Average value of existing building cases with outriggered frame and framed-tubed systems

Average Value of Sample Buildings with:	SW (cm)	C/T	E/(T-C)	TC/T
Outriggered Frame System	94	0.23	0.14	0.02
Framed Tube System	65	0.21	0.12	0.03

SW: Shear wall thickness C: Service core area E: Elevator area
T: Total floor area TC: Total column area

3.1.3.1. Outriggered Frame Buildings

The structural building material of outriggered frame buildings is reinforced concrete except the steel outriggers. There are number of 8 columns in a typical floor plan as in the case of Ping An Finance Center, Evolution Tower, Guangzhou CTF Finance Center, International Commerce Center and Lotte World Tower. The column dimensions are 170x220 cm which satisfies the ratio of the total column area to the floor plate area (TC/T), "0.002" of average value of existing buildings (Table 3.5). The shear wall thickness around the service core is specified as 100 cm with respect to the existing building cases (Table 3.6).

Table 3.6. Structural parameters for outriggered frame buildings

	SW (cm)	C/T	E/(T-C)	TC/T
Average Value of Sample Buildings	94	0.23	0.14	0.02
Values of Generic Building Models	100	0.23	0.14	0.02

SW: Shear wall thickness C: Service core area E: Elevator area
T: Total floor area TC: Total column area

The outrigger dimensions of "Lotte World Tower" is used as a reference while determining the dimensions of outrigger members. The outrigger dimensions of the Lotte World Tower are, 1600mm x 500mm x 80mm x 20mm (web: 80mm, flange: 20mm) (Kim, Jung and Kim, 2015). However, when the generic models are exposed to the design wind loads that has been given according to the fictitious geographical scenario of the generic buildings, the size of outrigger members of "Lotte World Tower" are found to be insufficient to resist against the axial loads. Therefore, the outrigger dimensions are modified in order to be safe resisting against wind loads as: 1600mm x 550mm x 140mm x 35mm (web: 140mm, flange: 35mm). Two level of outriggers with 2 story height is placed at 1/3 and 2/3 of the building (which corresponds to between 24’th to 25'th and 49'th to 51'st floors). In that way, the maximum story displacement to building height ratio, which should be around 1/500 (Günel and Ilgın, 2014), is satisfied when the building is subjected to the design wind loads. The typical floor plan with the indication of outriggers (red lines) of "primary core" version of the outriggered frame buildings is indicated in Figure 3.6.

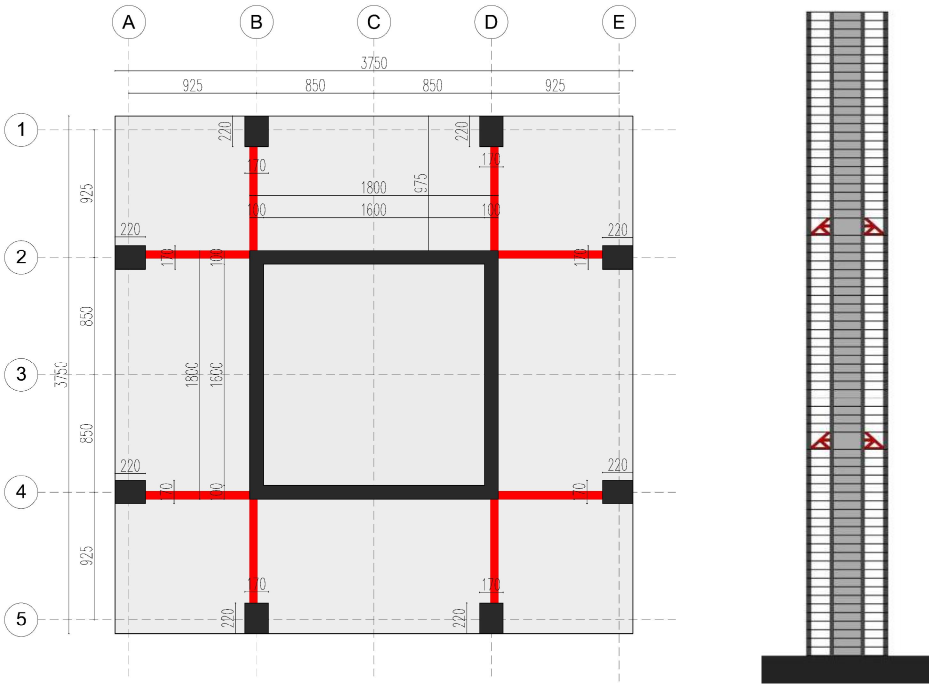


Figure 3.7. Typical floor plan (left) and elevation (right) of "primary core building" with outriggered frame system

If the outriggered frame building in Figure 3.7 utilizes recently developed elevator technology, the elevator footprint area within structural core decreases. This version is named as "outrigger building with reduced core" as demonstrated in Figure 3.8. In this case, two parameters of "primary core" outriggered frame buildings changes while the other two remains the same (SW and TC/T):

- E/(T-C): 0.07
- C/T: 0.177

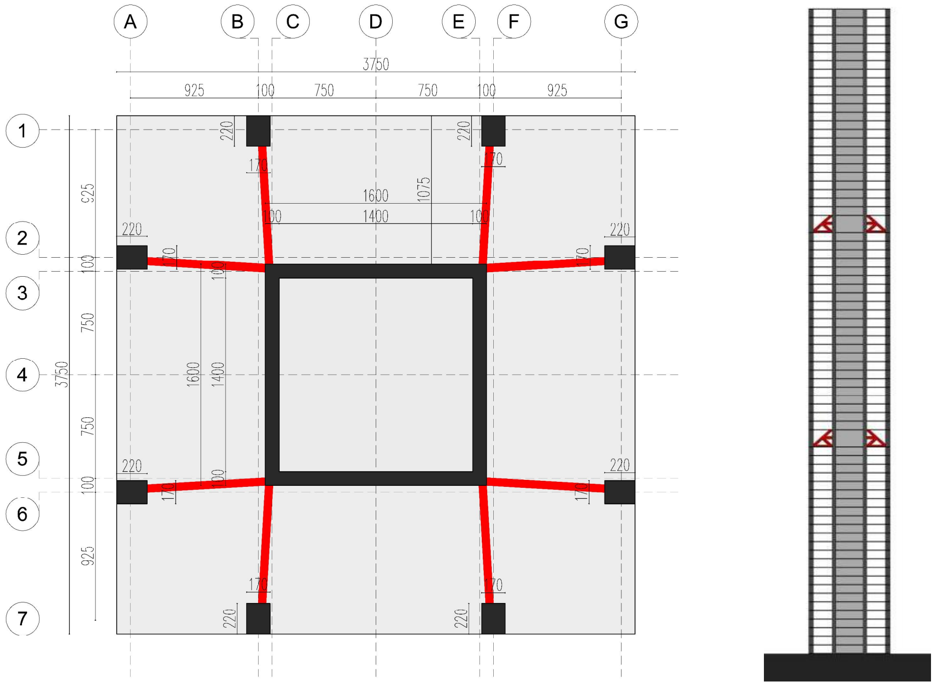


Figure 3.8. Typical floor plan (left) and elevation (right) of "reduced core building" with outriggered frame system

3.1.3.2. Framed-tube Buildings

The structural building material of framed-tube buildings is reinforced concrete (C90/105). Since the spacing between column axes of framed-tube buildings should be between 1.5 meter to 4.5 meter (Günel and Ilgın, 2014 and Sarkisian, 2012), the number of columns for each facade are arranged accordingly. There are 36 columns in a typical floor plan. In framed-tube buildings, the columns are used with deep spandrel beams. The beam dimensions are identified with the same dimensions of columns as in the case of 432 Park Avenue Tower. The column dimensions are determined as 105x105cm since the ratio of total column area to the floor plate area (TC/T) is "0.02" (Table 3.7).

Table 3.7. Structural parameters for framed-tube buildings

	SW (cm)	C/T	E/(T-C)	TC/T
Average Value of Sample Buildings	65	0.21	0.12	0.03
Values of Generic Building Models	65	0.22	0.14	0.03

SW: Shear wall thickness C: Service core area E: Elevator area
T: Total floor area TC: Total column area

The shear wall thickness of the framed-tube buildings is selected in accordance with the sample buildings. Consequently, the shear wall thickness of service core is determined as 65 cm (Table 3.7). The typical floor plan of "primary core" version of the framed-tube buildings is indicated in Figure 3.8.

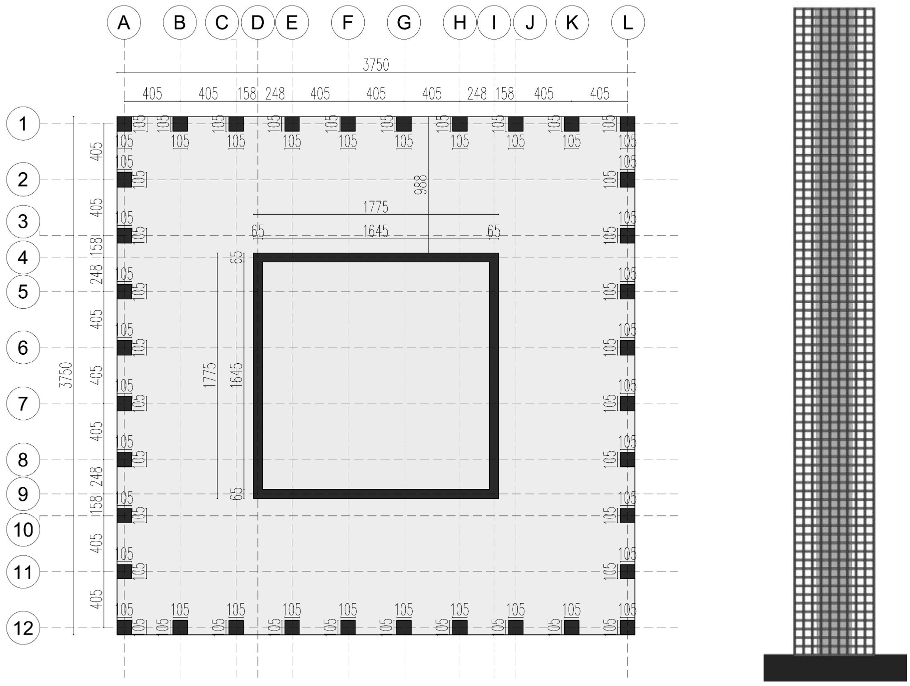


Figure 3.9. Typical floor plan (left) and elevation (right) of "primary core building" with framed-tube system

If the framed-tube building in Figure 3.9 utilizes the recently developed elevator technology instead of the current elevator system, the service core area decreases as demonstrated in Figure 3.10. In this case, two parameters of the building with "primary core" change while the other two remains the same (SW and TC/T):

- E/(T-C): 0.07
- C/T: 0.171

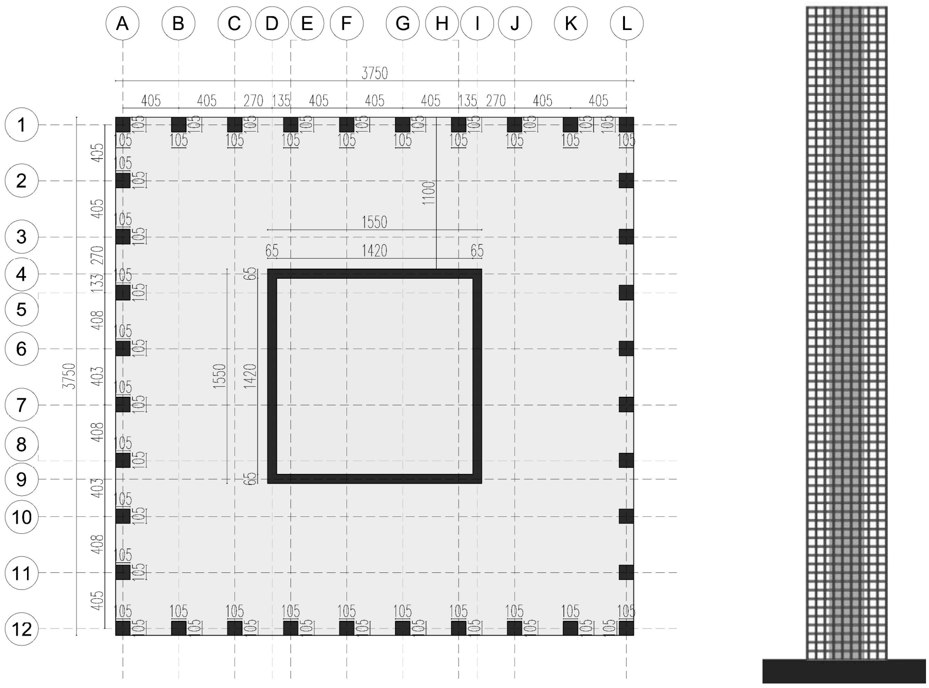


Figure 3.10. Typical floor plan (left) and elevation (right) of "reduced core building" with framed-tube system

3.1.4. The Software Used

ETABS V16.2.1

ETABS (Version 16.2.1) is a software package for the structural analysis and design of buildings. This program is developed by Computer & Structures Incorporation. The advantages of the program are:

• wide use by structural engineers for analysis and design of tall buildings
• providing a wide range of design codes for steel, concrete, composite and shear wall design
• 3D object-based modelling and visualization tools
• sophisticated and comprehensive design capabilities
• capacity and stress check of structural members
• compatibility with BIM based products

All the structural analyses under different load types and corresponding combinations as well as some basic capacity and design checks based on built-in specifications (i.e. ACI 318- 14 and ASCE 7-10) have been made by ETABS program.

3.2. Methodology

3.2.1. Definition of Load Cases

Buildings are subjected to dead loads, live loads and lateral loads. These loads are applied to the generic building models.

Since the site conditions of New York city is used in determination of seismic and wind loads, the latest available American standard in ETABS which is ASCE 7-10 is used in structural analysis. Minimum uniformly distributed live load for office buildings is specified as 2.4 kN/m² according to ASCE 7-10 standard (2010, p. 18). While defining the mass source data for structural analysis, the live load reduction factor is specified as 0.25 as indicated in ASCE 7-10 (2010).

Wind and Earthquake Loads Depending on Site Conditions

Wind and earthquake loads depend on site conditions of buildings. Thus, for the structural analysis of generic tall buildings, the scenario location is examined. For primary and reduced core building model cases, the building site is determined as Central Park region, New York. For both wind and earthquake cases, the information of the site conditions is obtained from ATC Hazards by Location database: "https://hazards.atcouncil.org/". The latitude and longitude of the area are indicated in Figure 3.10. The reference document which is used in the selection of parameters in the database is ASCE 7-10. For the wind load calculations, "Risk Category II" is selected. The resultant wind speed value is found as 115 mph (185 km/h) for this area and the wind exposure type is selected as "C".

The database is also utilized for earthquake calculations with the same latitude and longitude. For earthquake load calculations "Risk Category II" is selected. The site class is identified as "B" according to ASCE 7-10 document. The seismic characteristics of the site area indicated in Figure 3.11. The detailed parameters of this document are indicated in Figure A.1 in Appendix. The structural analysis process of buildings in ETABS are based on the load parameters obtained from this database.

Figure 3.11. Seismic characteristic of the site (https://hazards.atcouncil.org/)

Response Spectrum Analysis

For the seismic analysis of generic building models, response spectrum analysis is used which reveals the likely maximum seismic response of a structure with the contribution of each natural mode of vibration. For response spectrum analysis, response modification coefficient, "R" value, is determined as “6” and damping ratio is specified as “5 percent” according to the report (2017, version: 2.03) of Pacific Earthquake Engineering Centre (PEER) in 2017 (Table 3.8).

Table 3.8. Recommended values of "R" factors (PEER, 2017)

System Description	*R*
Systems with well-distributed zones of yielding, proportioned using principles of capacity design and with yielding occurring primarily in elements capable of local ductility of 4 or more without loss of more than 20% of peak load-carrying capacity	8
Bearing wall systems and coupled bearing wall systems meeting the detailing requirements of ACI 318 for Special Reinforced Concrete Shear Walls	6
Other Systems	*

An adequate number of modes are necessary for response spectrum analysis in order to satisfy a mass participation of minimum 90 percent in each response directions as stated in ASCE 7-10 (2010). The number of modes is specified as "50" for each generic building case in the scope of this research. Besides, as indicated in Section 12.9.4 of ASCE 7-10 (2010), a base shear should be calculated in each direction using the equivalent lateral force procedures. Since the building models are symmetric in “x” and “y” directions, response spectrum analysis is performed according to only “x” direction. According to ASCE 7-10 (2010), the combined response for the modal base shear should be at least 85 percent of the equivalent static base shear. Thus, the base shear is calculated by multiplying the forces with the formula given in Figure 3.12.

$$0.85 \times \frac{V}{V_t}$$

V: The equivalent static base shear (Section 12.8)
V_t: The base shear from the required load combination

$$V = C_s \times W$$

C_s: The seismic response coefficient (Section 12.8.1.1)
W: The effective seismic weight (Section 12.7.2)

$$C_s = \frac{S_{ds}}{\left[\frac{R}{I_e}\right]}$$

S_{ds}: The design spectral responce acceleration parameter in the short period range (Section 11.4.4 or 11.4.7)
R: Response modification factor (Table 12.2-1)
I_e: The importance factor (Section 11.5.1)

Figure 3.12. The calculated base shear formula according to ASCE 7-10 (2010)

Finally, generic building models are analyzed according to calculated base shear and then the structural members are controlled with stress-based design check in ETABS.

Wind Loads

In order to perform wind load analysis, the parameters of risk category, wind speed and the exposure type is determined according to ATC Hazards by Location database: "https://hazards.atcouncil.org/" as indicated before. Another important parameter in wind load analysis is gust factor which is defined in detail below.

Gust Factor

Wind loads are found by using ASCE 7-10 (ASCE, 2010) code. The calculated wind loads are assigned to each floor in accordance with the extends of the floor plan, wind direction and wind coefficient. The applied wind load has been calculated by using main wind force resisting system (MWFRS) directional procedure given in Chapter 27 of ASCE 7-10 (ASCE, 2010). Since the generic models used in this study are regular-shaped enclosed buildings, MWFRS method is accepted as fairly accurate for determining minimum design loads of tall buildings of all heights (ASCE, 2010).

Load Combinations

The load combinations which involves seismic and wind loads in ASCE 7-10 and in PEER (2017, version: 2.03) are:

- 1.2 DL + 1.0 LL + 1.0 WL
- 1.0 DL + 1.0 SD + 0.3 LL + 1.0 WL
- 1.0 DL + 0.5 LL + 1.0 EQx + 0.3 EQy
- 0.9 DL + 1.0 WL
- 0.9 DL + 1.0 EQx + 0.3 EQy

Each building model in this study is checked and redesigned if necessary for all design load combination cases automatically defined in ETABS based on ASCE 7-10 as given above (2010). However, the top drift comparisons have been made only for the most demanding wind load case as given below (Most demanding condition means the maximum base shear when each direction is evaluated.).

- 1.2 DL + 1.0 LL + 1.0 WL

The wind governs the design on the structural systems since the buildings in this study are 300 meters in height which is also defined as “supertalls” by CTBUH (Council of Tall Buildings and Urban Habitat). Such a generalization is limited with the seismicity of the region. In this study, the generic buildings are assumed to locate in Central Park Region in New York where design wind loads create larger demands on building models than earthquake loads do.

Since the building is symmetrical in x and y directions, the wind load is applied only along x direction. Because of the symmetry, the earthquake loads are defined x and y directions but the coefficient values of EQx and EQy (1 and 0.3) are not transposed in the load combination above.

3.2.2. Structural Analysis of Generic Building Models

The columns are modelled as frame elements and floor slabs and core walls are modelled as thin-shell elements in each building model of this study. In ETABS structural analysis, default meshing both for frame and shell elements have been used which inherently helps realistic distribution and accurate transfer of forces. Then, before running the analyses, the structural models are checked if the loads are distributed properly through meshes with “check” command in Analyze tab. The analysis is executed after being sure that there are no warnings about the model and the floor meshing is fine enough to transfer the loads among members.

In modelling and structural analysis process of generic buildings, there are two main objectives related to wind and earthquake loads. The first objective is that the structural components as well as the building itself should be strong enough to resist earthquake and wind loads safely. The second criteria, namely the serviceability criteria which is the maximum lateral top drift to building height ratio should be close to 1/500 (Günel and Ilgın, 2014).

According to the defined load cases and selected load combinations, both the outriggered frame and framed-tube buildings are analyzed in ETABS. The modelling analysis process is composed of three stages:

• analysis of buildings with "primary core"

• analysis of buildings with "reduced core"

• comparison of analysis of buildings with "primary core" and "reduced core"

3.2.2.1. Modelling and Analysis of Outriggered Frame Buildings

The typical floor plan of outriggered frame buildings with "primary core" and "reduced core" are indicated in Figure 3.6 and 3.7 before. Table 3.9 summarizes the building parameters in detail.

Table 3.9. Building parameters of outriggered frame buildings with "primary" and "reduced" core

O F _PRIMARY CORE		
C/T	**E/(T-C)**	**Aspect Ratio**
0.23	0.14	8
Building Height (m)	**Floors**	**Floor Height (m)**
300	75	4
T (m²)	**Width (m)**	**Length (m)**
1406.25	37.5	37.5
C (m²)	**Width (m)**	**Length (m)**
324	18	18
E (m²)		
151.515		
TOTAL COLUMN AREA PER FLOOR		
(n x a x b) / T =		0.0213
n x a x b (m²) =		29.92
n (n. of columns):		8
a x b (m²) =		3.74
column edge a (m):		1.7
column edge b (m):		2.2

O F _REDUCED CORE		
C/T	**E/(T-C)**	**Aspect Ratio**
0.18	0.07	8
Building Height (m)	**Floors**	**Floor Height (m)**
300	75	4
T (m²)	**Width (m)**	**Length (m)**
1406.25	37.5	37.5
C (m²)	**Width (m)**	**Length (m)**
248.2425	16	16
E (m²)		
75.7575		
TOTAL COLUMN AREA PER FLOOR		
(n x a x b) / T =		0.0213
n x a x b (m²) =		29.92
n (n. of columns):		8
a x b (m²) =		3.74
column edge a (m):		1.7
column edge b (m):		2.2

All models are analyzed according to the wind load combination (1.2 DL + 1.0 LL + 1.0 WL). The results are comparatively presented in Table 3.10.

Table 3.10. Comparison of "primary" and "reduced" core models of outriggered frame system under wind load combination

Load Combination for Wind	Outriggered Frame_Primary	Outriggered Frame_Reduced
Top Drift:	642.927 mm	787.406 mm
Top Drift to Height Ratio:	0.0021 (1/476)	0.0026 (1/385)
Period (T):	7.592	8.19
Gust Factor:	1.516	1.554
Base Reactions (Fx):	-57130.75	-55487.59
Core Moment:	-4317319	-4010550
Total Moment:	-8330352	-8525453

The results summarized in Table 3.10 verify that, as the service core is reduced, the maximum top displacement also increases. Furthermore, the ratio of moment-share between the structural components of the service core and the perimeter columns changes. When the core area is reduced, the lateral loads and accordingly the moments over the perimeter columns also increases. Consequently, the structural system becomes more vulnerable against the wind loads by the service core decrease.

3.2.2.2. Modelling and Analysis of Framed-tube Buildings

The typical floor plan of framed-tube buildings with "primary core" and "reduced core" are demonstrated in Figure 3.8 and 3.9 earlier. Detailed parameters of both buildings are indicated in Table 3.11.

Table 3.11. Building parameters of framed-tube buildings with "primary" and "reduced" core

F T _PRIMARY CORE		
C/T	**E/(T-C)**	**Aspect Ratio**
0.22	0.14	8
Building Height (m)	**Floors**	**Floor Height (m)**
300	75	4
T (m²)	**Width (m)**	**Length (m)**
1406.25	37.5	37.5
C (m²)	**Width (m)**	**Length (m)**
315.06	17.75	17.75
E (m²)		
152.77		
TOTAL COLUMN AREA PER FLOOR		
(n x a x b) / T =		0.03
n x a x b (m²) =		39.69
n (n. of columns):		36
a x b (m²) =		1.1025
column edge a (m):		1.05
column edge b (m):		1.05

F T _REDUCED CORE		
C/T	**E/(T-C)**	**Aspect Ratio**
0.17	0.07	8
Building Height (m)	**Floors**	**Floor Height (m)**
300	75	4
T (m²)	**Width (m)**	**Length (m)**
1406.25	37.5	37.5
C (m²)	**Width (m)**	**Length (m)**
238.68	15.5	15.5
E (m²)		
76.38		
TOTAL COLUMN AREA PER FLOOR		
(n x a x b) / T =		0.03
n x a x b (m²) =		39.69
n (n. of columns):		36
a x b (m²) =		1.1025
column edge a (m):		1.05
column edge b (m):		1.05

The perimeter columns and spandrel beams of the framed-tube buildings with "primary core" and "reduced core" are controlled by checking the strength of the structural components under the wind and seismic load combinations. All the structural members of the framed-tube building with “primary” core satisfy a strength limit state under the wind and the seismic load combinations. However, although the structural members of the framed-tube building with “reduced” core is strong enough to resist wind loads, some of the members are vulnerable to earthquake loads. Since the longitudinal reinforcement area required for axial force and biaxial moment design exceeds the maximum allowed percentage for 52 columns, the cross-sectional area of these columns has been increased and the design has been repeated.

The structural analysis results of the framed-tube buildings under the wind load combination is presented in Table 3.12.

Table 3.12. Comparison of "primary" and "reduced" core models of framed-tube system under wind load combination

Load Combination for Wind	Framed Tube_Primary	Framed Tube_Reduced
Top Drift:	630.325 mm	711.429 mm
Top Drift to Height Ratio:	0.0021	0.0024
Period (T):	7.98	8.368
Gust Factor:	1.541	1.565
Core Moment:	-3148331	-2620938
Perimeter Moment:	-5374571	-6034758
Total Moment:	-8522902	-8655696
Fx (base reactions):	-55023.4063	-55880.3574
My (base reactions):	-8746461	-8882681

3.2.2.3. Evaluation of Primary and Reduced Core Comparisons

The structural analysis results of outriggered-frame and framed-tube buildings showed that, if the area of service core gets smaller due to the reduction in necessary elevator footprint, the structure of tall buildings become more sensitive to wind and seismic induced loads. Thus, it is necessary to strengthen the structural system of "reduced" core in order to resist wind and earthquake loads for a given level of safety equivalent to the "primary" core system in terms of top drift.

3.2.3. Definition of Analysis Flowchart

Methodological process of this study can be summarized in sequence as:

- investigation of the characteristics of existing buildings with outriggered frame and framed-tube buildings around 300 meters,
- creating generic models with outriggered frame and framed-tube systems based on the survey of existing building cases (primary core models),
- deriving the generic models with reduced service core area (reduced core models),
- applying lateral loads to the building models
- analysis and comparison of the building models with "primary" and "reduced" core for outriggered frame and framed-tube systems.

When the structural analysis results for "primary" and "reduced" core systems are compared, it is concluded that the dimensions of the existing structural members should be increased or new members should be added to the system. The main objective of strengthening the reduced core system is to reach the equivalent top drift to building height ratio of the "primary" core version of this system. Thus, the determination of the structural member sizes and structural analysis is an iterative process. As a result, the methodology can be identified in two main phases as given in Figure 3.13. The methodological process is described for each building model with both outriggered frame and framed-tube systems. The first phase has been summarized and the second phase is explained in the next section.

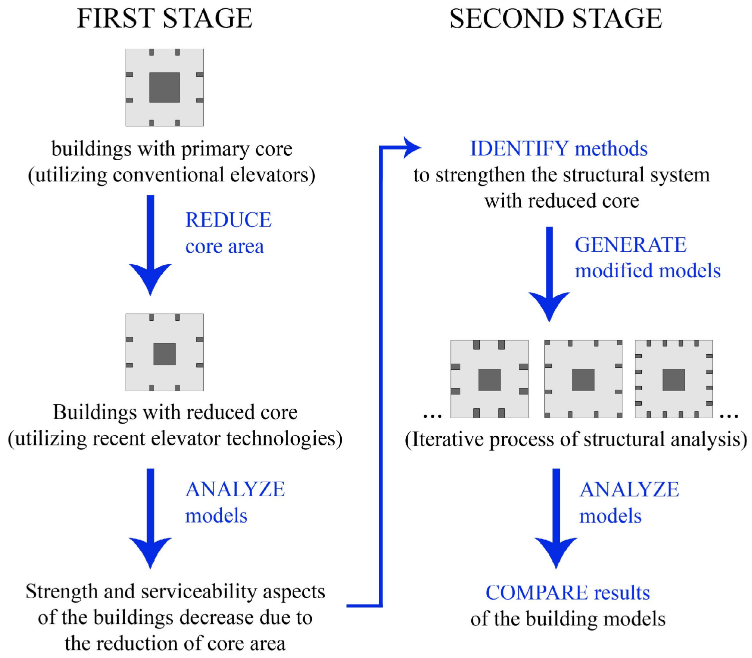


Figure 3.13. Flow chart of methodology

3.2.4. Methods to Strengthen the Structural Systems of Reduced Core Buildings

The methods to strengthen the structural system of outriggered frame buildings with "reduced" core are listed below:

• Option 1: increasing cross-section area of existing columns with the same width to length ratio,

• Option 2: increasing the number of columns at each facade,

• Option 3: addition of more outrigger levels and/or belt trusses,

• Option 4: increasing the thickness of shear wall at the service core,

• Option 5: combination of some of these methods.

The methods to strengthen the framed-tube building with "reduced" core are considered by prioritizing reinforcement of the columns to make them adequate for all loads, particularly for seismic action. These methods can be grouped as:

• Option 1: increasing the size of the framing elements (columns and spandrel beams),

• Option 2: increasing the cross-section area of columns,

• Option 3: increasing the thickness of shear wall at the service core,

• Option 4: increasing the number of columns at each facade with equal column spacing,

• Option 5: addition of outrigger levels.

Based on these methods to strengthen the structural system of "reduced" core versions of outriggered frame and framed-tube building models, generic computer models are prepared in ETABS. The characteristics of the modified models for outriggered frame and framed-tube buildings are presented below.

Reinforced Building Model Variations for Outriggered Frame Buildings

There are 11 computer models produced to strengthen the "reduced" core version of outriggered frame building. The details of the structural members are presented in the tables below. Besides, typical floor plans with the demonstration of outriggers and belt trusses are presented. The red lines symbolize outrigger members and the green ones symbolizes belt trusses. As outrigger members, each belt truss member that is used in generic building models are identical in this study. The dimensions of outrigger and belt truss members of the generic building models are determined with the modification of the outrigger and belt trusses of "Lotte World Tower". These dimensions are modified in order to be capable of resisting wind loads. The outrigger dimensions that are used in generic building models are determined as 1600mm x 550mm x 140mm x 35mm (web: 140mm, flange: 35mm) as indicated earlier. The dimensions of belt truss members of "Lotte World Tower" are 550mm x400mm x15mm x50 mm (web: 50mm and flange: 15mm) while the modified version of belt truss members used in this study is as 550mm x400mm x20mm x70 mm. The schematic drawings demonstrating the connection of outriggers and belt trusses are given in Figure 3.14.

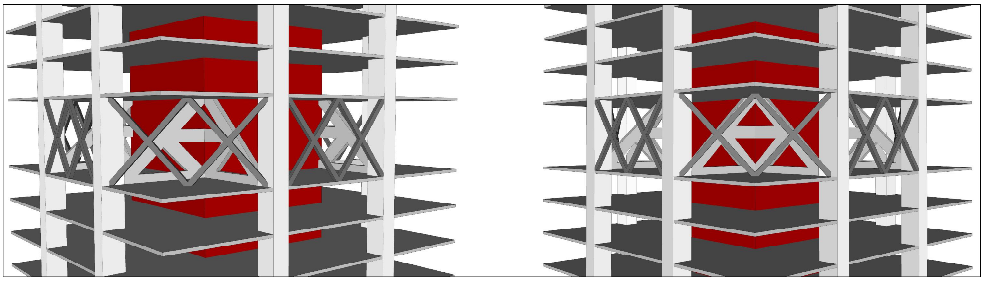


Figure 3.14. Outrigger levels with belt trusses

The generic buildings are named by starting with an abbreviation of the structural system type. Then, they are numerated based on the method to strengthen the structural system. The outriggered frame buildings are named as "OF_option number of outriggered frame buildings" while the framed-tube buildings are named as "FT_option number of framed-tube buildings". In addition, the buildings which utilizes current elevators systems are named as "OF_Primary" or "FT_Primary" while the buildings with the recently developed elevator technology are named as "OF_Reduced" or "FT_Reduced".

OF_OPT_1

In this model, the existing column dimensions are increased with the same width to length ratio and then analyzed several times until the maximum top displacement of the model is equivalent to the maximum top displacement “OF_Primary”.

Table 3.13. Properties of structural members in model "OF_OPT_1"

Column Type-a Dimensions:	2.1x2.7 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	45.36 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25 and 49-50
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.18

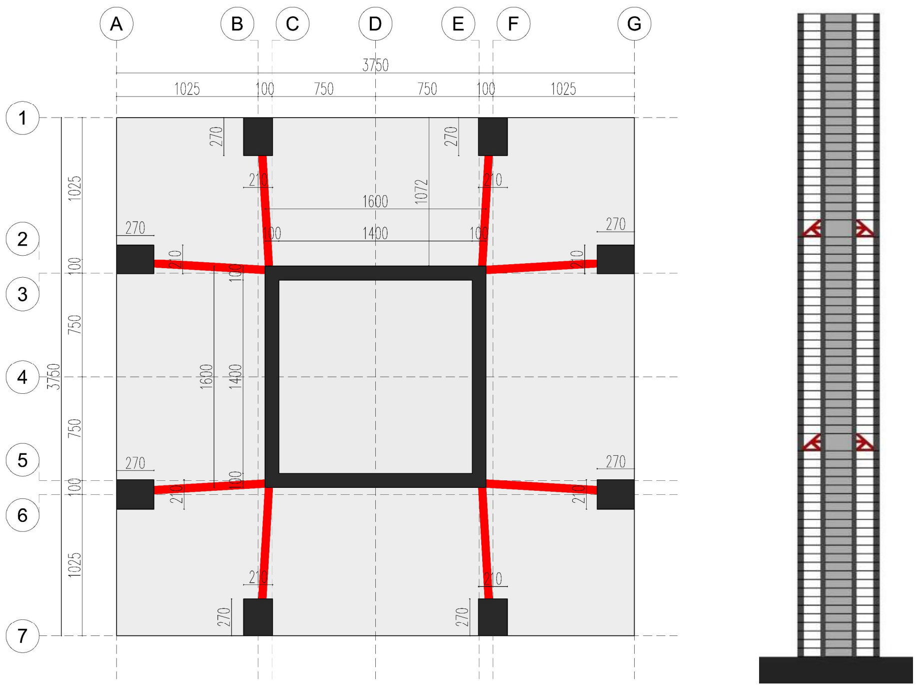


Figure 3.15. Typical floor plan and elevation of model "OF_OPT_1" with outriggers

OF_OPT_2a

Four square columns are added to the corners of the building. The dimensions of the columns are increased and then analyzed iteratively.

Table 3.14. Properties of structural members in model "OF_OPT_2a"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	2.5x2.5 m
Number of Columns:	4
Total Column Area per Floor:	28.57 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25 and 49-50
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

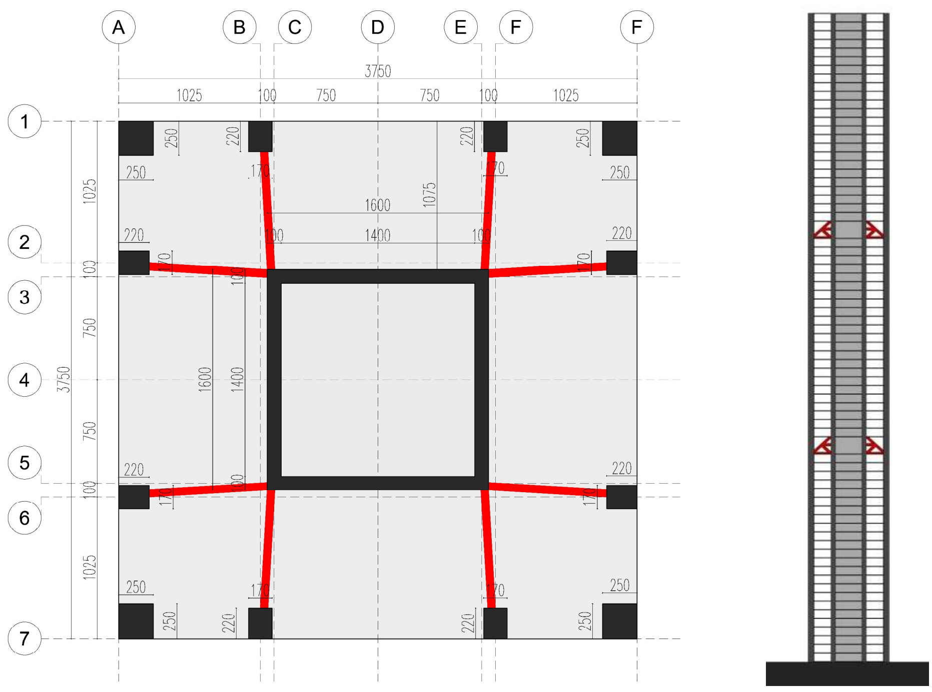


Figure 3.16. Typical floor plan and elevation of model "OF_OPT_2a" with outriggers

OF_OPT_2b

Four square columns are added to the corner with the same cross-section area of existing columns. In addition, 4 more columns are added in the middle of each facade with the same dimensions of existing columns.

Table 3.15. Properties of structural members in model "OF_OPT_2b"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	12
Column Type-b Dimensions:	2.0x2.0 m
Number of Columns:	4
Total Column Area per Floor:	60.88 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25 and 49-50
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.04
Core to Floor Area Ratio:	0.18

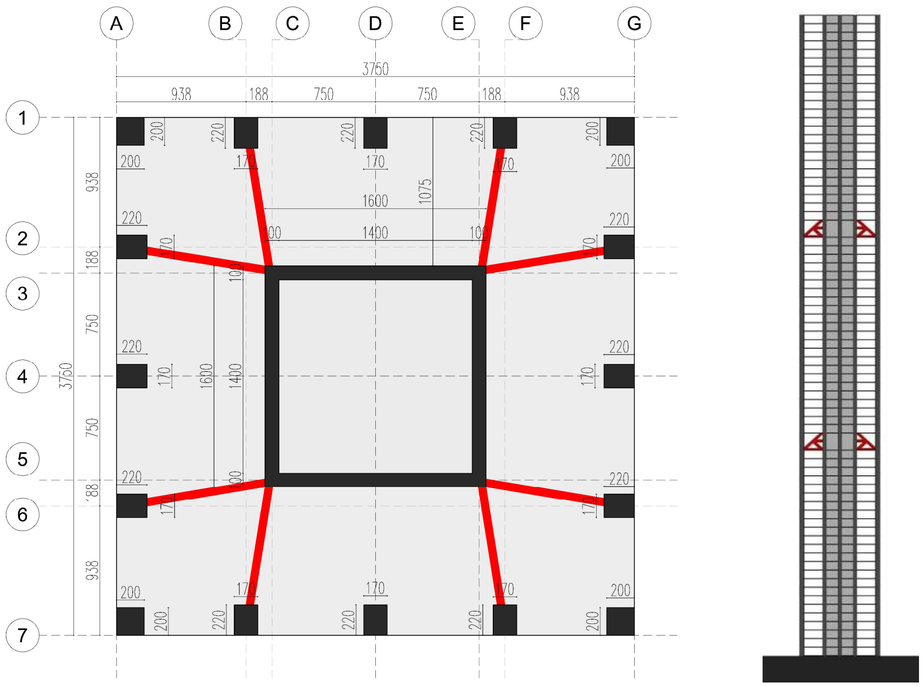


Figure 3.17. Typical floor plan and elevation of model "OF_OPT_2b" with outriggers

OF_OPT_2c

The number of columns is increased with equal column spacing and without changing the column size. Only the corner columns have the same footprint area with the rest of the columns. There are six columns at each facade.

Table 3.16. Properties of structural members in model "OF_OPT_2c"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	16
Column Type-b Dimensions:	2.0x2.0 m
Number of Columns:	4
Total Column Area per Floor:	75.8 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25 and 49-50
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.00
Core to Floor Area Ratio:	0.18

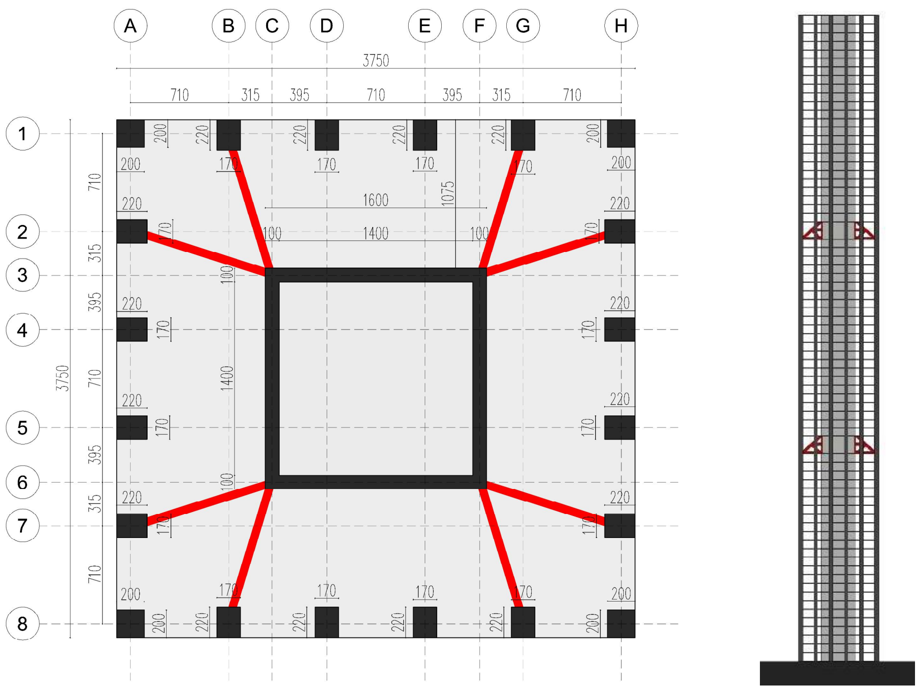


Figure 3.18. Typical floor plan and elevation of model "OF_OPT_2c" with outriggers

OF_OPT_3a

In model version OF_OPT_3a, belt trusses are added to the outrigger floor levels.

Table 3.17. Properties of structural members in model "OF_OPT_3a"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	29.92 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25 and 49-50
Belt Truss Floors:	24-25 and 49-50
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

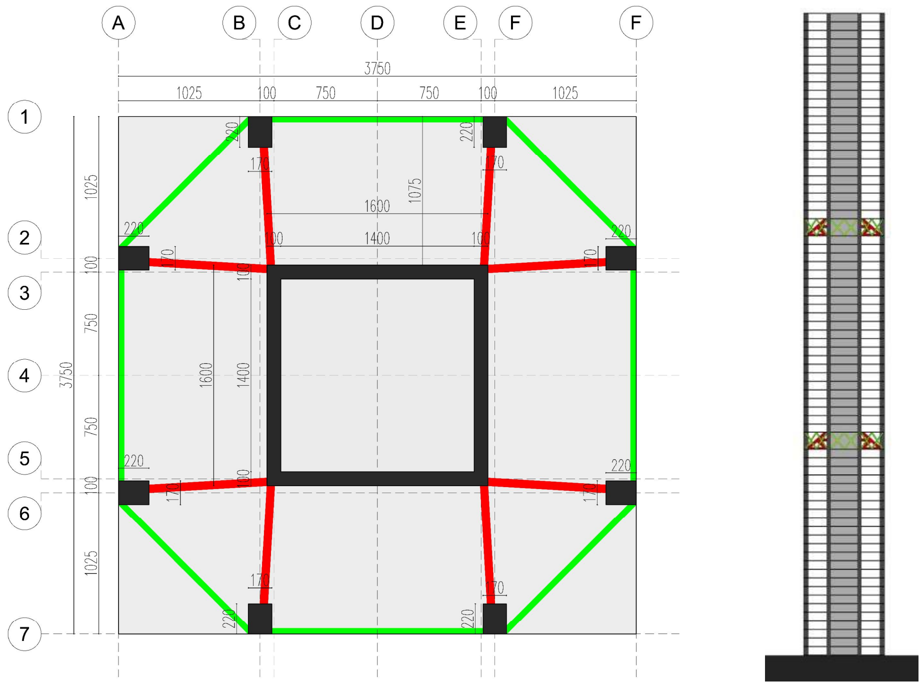


Figure 3.19. Typical floor plan and elevation of model "OF_OPT_3a" with the demonstration of outriggers and belt trusses

OF_OPT_3b

One level of double storey outriggers with surrounding belt trusses are added at the top of the building. In addition, the outrigger levels are surrounded by belt trusses.

Table 3.18. Properties of structural members in model "OF_OPT_3b"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	29.92 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25, 49-50 and 73-74
Belt Truss Floors:	24-25, 49-50 and 73-74
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

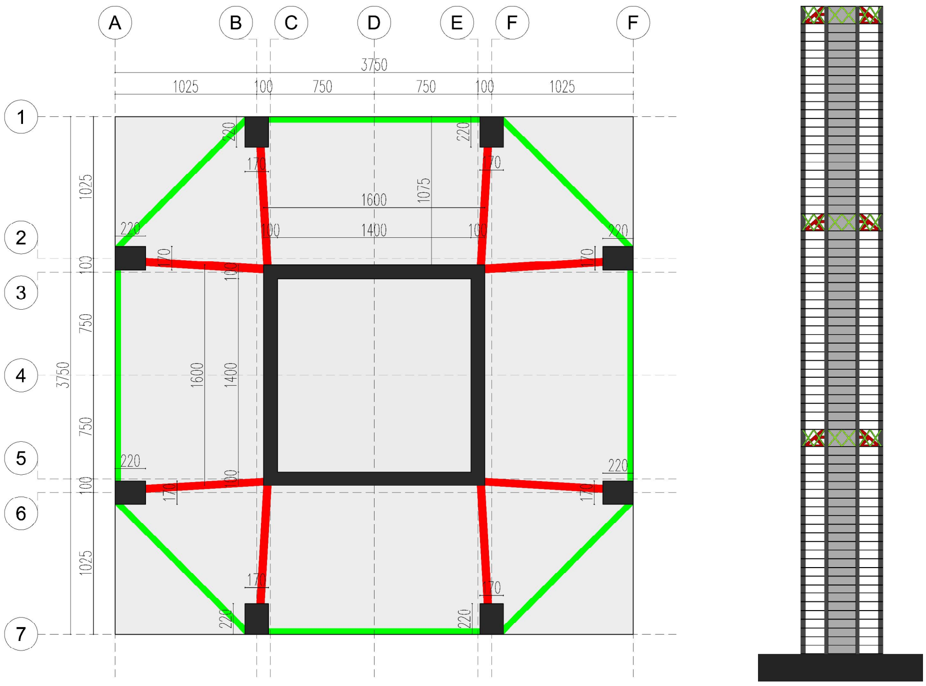


Figure 3.20. Typical floor plan and elevation of model "OF_OPT_3b" with the demonstration of outriggers and belt trusses

OF_OPT_3c

The number of outrigger levels are increased in model version "OF_OPT_3c". Double story height outriggers are placed at 1/4, 2/4 and 3/4 of the height of the building are replaced with the original double story height outriggers at 1/3 and 2/3 of the height of the building. Besides, belt trusses surrounded the outrigger floor levels.

Table 3.19. Properties of structural members in model "OF_OPT_3c"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	29.92 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	18-19, 37-38 and 55-56
Belt Truss Floors:	18-19, 37-38 and 55-56
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

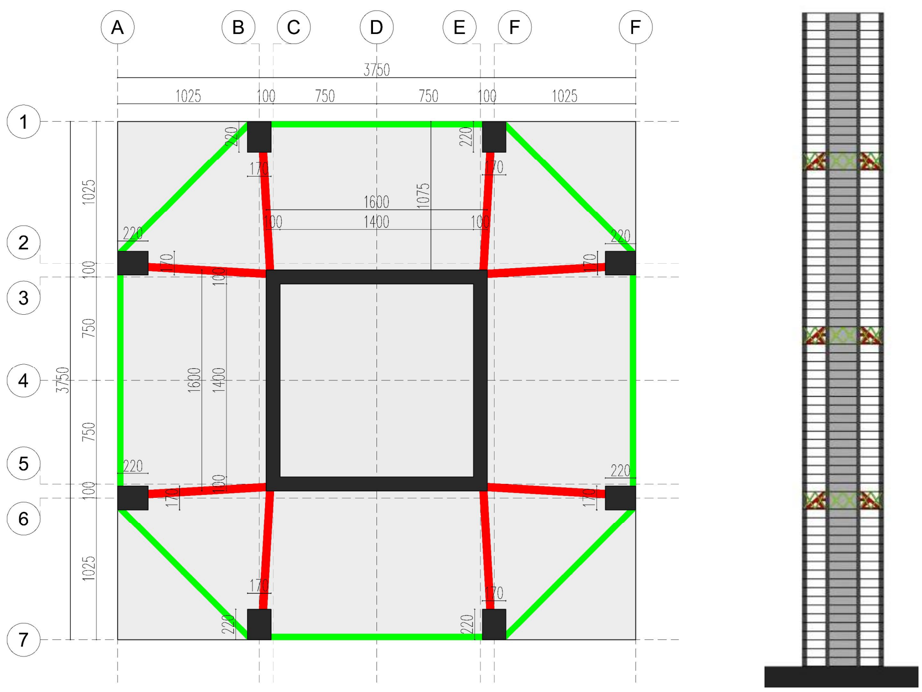


Figure 3.21. Typical floor plan and elevation of model "OF_OPT_3c" with outriggers and belt trusses

OF_OPT_3d

Model version OF_OPT_3d is obtained by addition of a double story belt truss level at the top of the model version "OF_OPT_3c".

Table 3.20. Properties of structural members in model "OF_OPT_3d"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	29.92 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	18-19, 37-38 and 55-56
Belt Truss Floors:	18-19, 37-38, 55-56 and 73-74
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

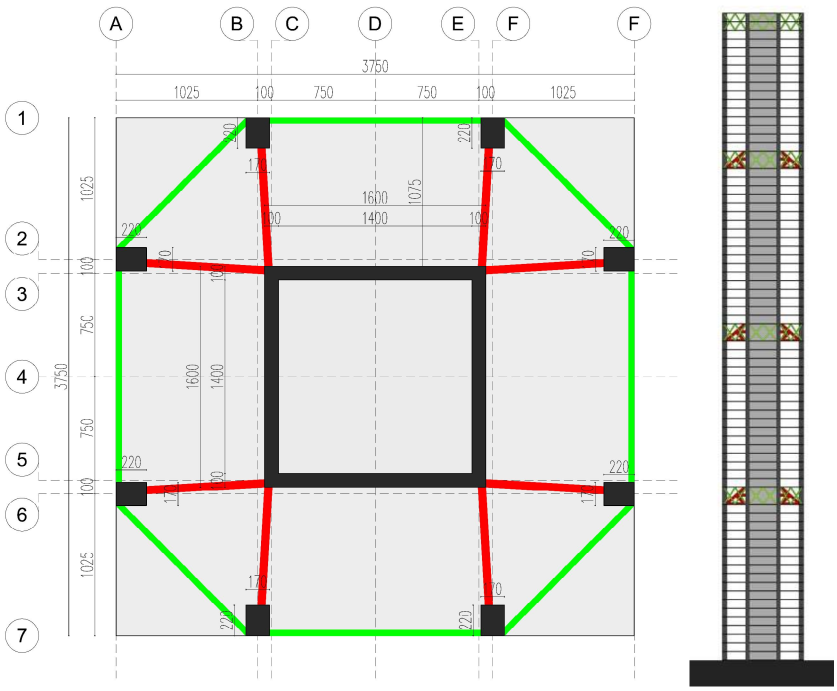


Figure 3.22. Typical floor plan and elevation of model "OF_OPT_3d" with outriggers and belt trusses

OF_OPT_3e

In this model version, 4 level of double story outriggers are replaced to the structure. The outriggers are embedded at 1/5, 2/5, 3/5 and 4/5 of the building.

Table 3.21. Properties of structural members in model "OF_OPT_3e"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	29.92 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	14-15, 29-30, 44-45, 59-60
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

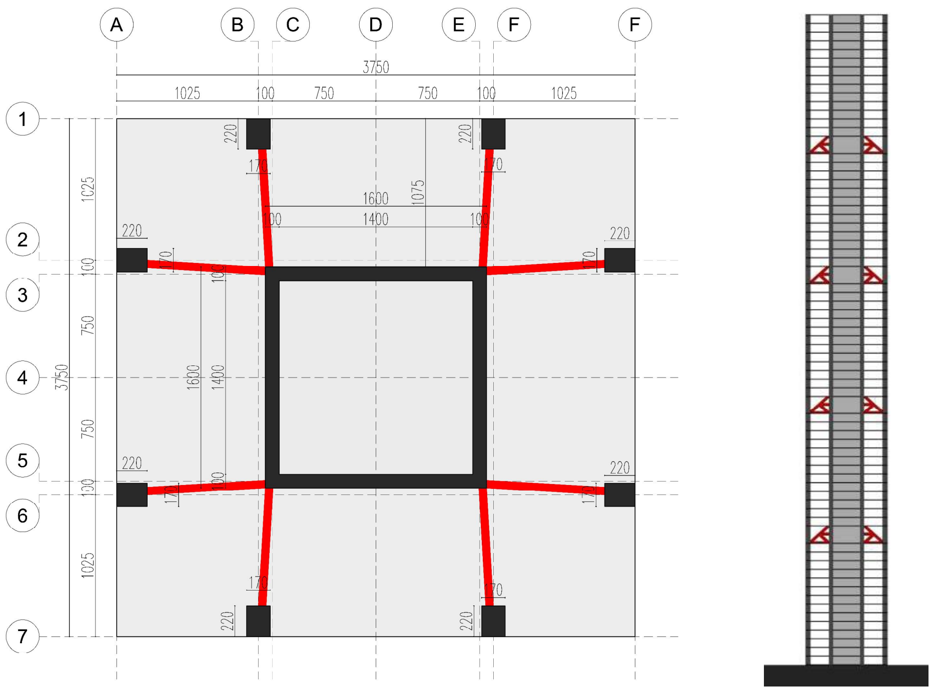


Figure 3.23. Typical floor plan and elevation of model "OF_OPT_3e" with the demonstration of outriggers

OF_OPT_4a

4 corner columns are embedded to the structural system and they are connected to the other columns with belt trusses in order to increase the efficiency of the system.

Table 3.22. Properties of structural members in model "OF_OPT_4a"

Column Type-a Dimensions:	1.7x2.2 m
Number of Columns:	8
Column Type-b Dimensions:	1.5x1.5 m
Number of Columns:	4
Total Column Area per Floor:	38.92 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	24-25 and 49-50
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.18

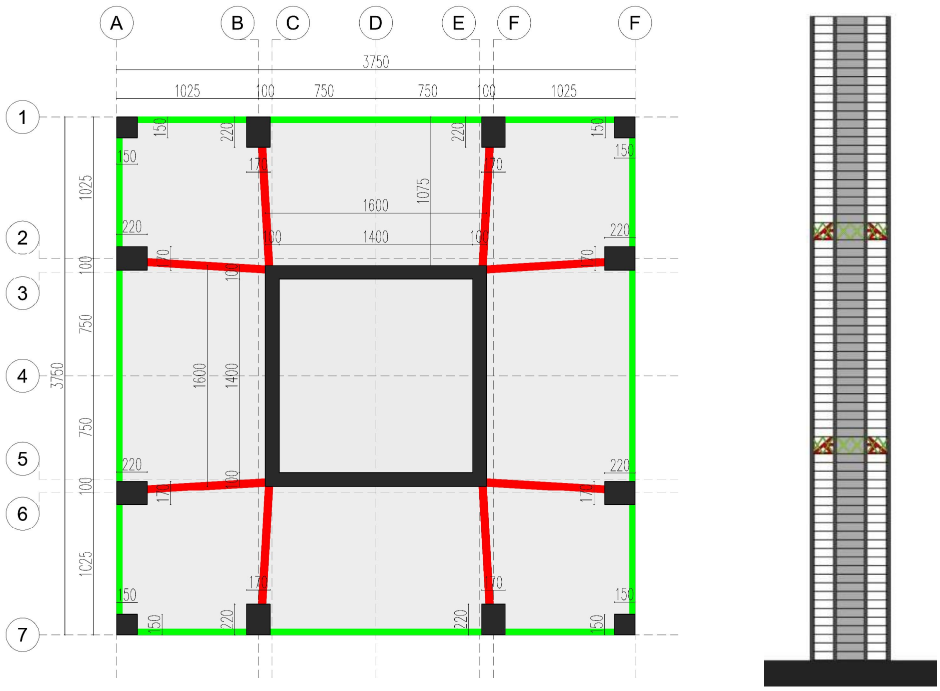


Figure 3.24. Typical floor plan and elevation of model "OF_OPT_4a" with outriggers and belt trusses

OF_OPT_4b

If the columns of model "OF_OPT_3c" is increased, model "OF_OPT_4b" is obtained. The other properties of model "OF_OPT_3c" remains the same.

Table 3.23. Properties of structural members in model "OF_OPT_4b"

Column Type-a Dimensions:	1.75x2.25 m
Number of Columns:	8
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	31.5 m²
Beam Dimensions:	-
Thickness of Core Wall:	100 cm
Outrigger Floors:	18-19, 37-38 and 55-56
Belt Truss Floors:	-
Total Column to Floor Area Ratio:	0.02
Core to Floor Area Ratio:	0.18

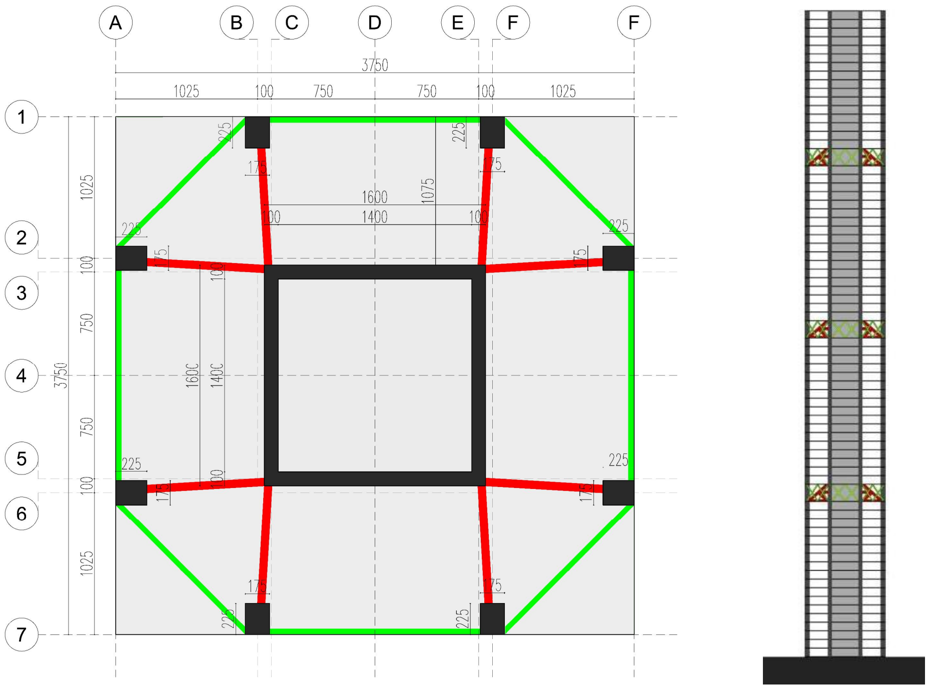


Figure 3.25. Typical floor plan and elevation of model "OF_OPT_4b" with outriggers

Reinforced Building Model Variations for Framed-tube Buildings

There are 5 computer models produced to strengthen the "reduced" core version of framed-tube building. The details of the structural members are presented in the tables below. Besides, typical floor plans with the demonstration of outriggers (if any) are presented. The red lines symbolize outriggers.

FT_OPT_1

The dimensions of the columns and beams are increased as 1.1 to 1.1 meter while the corner columns are 1.15 to 1.15 meter in order to be satisfy safety against seismic loads.

Table 3.24. Properties of structural members in model "FT_OPT_1"

Column Type-a Dimensions:	1.10x1.10 m
Number of Columns:	32
Column Type-b Dimensions:	1.15x1.15 m
Number of Columns:	4
Total Column Area per Floor:	44.01 m²
Beam Dimensions:	1.10x1.10 m
Thickness of Core Wall:	65 cm
Outrigger Floors:	-
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.17

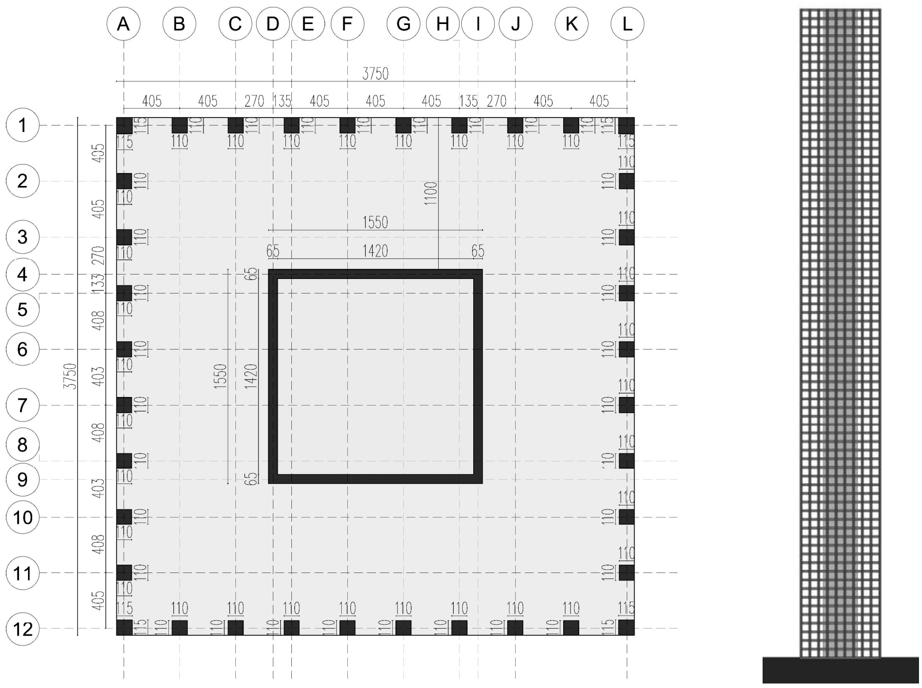


Figure 3.26. Typical floor plan and elevation of model FT_OPT_1

FT_OPT_2

In that model version, only the size of the columns is equally increased without increasing cross-section area of beams.

Table 3.25. Properties of structural members in model "FT_OPT_2"

Column Type-a Dimensions:	1.15x1.15 m
Number of Columns:	36
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	47.61 m²
Beam Dimensions:	1.05x1.05 m
Thickness of Core Wall:	65 cm
Outrigger Floors:	-
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.17

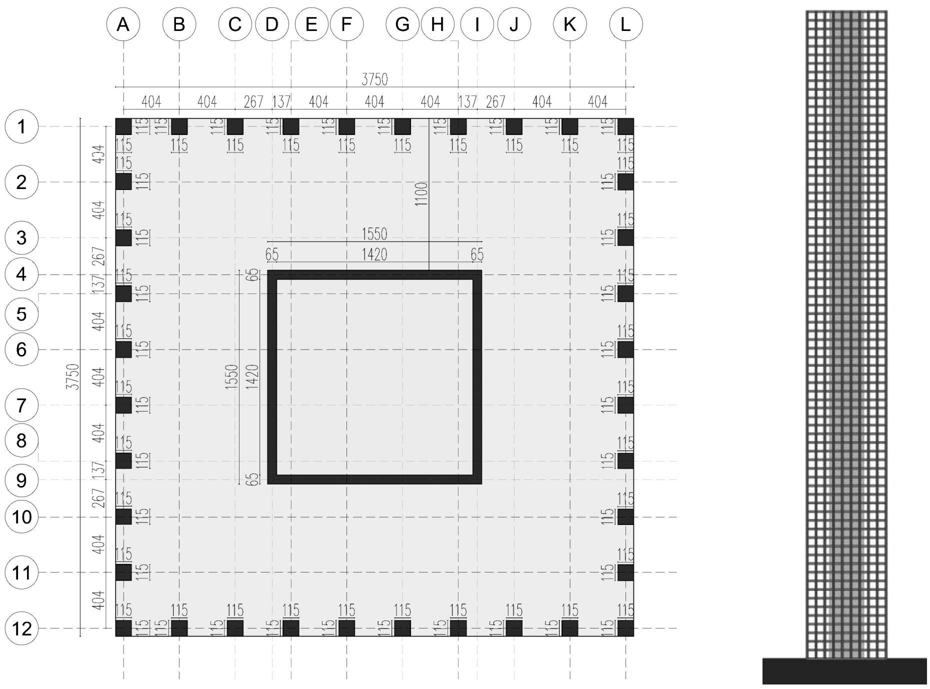


Figure 3.27. Typical floor plan and elevation of model FT_OPT_2

FT_OPT_3

The number of columns is increased without changing the column dimension. The column spacing is same in each facade.

Table 3.26. Properties of structural members in model "FT_OPT_3"

Column Type-a Dimensions:	1.05x1.05 m
Number of Columns:	40
Column Type-b Dimensions:	-
Number of Columns:	-
Total Column Area per Floor:	44.1 m²
Beam Dimensions:	1.05x1.05 m
Thickness of Core Wall:	65 cm
Outrigger Floors:	-
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.17

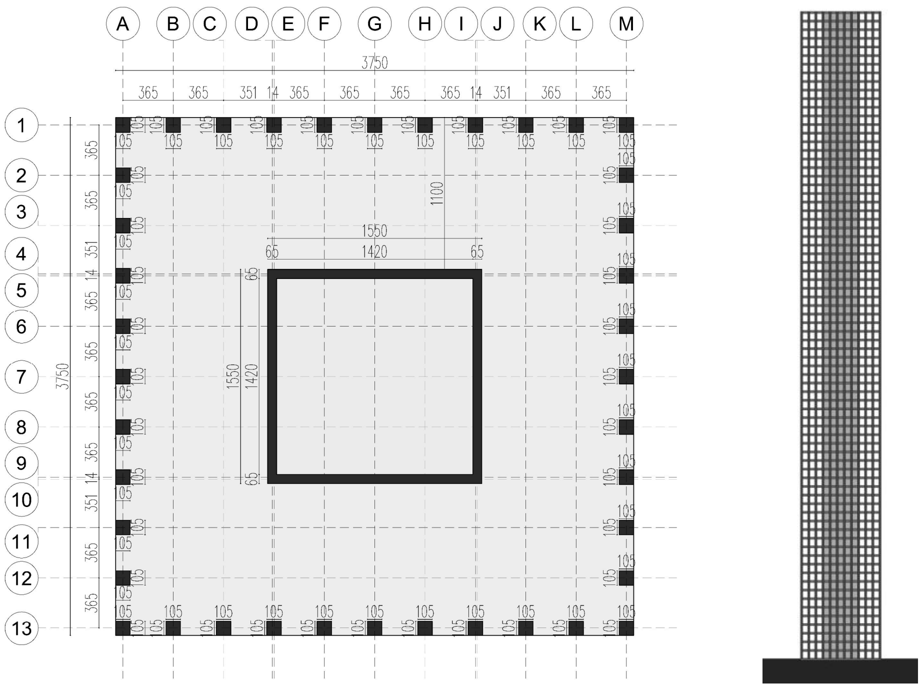


Figure 3.28. Typical floor plan and elevation of model FT_OPT_3

FT_OPT_4a

Firstly, the size of corner columns is increased to interfere failure due to seismic loads and then one of outrigger with double story height is embedded at the 1/2 of the building height.

Table 3.27. Properties of structural members in model "FT_OPT_4a"

Column Type-a Dimensions:	1.05x1.05 m
Number of Columns:	32
Column Type-b Dimensions:	1.25x1.25 m
Number of Columns:	4
Total Column Area per Floor:	41.53 m²
Beam Dimensions:	1.05x1.05 m
Thickness of Core Wall:	65 cm
Outrigger Floors:	37-38
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.17

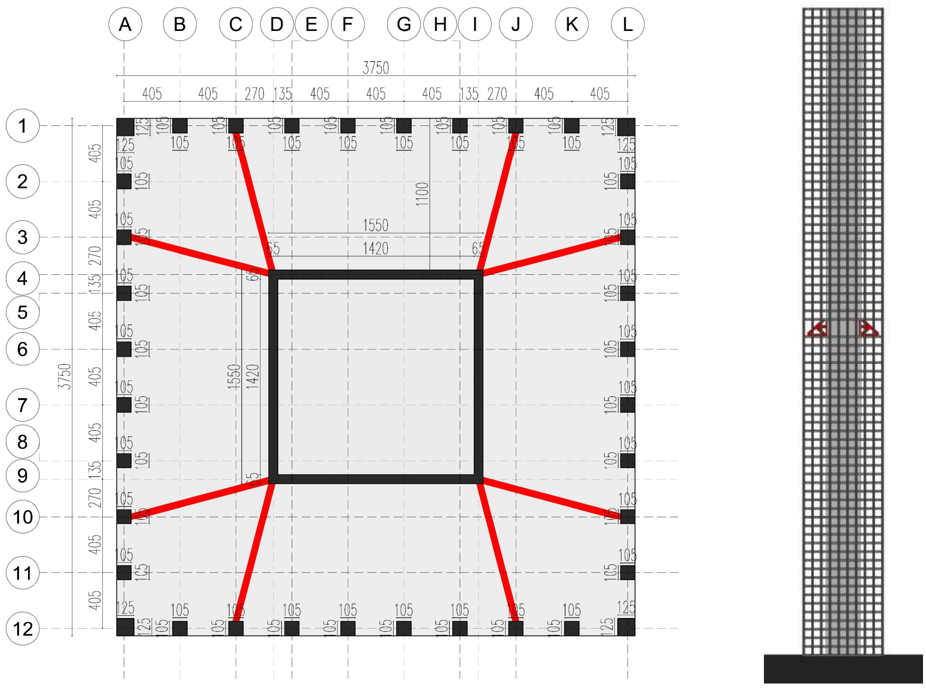


Figure 3.29. Typical floor plan and elevation of model "FT_OPT_4a"

FT_OPT_4b

As in the model "FT_OPT_4a", the column size is increased. However, the double story outriggers are added at the top of the structure.

Table 3.28. Properties of structural members in model "FT_OPT_4b"

Column Type-a Dimensions:	1.05x1.05 m
Number of Columns:	32
Column Type-b Dimensions:	1.25x1.25 m
Number of Columns:	4
Total Column Area per Floor:	41.53 m²
Beam Dimensions:	1.05x1.05 m
Thickness of Core Wall:	65 cm
Outrigger Floors:	73-74
Total Column to Floor Area Ratio:	0.03
Core to Floor Area Ratio:	0.17

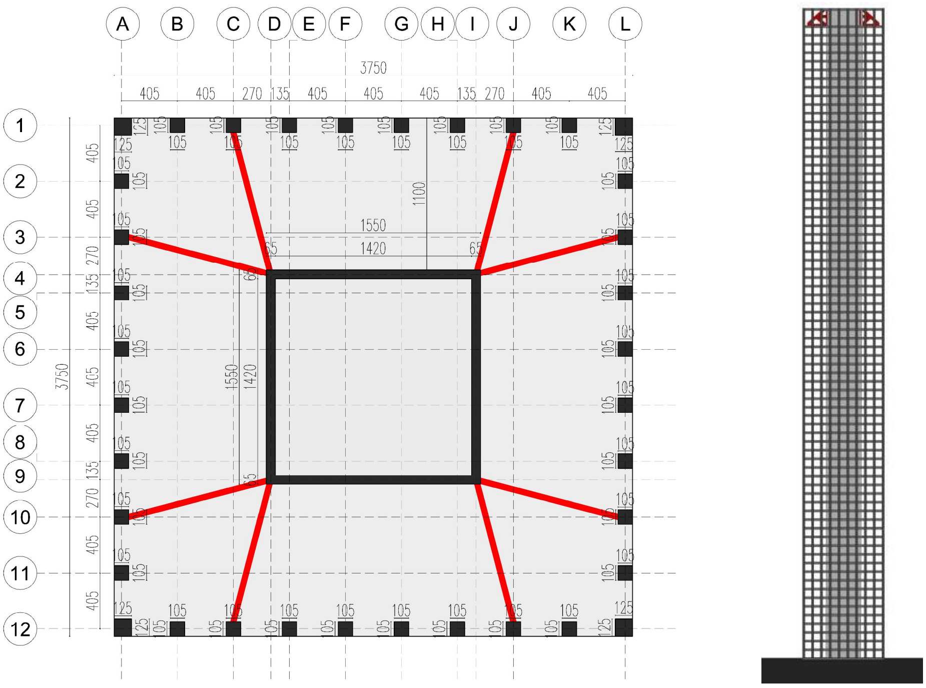


Figure 3.30. Typical floor plan and elevation of model "FT_OPT_4b"

CHAPTER 4

RESULTS AND DISCUSSION

In the previous chapter, floor plans and structural components of the modified models with outriggered frame and framed-tube systems are presented. In this chapter, the structural analysis results of these modified models under wind and seismic loads are evaluated. Wind velocity profiles and response spectra are equivalent for primary core, reduced core models and modified models but the wind load may slightly change because of gust factor. The same applies for response spectrum as well. The base shear due to seismic action changes due to the slight differences between periods of alternative models.

The structural analysis results and plan layouts of various building models are evaluated in structural and architectural point of view and compared to the "primary" core models.

4.1. Evaluation of the Top Drift of Outriggered Frame and Framed-tube Building Models Under Wind Load Combination

In the generation process of the various building models, the size of each structural member is determined in a way that they should be robust enough to resist against seismic and wind loads. The secondary consideration when determining the dimensions of the structural members is that to reach fairly close to the roof drift ratio of primary core versions of outriggered frame and framed-tube buildings which is equal to “0.0021”. The modified buildings whose roof drift ratio is equal to or less than “0.0021” are accepted as “successful”. Yet, some building models could not reach the targeted top displacement value by increasing the number or the size of the structural members. The maximum top displacements under wind load combinations of outriggered frame and framed-tube buildings are given in Figures 4.1 and 4.2.

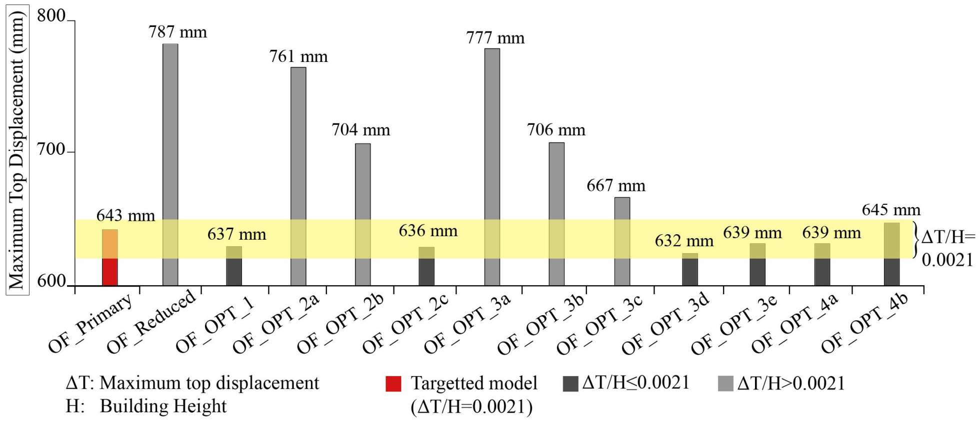


Figure 4.1. Maximum top displacement to building height ratio of outriggered frame buildings

According to Figure 4.1, seven model versions are successful among twelve models (OF_OPT_1, OF_OPT_2c, OF_OPT_3d, OF_OPT_3e, OF_OPT_4a and OF_OPT_4b) whose maximum top displacement is "0.0021" of the building height. By sufficiently enlarging each column of the model of “OF_Reduced”, the roof drift becomes equivalent to “0.0021” as in model “OF_OPT_1”. In model "OF_OPT_2a", four corner columns are added to the structural system. Regardless of the enlargement of each corner column, the structural system could not reach the targeted drift ratio of "0.0021". However, when the corner columns are connected to the structural system with addition of belt trusses at outrigger levels (which corresponds to model "OF_OPT_4a"), the top displacement to building height ratio of the building can reach the value of "0.0021" through being a more integrated entity. In model "OF_OPT_2b", in addition to the corner columns, four more columns are added in the middle of each facade. In other words, there are number of five columns with approximately the same cross-section area in each facade. Nevertheless, the number of columns is insufficient to reach the targeted drift ratio under wind loads. Thus, the number of columns is increased with equal spacing and without changing the column size as in model "OF_OPT_2c". With these modifications, the model “OF_OPT_2c” is succeeded to reach the targeted drift ratio as in Figure 4.1.

In model versions "OF_OPT_3a", "OF_OPT_3b" and "OF_OPT_3c", surrounding the outrigger levels with belt trusses (OF_OPT_3a), or the addition of one more level of double-story outriggers (OF_OPT_3b and OF_OPT_3c) to the building with "reduced" core could not reduce enough the maximum top displacement of the system as targeted. Even so, with some modifications of model "OF_OPT_3c", the targeted top displacement to building height ratio of "0.0021" can be obtained. There are three levels of double story outriggers with belt trusses in model "OF_OPT_3c". If the top two floor levels of model "OF_OPT_3c" are surrounded by belt trusses which corresponds to model "OF_OPT_3d", top displacement decreases enough to achieve the target value. Increasing the column dimensions as an alternative modification on model “OF_OPT_3c” corresponds model “OF_OPT_4b” and yields a top drift ratio of “0.0021”. In addition, by integrating 4 level of double-story outriggers to the structural system at 1/5, 2/5, 3/5 and 4/5 of the building height (OF_OPT_3e), the maximum top displacement can also ensure the target value of "0.0021".

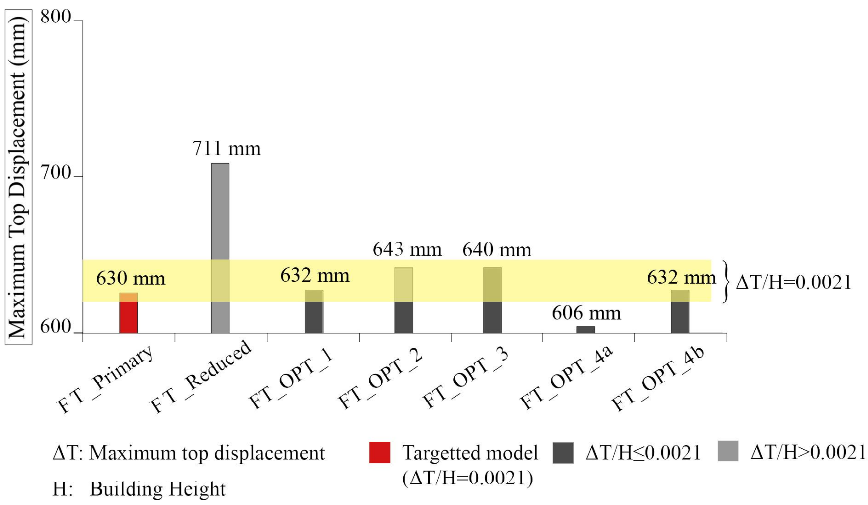


Figure 4.2. Maximum top displacement to building height ratio of framed-tube buildings

All the modified building models with framed-tube system whose top drift ratio under the wind load combination is equal to "0.0021" (FT_OPT_1, FT_OPT_2, FT_OPT_3 and FT_OPT_4b) or less than "0.0021" (FT_OPT_4a) and it is given in Figure 4.2. In model "FT_OPT_1" all the column and beam dimensions are increased equally whereas the size of the corner columns has been made slightly bigger than the other column dimensions to satisfy design constraints against seismic loading. As a result, model “FT_OPT_1” is succeeded to ensure targeted drift ratio.

If the width and length of the columns in model “FT_Reduced” are equally increased by 10 cm with a 5 cm reduction in spandrel beam depth, which corresponds to model “FT_OPT_2”, the targeted drift ratio of “0.0021” is ensured. (It should be noted that, the reinforced concrete or beam members of all modified models are increased as multiples of 5 cm due to constructability in each iterative analysis process). By increasing the number of columns (FT_OPT_3), the targeted value of top displacement to building height can also be ensured.

In model "FT_OPT_4a" where, double story outriggers are added at the middle of the building height, the top drift ratio less than targeted drift ratio has been achieved. Alternatively, if the double-story outriggers are placed at the top of the building, which corresponds to model “FT_OPT_4b”, the top drift ratio reaches the targeted value of “0.0021”.

According to the results given above, the selected model variations of outriggered frame (six models) and framed-tube buildings (five models) with the top displacement to building height ratio of "0.0021" are examined in next sections.

Comparison of "reduced" core building models of outriggered frame to framed-tube

The structural analysis results are evaluated by comparison of various models of reduced core system, either outriggered-frame or framed-tube, with corresponding to "primary" core buildings. In other words, the comparisons between top drift values have been made within a particular structural system. In addition to this, similar comparisons can be made between structural systems. It can be concluded that the effect of the decrease in service core area depends on the type of the structural system. The top displacement of the outriggered frame building (643 mm) increases (787 mm) with 22 percent when the service core area is reduced (Figure 4.1). However, if the service core of the framed-tube building is reduced, the top displacement increases only 12.9 percent (from 630 mm to 711 mm, Figure 4.2). The relative increase in top displacement of outrigger-framed system with reduced core is more because the contribution of service core to the structural system in outriggered frame systems (which is an example to interior structures) is much more than in framed-tube systems (which is an example to exterior structures).

4.2. Evaluation of Successful Modified Models with Ouriggered Frame and Framed-tube System

Six models of outriggered frame system with reduced core and five alternatives of framed-tube system with reduced core satisfy the initial drift constraint. Alternative approaches which are used in selected building models with outriggered frame and framed-tube systems are further investigated in this study. These approaches are:

• increasing the existing column dimensions

• increasing the number of columns

• increasing the thickness of the shear walls

• increasing the number of outriggers and/or belt trusses

• combination of some of these methods

The effects of these approaches are examined according to several aspects that are given below:

• change in leasable area of office floors

• how the structural behavior of the system is shaped by these modifications

• the change in structural material usage

• floor plan configuration and panoramic view through building facade

By the application of these modifications, some building models reach the targeted top drift and accepted as successful. The successful building models with outriggered frame buildings are given in Table 4.1 and with framed-tube buildings are given in Table 4.3. However, the reduced core models and some variants of reduced core model is unable to ensure the targeted top drift ratio which are given in Table 4.2 for outriggered frame systems and Table 4.4 for framed-tube systems.

Table 4.1. Key plans and elevations of the successful buildings with outriggered frame system

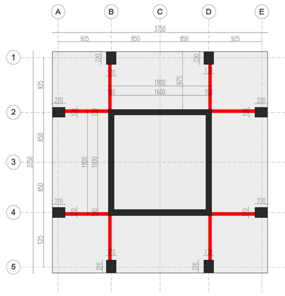
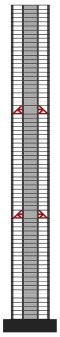
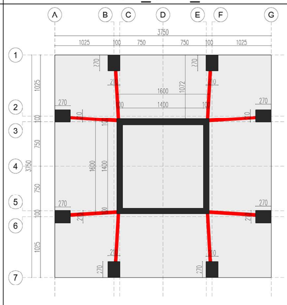
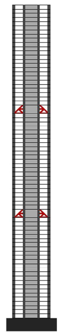
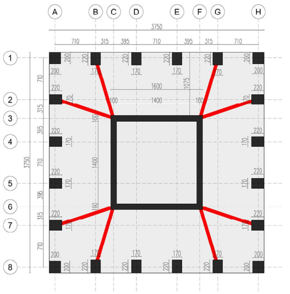
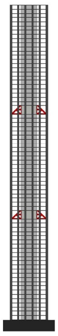
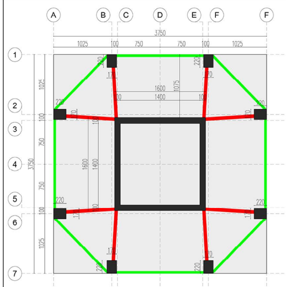
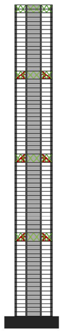
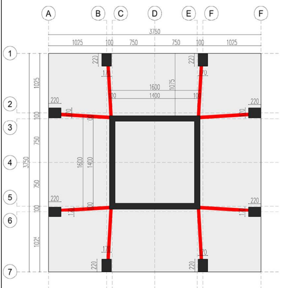
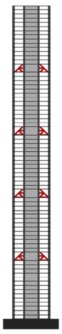
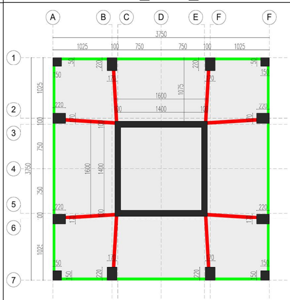
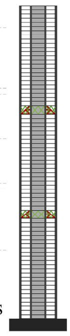
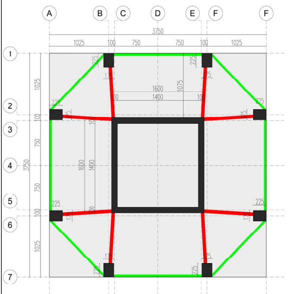
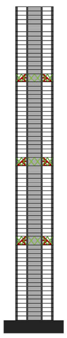
OF_Primary	OF_OPT_1
  the building utilizing current elevator systems (primary core)	  each column size is increased with the same proportions
OF_OPT_2c	**OF_OPT_3d**
  number of columns are increased with equal spacing	  3 level of outriggers surrounded with belt trusses and a top level of belt trusses
OF_OPT_3e	**OF_OPT_4a**
  4 level of outriggers	  addition of corner columns and belt trusses at outrigger levels
OF_OPT_4b	
  3 level of outriggers surrounded with belt trusses and larger columns	

Table 4.2. Key plans and elevations of the unsuccessful buildings with outriggered frame system

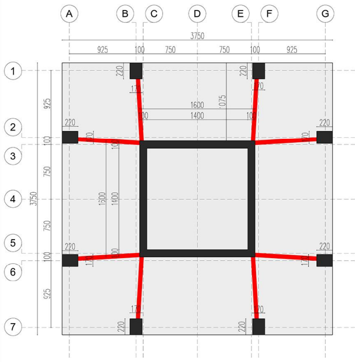
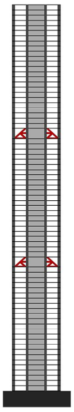
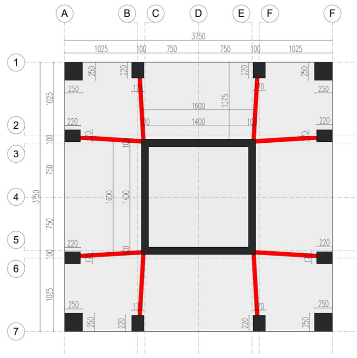
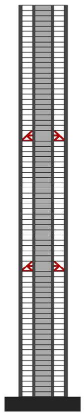
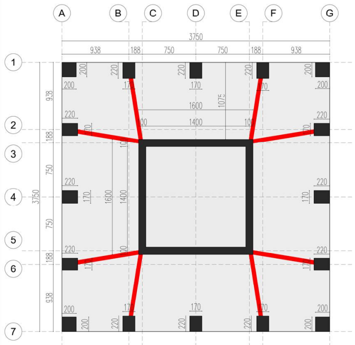
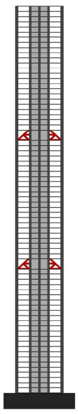
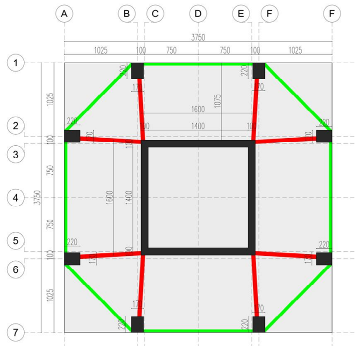
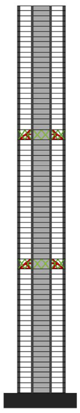
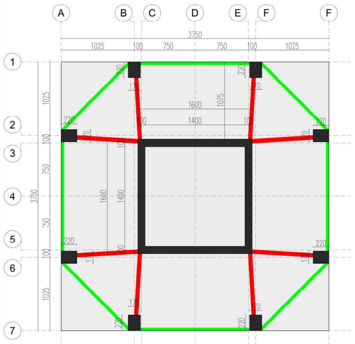
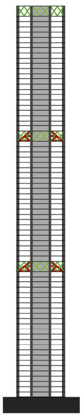
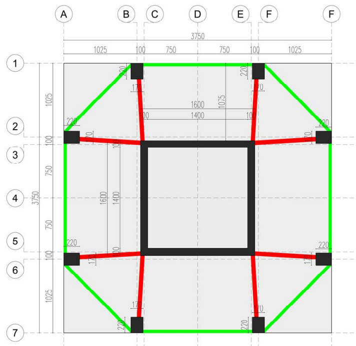
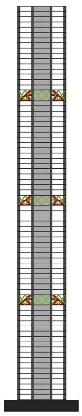
OF_Reduced	**OF_OPT_2a**
  the building utilizing recent elevator systems (reduced core)	  reduced core building with corner columns
OF_OPT_2b	**OF_OPT_3a**
  reduced core building with corner and middle columns	  reduced core building with belt truss addition to outrigger levels
OF_OPT_3b	**OF_OPT_3c**
  reduced core building with top level outrigger and belt truss addition to out. levels	  reduced core building with one more level of outriggers (3 level of outriggers in total)

Table 4.3. Key plans and elevations of the successful buildings with framed-tube system

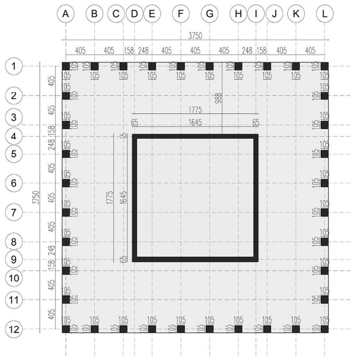
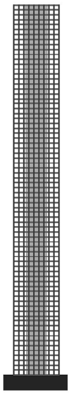
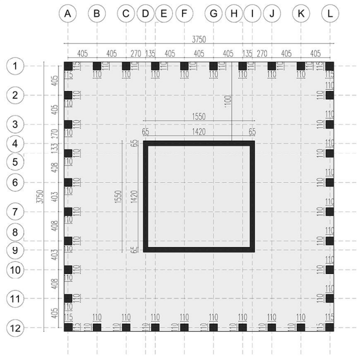
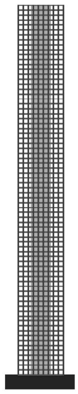
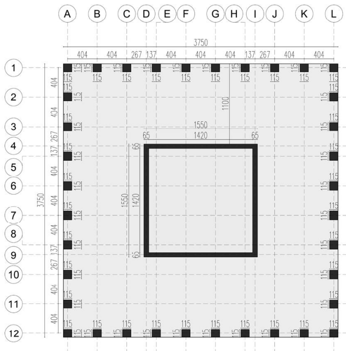
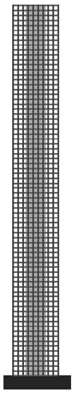
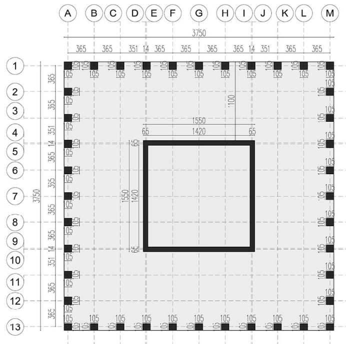
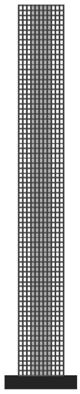
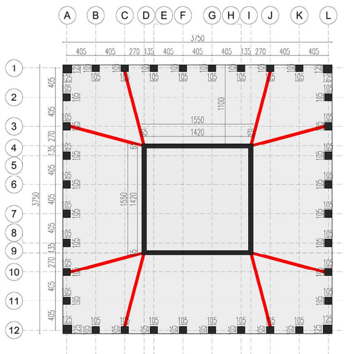
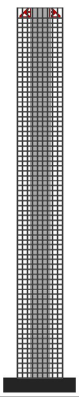
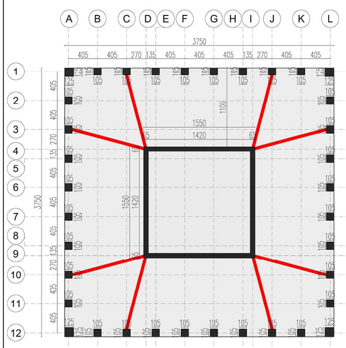
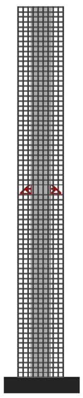
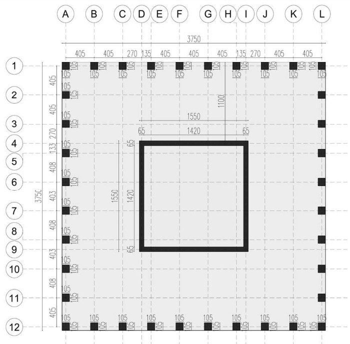
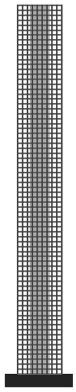
FT_Primary	FT_OPT_1
  the building utilizing current elevator systems (primary core)	  each column and beam dimensions are increased
FT_OPT_2	**FT_OPT_3**
  reduced core building with bigger columns and smaller beams	  number of columns are increased (with a different modulation)
FT_OPT_4a	**FT_OPT_5b**
  corner column dimensions are increased and a top level outrigger level is added	  reduced core building with bigger corner columns with one level of outrigger in the middle

Table 4.4. Key plan, elevation and brief explanations of the unsuccessful building with framed-tube system (only the reduced core)

FT_Reduced





the building utilizing recent elevator systems (reduced core)

4.2.1. Leasable Area

Mueller (2016) claimed that the elevator footprint decreases up to 50 percent with the application of recently developed elevator technologies. When the service core area of "primary" core buildings is decreased based on this estimate, the leasable area of the "reduced" core should increase. The expected increase in leasable area can be found for outriggered-frame and tube systems. When compared to the outriggered building with "primary" core, the leasable area of the "reduced" core model with outriggered frame would increase "4828 m²" or "6.46 percent" if the original reduced core system (OF_Reduced) satisfied the top drift limitation. Nevertheless, to reduce the top drift below reference level (top drift of OF_Primary), several improvements in structural system have been made. As shown in Table 4.5 and Figure 4.3, the maximum leasable area is achieved in model "OF_OPT_4a" with 5.61 percent increase. The least leasable area increase is in model “OF_OPT_3e” with 0.46 percent.

Table 4.5. Properties of the selected outriggered frame buildings

	OF_ Primary	OF_ Reduced	OF_ OPT_1	OF_ OPT_2c	OF_ OPT_3d	OF_ OPT_3e	OF_ OPT_4a	OF_ OPT_4b
Typical Column Area (m^2)	3.74	3.74	5.67	3.74	3.74	3.74	3.74	3.94
Corner Column area (m^2)	-	-	-	4.00	-	-	2.25	-
Number of Typical Columns	8	8	8	16	8	8	8	8
Number of Corner Columns	-	-	-	4	-	-	4	-
Total Column Area per Floor (m^2)	30	30	45	76	30	30	39	32
Service Core Area per Floor (m^2)	324	256	256	256	256	256	256	256
Gross Floor Area per Floor (m^2)	1406	1406	1406	1406	1406	1406	1406	1406
Leasable Area per Floor (m^2)	1052	1120	1105	1074	1120	1120	1111	1119
Number of Removed Floors	2	2	2	2	3	4	2	3
Number of Ooutrigger Floors	2	2	2	2	3	4	2	3
Number of Office Floors	71	71	71	71	69	67	71	69
Total Floor Area (m^2)	102656	102656	102656	102656	101250	99844	102656	101250
Total Leasable Area (m^2)	74715	79543	78447	76283	77303	75062	78904	77194
Leasable Area Increase compared to "Primary"(m^2)	-	4828	3732	1568	2587	347	4189	2478

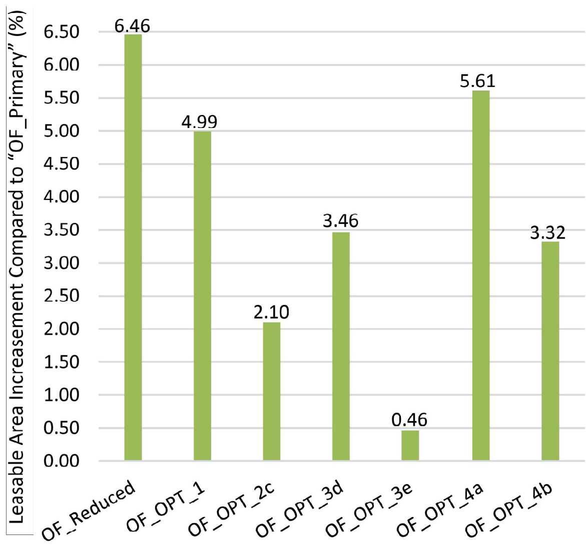


Figure 4.3. Leasable increase of outriggered frame buildings compared to "OF_Primary"

The expected leasable area increase based on the current literature is also calculated for the "reduced" core building with framed-tube system. The difference between the leasable area of the "primary" and the "reduced" core buildings with framed-tube systems is equal to "5610.94 m²" with "7.11" percent increase (Table 4.4). When the selected modified models are examined, the maximum leasable area is obtained with the model "FT_OPT_4a" with 6.95 percent. Nevertheless, the difference between the expected increase (84473 m² in the "reduced" model) and the maximum increase (84149 m² in model "FT_OPT_1") in leasable area is equal to "324 m²" or "0.41 percent" (Figure 4.4 and Table 4.4).

Table 4.6. Properties of the selected framed-tube buildings

	FT_ Primary	**FT_ Reduced**	**FT_ OPT_1**	**FT_ OPT_2**	**FT_ OPT_3**	**FT_ OPT_4a**	**FT_ OPT_4b**
Typical Column Area (m²)	1.10	1.10	1.21	1.32	1.10	1.10	1.10
Corner Column area (m²)	-	-	1.32	-	-	1.56	1.56
Number of Typical Columns	36	36	32	36	40	32	32
Number of Corner Columns	-	-	4	-	-	4	4
Total Column Area per Floor (m²)	40	40	44	48	44	42	42
Service Core Area per Floor (m²)	315	240	240	240	240	240	240
Gross Floor Area per Floor (m²)	1406	1406	1406	1406	1406	1406	1406
Leasable Area per Floor (m²)	1051	1126	1122	1118	1122	1124	1124
Number of Removed Floors	0	0	0	0	0	1	1
Number of Ooutrigger Floors	0	0	0	0	0	1	1
Number of Office Floors	75	75	75	75	75	73	73
Total Floor Area (m²)	105469	105469	105469	105469	105469	102656	104063
Total Leasable Area (m²)	78862	84473	84149	83886	84143	82086	82086
Leasable Area Increase compared to "Primary"(m²)	-	5611	5287	5024	5280	3224	3224

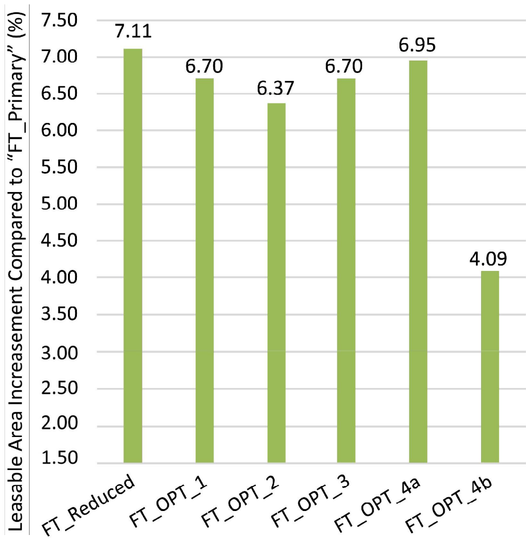


Figure 4.4. Leasable increase of framed-tube buildings compared to "FT_Primary"

To summarize, even if the expected increase in leasable area when compared to the building model versions with reduced core cannot fully achieved, the leasable area of all the models increases in some degree. When the modified building models of both structural systems are compared to each other, the realized leasable area increasement in framed-tube buildings "6.95 percent" are more than the realized leasable area increasement in outriggered frame building models, "5.61 percent" (Tables 4.3 and 4.4). Thus, it can be concluded that the framed-tube buildings are more efficient than outriggered frame systems in terms of the acquired leasable area increase due to use of recently developed elevator technologies. When the service core area is decreased, the buildings with outrigger systems is much more affected than the buildings with framed-tube systems in terms of structural strength so the structural system should be supported with more structural components which results in less net floor area.

4.2.2. Behavior of the Structural Systems

The structural systems are classified into two main groups according to the amount of contribution of the core and the perimeter columns to resist lateral loads. When the "primary" core buildings of outriggered frame and framed-tube systems are subjected to wind load combination, the base moment which is shared between the service core and the perimeter columns differs. The moment carried by the service core and the perimeter columns of the outriggered frame building with the "primary" core is almost the same (Figure 4.5). However, in the framed-tube building with the "primary" core, the moment carried by the perimeter columns are almost twice of the moment at service core (Figure 4.6). By the reduction of the service core area, the perimeter columns become more dominant in the share of base moments for both structural systems. However, the base moment-share between the core and the perimeter columns differ based on the modifications of the structural systems.

In the selected outriggered frame buildings, base moments in the perimeter columns are more than the base moments in the service core. As much as the perimeter columns share a bigger portion of the base moments, the structural system acts like a "framed-tube building". The base moment share between the core and the perimeter columns of each selected building is given in Table 4.7 in percentages.

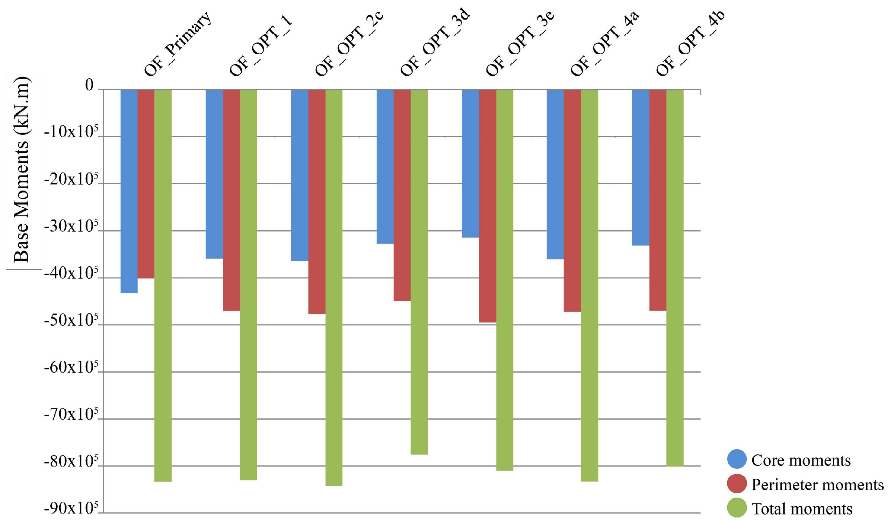


Figure 4.5. Base moments of outriggered frame buildings

Table 4.7. Base moment share in percentage of outriggered frame buildings

	Core (%)	Perimeter (%)
OF_Primary	51.83	48.17
OF_OPT_1	43.34	56.66
OF_OPT_2c	43.27	56.73
OF_OPT_3d	42.13	57.87
OF_OPT_3e	38.84	61.16
OF_OPT_4a	43.32	56.68
OF_OPT_4b	41.31	58.69

In the selected framed-tube models of "FT_OPT_1", "FT_OPT_2", "FT_OPT_3", "FT_OPT_4a" and "FT_OPT_4b", the moments at the perimeter columns are more than the building with the "primary" core model. As a result, the base moments at the perimeter columns increases so all the building models continue to display tubular behavior.

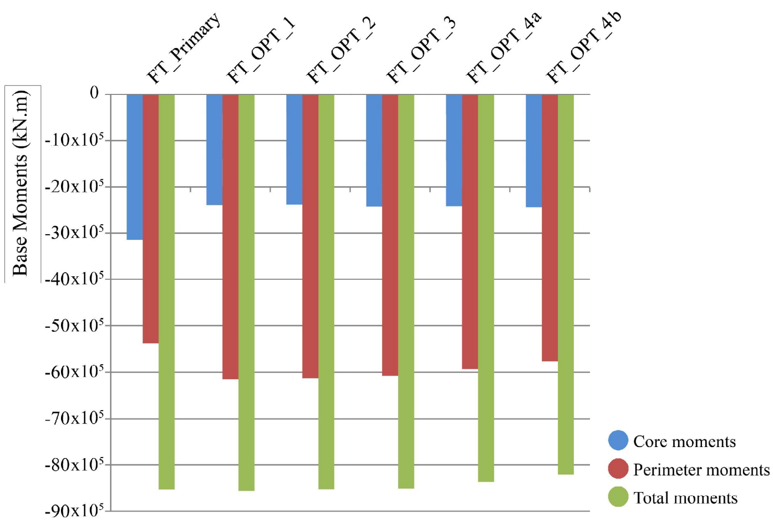


Figure 4.6. Base moments of framed-tube buildings

Table 4.8. Base moment share in percentage of framed-tube buildings

	Core (%)	Perimeter (%)
FT_Primary	36.94	63.06
FT_OPT_1	28.05	71.95
FT_OPT_2	28.07	71.93
FT_OPT_3	28.54	71.46
FT_OPT_4a	29.00	71.00
FT_OPT_4b	29.79	70.21

4.2.3. The quantity of Structural Material Usage

The modifications that are applied to the reduced service core of outriggered frame and framed-tube buildings comprises either increasing the cross-section area of existing columns or adding new structural members like columns or outriggers and belt trusses. In each modification type, the amount of structural material usage changes. In the scope of this study, the quantity of structural material usage is investigated according to two main aspects:

• the amount of reinforced concrete which is used in columns, beams, shear walls and floors,

• the amount of steel based on the number of outrigger and belt truss levels

In the calculation of the quantity of reinforced concrete, the building foundation is disregarded.

Total concrete use for the successful modified models with outriggered frame system is given in Table 4.9. The concrete use is minimum in model "OF_OPT_3e" which is "4.14 percent" less than the concrete use in the "primary" core building version (Figure 4.7). However, in this model, two more outrigger levels are added to the building. If the buildings with only two outrigger levels as in the "primary" core version is examined, concrete use is minimum in the model ""OF_OPT_1" (Table 4.9) with only "1.6 percent" more than the "primary" core building version (Figure 4.7).

Table 4.9. Amount of concrete use and outriggers and belt truss levels in outriggered frame buildings

	OF_ Primary	OF_ OPT_1	OF_ OPT_2c	OF_ OPT_3d	OF_ OPT_3e	OF_ OPT_4a	OF_ OPT_4b
Concrete quantity of columns (m^3)	8737	13245	22145	8617	8497	11365	9072
Concrete quantity of shear walls (m^3)	20400	18000	18000	18000	18000	18000	18000
Concrete quantity of floors (m^3)	102656	102656	102656	101250	99844	102656	101250
Total concrete use (m^3)	131793	133901	142802	127867	126341	132021	128322
Number of double-storey outrigger levels	2	2	2	3	4	2	3
Number of double-storey belt truss levels	-	-	-	4	-	2	3

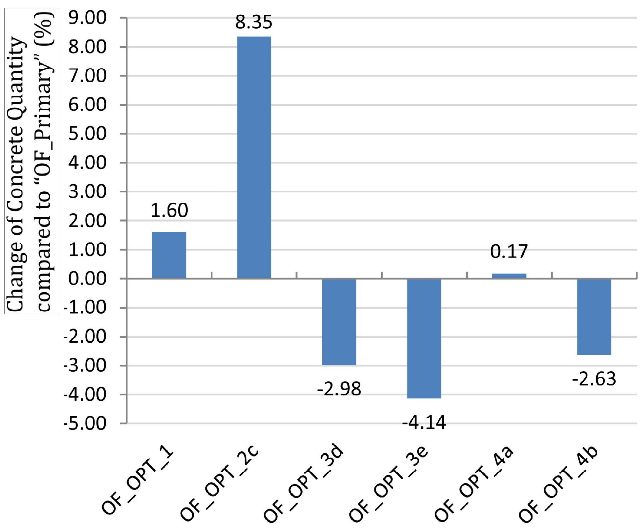


Figure 4.7. Change of concrete quantity compared to the outriggered frame building with the "primary" core in percentages

The amount of concrete use and the number of outrigger and belt truss levels with framed-tube buildings are given in Table 4.10. The reinforced concrete use is minimum in model "FT_OPT_4b" that is “1.25 percent” less than reinforced concrete use in “FT_Primary”. However, even if the total concrete use is relatively less, one level of double story outriggers is integrated to the structural system. The second minimum total reinforced concrete use without outrigger levels belongs to model "FT_OPT_2" (Table 4.10). It is only “0.57 percent” more than the reinforced concrete use in model “FT_Primary”. The change in the amount of reinforced concrete use of the selected framed-tube buildings when compared to the building with "primary" core is indicated in Figure 4.9.

Table 4.10. Amount of concrete use and outriggers and belt truss levels in framed-tube buildings

	FT_ Primary	FT_ OPT_1	FT_ OPT_2	FT_ OPT_3	FT_ OPT_4a	FT_ OPT_4b
Concrete quantity of columns (m^3)	11907	13203	14256	12036	12432	12293
Concrete quantity of beams (m^3)	12403	13613	11250	12403	12210	12238
Concrete quantity of floors (m^3)	105469	105469	105469	105469	104063	104063
Concrete quantity of shear walls (m^3)	3335	2896	2896	4318	2857	2857
Total concrete use (m^3)	133113	135180	133871	134226	131562	131450
Number of double-storey outrigger levels	-	-	-	-	1	1
Number of double-storey belt truss levels	-	-	-	-	-	-

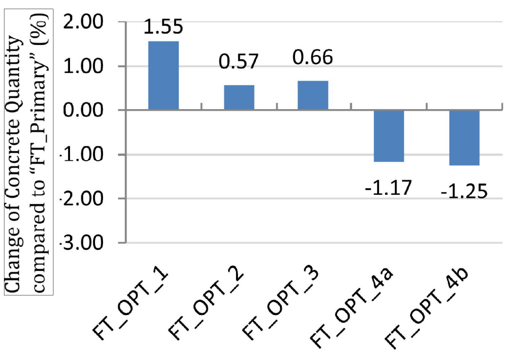


Figure 4.8. Change of concrete quantity compared to the framed-tube building with the "primary" core in percentages

4.2.4. Panoramic View and Access to Natural Light

Natural light for daylight intake is essential for building users. If the number or the width of perimeter columns or beam depth increases, the amount of natural light that penetrates through the building floors decreases. Besides, when the number of columns is increased as in the building models of "OF_OPT_2c", "OF_OPT_4a" and "FT_OPT_3", the panoramic view from the building floors are obstructed by these columns. Especially, the disadvantage of framed-tube system is the obstruction of panoramic view with the use of deep spandrel beams and closely spaced columns.

In tall buildings, lease span is another factor that affects the amount of natural light intake to the building floors. When the service core area is reduced, the natural light cannot reach to the floor area close to the core. As mentioned before, even some countries limited the maximum lease span because of the natural light use. The lease span of the outriggered frame building with "primary" core is "9.75 m", while it is “9.88 m” in the framed-tube building with “primary” core. If the service core area is reduced due to utilization of the new elevator technologies, lease span increases to “10.75 m” in the modified models with outriggered frame system and “11.00 m” in the modified models with framed-tube system.

CHAPTER 5

CONCLUSION

The amount of leasable area has great importance in tall building design because it should compensate the high land prices and the expensive construction of tall buildings. Mueller (2016) claimed that with the new developments in elevator technologies, the footprint of elevators decreases up to 50 %. Assuming that the service core area decreases proportional with the reduction in elevator footprint area, one may expect an increase in net leasable area. However, the service core usually used as a structural member that primarily resist lateral loads. Thus, due to the decrease in core area in tall buildings, the stiffness and strength limits can be infringed. The level of contribution of the structural core to the building performance also varies depending on the type of the structural system. Tall building structural systems are mainly classified according to the distribution of the main lateral load resisting structural elements over the building. There are exterior buildings, in which the main lateral load resisting structural elements are placed at the building perimeter, and interior buildings, in which the main lateral load resisting structural elements are placed within the interior of the building.

In this study, generic buildings are produced with outriggered frame systems (as an example to interior structures) and with framed-tube systems (as an example to exterior structures) according to the existing building examples which utilize current traditional elevator technologies. Then, the service core of the buildings is reduced according to the assumption that they utilize recently developed elevator technologies. When the service core area is reduced, the wind induced top drift of the building with outriggered frame system is increased more than the top drift of framed-tube system. Then, the reduced core building versions of each structural system is strengthened by several modifications by considering particular architectural and structural aspects of outriggered frame and framed-tube systems. The aim of these modifications is to reduce the top drift ratio to its initial value (0.0021). Various building models are generated according to these modifications with outriggered frame and framed-tube systems and design wind lateral loads are applied to each building model in ETABS. The structural analysis results and building features of these various models are compared to the primary core versions of outriggered frame and framed-tube systems. Then the results are evaluated in terms of economics, the evolution of structural systems and architectural considerations.

5.1. Evaluation of Economics through the Modified Building Models

It is claimed in the literature that with the application of recently developed elevator technologies net floor area increases which is economically quite valuable in tall buildings. However, when these elevator technologies are applied to tall buildings, the quantity of structural components should be increased in order to improve the lateral performance of weakened structural system due to the reduction of the service core. For example, in some of the building models, the size of columns or the number of columns is increased. The expected increase without structural modifications in outriggered frame buildings is equal to “6.46 percent” whereas the maximum increase among the successful modified outriggered frame buildings is equal to “5.61 percent”. For framed-tube buildings, the difference between the expected (7.11 percent) and the real increase (6.95 percent) in maximum leasable area is less than the difference in outriggered frame systems. It means that, more leasable area can be obtained for the buildings with framed-tube systems by the utilization of recently developed elevator technologies.

For office buildings, there should be mechanical levels approximately in every 20 floors and for mixed-use buildings it should be in every 25 floors (CTBUH Tall Buildings Height Calculators, n.d.). In most of the tall buildings with outriggers, the outrigger levels are superposed on the mechanical floor levels for floor area efficiency.

However, the existence of mechanical floors and the influence of this on outrigger location as well as corresponding loss in net leasable area haven't been used as a variable in this study. The location of the outrigger levels has been identified by using the optimum structural location formula given by Smith and Coull (1991).

There are other factors which affect the economics of tall buildings such as quantity of structural materials and use of outriggers and belt trusses. When the number of columns or the size of the columns increases, the amount of concrete used for the building also increases. Yet, the total amount of concrete use in some of the building models decreases up to "4.14 percent" in outriggered frame system and up to "1.17 percent" in framed-tube system in comparison to their primary core building versions. Even if the total amount of concrete decreases in some of the building cases, their structural system is supported with additional steel outriggers and/or with steel belt trusses. Choi, Ho, Joseph and Mathias (2014) indicated that the use of outrigger or belt truss can significantly slow the erection process of tall buildings. Besides, the construction cost increases due to the cost of complex construction techniques of outriggers and belt trusses. Thus, for a holistic approach to building economics, the gain in leasable area should be evaluated together with the increased costs due to the increase in the amount of structural material use (concrete and structural steel) and workmanship and prolonged time of construction.

5.2. Evolution of Structural Systems by Use of Recently Developed Elevator Technologies

The modification methods to strengthen the structural system of the buildings having reduced service core can be achieved by the increase of total cross-section area of the structural members at the building perimeter. In all successful trials, base moment resulted from the wind loads at the service core decreases while it increases at the perimeter columns when compared to the outriggered frame building with primary core. Especially in one of the models with increased number of columns having 20 columns on a typical floor, since the number of columns substantially increases, the structure inherently behaves like a tubular system. Yet, since there are no deep spandrel beams, the perimeter of the structural system is not that efficient. In conclusion, most of the modified buildings with outrigger systems start exhibiting "tubular behavior".

If the base moment share between the core and the perimeter of the modified reduced core building versions with framed-tube systems are evaluated, in each building case the perimeter members carry the bigger portion of the base moments. Thus, it can be inferred that structural systems of tall buildings around 300 meters start to be transformed into exterior structures if the use of recently developed elevator systems become widespread.

5.3. Evaluation of the Architectural Considerations via Utilizing Recently Developed Elevator Technologies

The modifications in order to satisfy the strength and serviceability limits of tall building models with reduced core, for both outriggered frame and framed-tube systems lead to reduction in panoramic view from interior and in benefiting from natural light in terms of architectural point of view. As the number or the width of the perimeter columns increases, the panoramic view from the building interior is obstructed and the natural light that penetrates throughout the building facade decreases. In addition, the amount of natural light within the usable floor area is a function of lease span. As the lease span increases, the both the quality and quantity of natural light at places close to the building core reduces. Indeed, as it is indicated in the literature, some countries identified a certain limit for maximum allowable lease span for tall buildings, in order to efficiently benefitting from natural light. The increase in lease span increase is equal to 1 meter and 1.12 meter for the modified outriggered frame and framed-tube buildings, respectively. It means that even if more leasable area can be obtained by the utilization of recently developed elevator technologies, users close to the service core may not benefit from the natural light enough.

5.4. Research Summary

The research question of this study is that how tall buildings' structure and design can be affected by the reduction of service core area especially resulted from considerable decrease in elevator footprint area. In order to analyze the effects of service core reduction, firstly the characteristics of structural system of existing tall buildings are investigated. Based on the existing tall building examples, typical office building models with a height of 300m are generated and analyzed under specific lateral load cases. The results of the structural analysis of computer models reveal that service core reduction increases the top drift of a tall building with outriggered frame structural system (interior structure) more than a building with framed-tube structural system (exterior structure). Besides, when the footprint of a core decreases, the amount of lateral load that should be resisted by perimeter columns increases so the structural systems of the building models are strengthened with some modifications. These modifications affect structural material use, the behavior of the structural system, floor plan configuration, panoramic view from inside and the amount of natural light penetrates through floors. Although the leasable area is increased in some successful trials, this study aims to present the structural and architectural trade-offs originated from the decrease in the area of the core. By presenting the economic, structural and architectural aspects of diverse modified building models, it is aimed to produce a source to be used for choosing optimum configurations in case of using recently developed elevators. An optimum, or namely the best, building configuration among modified buildings cannot be simply addressed since it depends on multiple factors for decision makers (such as architect, contractor, building owner, etc.), different perspectives (such as building economics, sustainability, constructability, etc.) and different conditions and specifications depending on the location (cost of material and workmanship, architectural requirements, current trends in tall building industry, etc.).

As Trabucco (2010) indicated, the current service core is the result of a long evolutionary design process and it continues to evolve. The results of this study can provide insight into how the structures of tall buildings will be affected by the evolution of the service core which is going to be shaped, mainly, by the developments of recently developed elevator technologies.

5.5. Recommendation for Future Research

In the scope of this research, as an example of interior structures, outriggered frame system is investigated and as an example of exterior structures, framed-tube system is investigated. In order to have a broader perspective on the effects of the service core reduction on tall building structures, other structural systems can be studied in future studies.

In generating building models, only the central service core configuration is selected for this research since it is the most commonly used core configuration. In future researches, other core configurations can also be evaluated.

Since the recently developed elevator technologies are especially efficient and feasible to be used in tall buildings with higher or equal to 300 meters, the height of the building models is specified as 300 meters for this study. However, since there is no height limit in the use of these elevator technologies, taller building models can be generated to comprehend the changes in the structural behavior and performance as the building height increases.

In order to modify the structural systems of the building models with the reduced service core, the cross-sectional area of structural members is increased, new columns and beams are put and outrigger and belt truss levels are added into the structural systems. By these modifications, the maximum top displacement of the structural system is reduced under lateral loads. However, slab thicknesses have been assumed the same for all buildings regardless of the lease span in order to scrutinize the effects of core reduction on the lateral load resisting system of a tall building.

There are alternative mechanical design approaches to decrease the maximum top displacement of tall buildings, such as tuned mass dampers. They reduce the amplitude of vibration with the absorption of kinetic energy from the system. Another research field can be based on to understand the effects and efficiency of mechanical design approaches in the reduction of maximum top displacement in tall buildings with the smaller service core.

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APPENDICES

A. Parameters for Structural Modelling and Analysis

Table A.1. Site Classes according to ASCE 7-10 for seismic loads (2010)

Table 20.3-1 Site Classification

Site Class
A. Hard rock
B. Rock
C. Very dense soil and soft rock
D. Stiff soil
E. Soft clay soil

Table A.2. Risk Category of structures according to ASCE 7-10 for seismic and wind loads

Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent a low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life.	III
Buildings and other structures, not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.	
Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where their quantity exceeds a threshold quantity established by the authority having jurisdiction and is sufficient to pose a threat to the public if released.	
Buildings and other structures designated as essential facilities.	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community.	
Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity exceeds a threshold quantity established by the authority having jurisdiction to be dangerous to the public if released and is sufficient to pose a threat to the public if released.[a]	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures.	

[a]Buildings and other structures containing toxic, highly toxic, or explosive substances shall be eligible for classification to a lower Risk Category if it can be demonstrated to the satisfaction of the authority having jurisdiction by a hazard assessment as described in Section 1.5.2 that a release of the substances is commensurate with the risk associated with that Risk Category.

Table A.3. Minimum thickness of slabs without interior beams (Ayres and MacArthur, 1993)

	Without drop panels‡			With drop panels‡		
	Exterior panels		Interior panels	Exterior panels		Interior panels
f_y, MPa†	Without edge beams	With edge beams§		Without edge beams	With edge beams§	
280	**ℓ_n/33**	**ℓ_n/36**	**ℓ_n/36**	**ℓ_n/36**	**ℓ_n/40**	**ℓ_n/40**
420	**ℓ_n/30**	**ℓ_n/33**	**ℓ_n/33**	**ℓ_n/33**	**ℓ_n/36**	**ℓ_n/36**
520	**ℓ_n/28**	**ℓ_n/31**	**ℓ_n/31**	**ℓ_n/31**	**ℓ_n/34**	**ℓ_n/34**

*For two-way construction, ℓ_n is the length of clear span in the long direction, measured face-to-face of supports in slabs without beams and face-to-face of beams or other supports in other cases.

†For f_y between the values given in the table, minimum thickness shall be determined by linear interpolation.

‡Drop panels as defined in 13.2.5.

§Slabs with beams between columns along exterior edges. The value of α_f for the edge beam shall not be less than 0.8.

Table A.4. Gust Factor calculation for flexible or dynamically sensitive buildings or other structures in Section 26.9.5 of ASCE 7-10 (2010)

$$G_f = 0.925\left(\frac{1+1.7I_{\bar{z}}\sqrt{g_Q^2Q^2+g_R^2R^2}}{1+1.7g_vI_{\bar{z}}}\right) \quad (26.9\text{-}10)$$

g_Q and g_v shall be taken as 3.4 and g_R is given by

$$g_R = \sqrt{2\ln(3{,}600n_1)} + \frac{0.577}{\sqrt{2\ln(3{,}600n_1)}} \quad (26.9\text{-}11)$$

R, the resonant response factor, is given by

$$R = \sqrt{\frac{1}{\beta}R_nR_hR_B(0.53+0.47R_L)} \quad (26.9\text{-}12)$$

$$R_n = \frac{7.47N_1}{(1+10.3N_1)^{5/3}} \quad (26.9\text{-}13)$$

$$N_1 = \frac{n_1L_{\bar{z}}}{\bar{V}_{\bar{z}}} \quad (26.9\text{-}14)$$

$$R_\ell = \frac{1}{\eta} - \frac{1}{2\eta^2}(1-e^{-2\eta}) \quad \text{for} \quad \eta > 0 \quad (26.9\text{-}15a)$$

$$R_\ell = 1 \quad \text{for} \quad \eta = 0 \quad (26.9\text{-}15b)$$

where the subscript ℓ in Eqs. 26.9-15 shall be taken as h, B, and L, respectively, where h, B, and L are defined in Section 26.3.

n_1 = fundamental natural frequency
$R_\ell = R_h$ setting $\eta = 4.6n_1h/\bar{V}_{\bar{z}}$
$R_\ell = R_B$ setting $\eta = 4.6n_1B/\bar{V}_{\bar{z}}$
$R_\ell = R_L$ setting $\eta = 15.4n_1L/\bar{V}_{\bar{z}}$
β = damping ratio, percent of critical (i.e. for 2% use 0.02 in the equation)
$\bar{V}_{\bar{z}}$ = mean hourly wind speed (ft/s) at height $\bar{z}$ determined from Eq. 26.9-16:

$$\bar{V}_{\bar{z}} = \bar{b}\left(\frac{\bar{z}}{33}\right)^{\bar{\alpha}}\left(\frac{88}{60}\right)V \quad (26.9\text{-}16)$$

In SI: $\bar{V}_{\bar{z}} = \bar{b}\left(\frac{\bar{z}}{10}\right)^{\bar{\alpha}}V$

where $\bar{b}$ and $\bar{\alpha}$ are constants listed in Table 26.9-1 and V is the basic wind speed in mi/h.

ATC Hazards by Location

Search Information

Coordinates:	40.7652, -73.9797
Timestamp:	2018-12-05T18:25:15.238Z
Hazard Type:	Seismic
Reference Document:	ASCE7-10
Risk Category:	I
Site Class:	B
Report Title:	Seismic

Map Results

Text Results

Basic Parameters

Name	Value	Description
S_S	0.28	MCE_R ground motion (period=0.2s)
S_1	0.072	MCE_R ground motion (period=1.0s)
S_{MS}	0.28	Site-modified spectral acceleration value
S_{M1}	0.072	Site-modified spectral acceleration value
S_{DS}	0.187	Numeric seismic design value at 0.2s SA
S_{D1}	0.048	Numeric seismic design value at 1.0s SA

Additional Information

Name	Value	Description
SDC	B	Seismic design category
F_a	1	Site amplification factor at 0.2s
F_v	1	Site amplification factor at 1.0s
PGA	0.168	MCE_G peak ground acceleration
F_{PGA}	1	Site amplification factor at PGA
PGA_M	0.168	Site modified peak ground acceleration
T_L	6	Long-period transition period (s)
SsRT	0.28	Probabilistic risk-targeted ground motion (0.2s)
SsUH	0.321	Factored uniform-hazard spectral acceleration (2% probability of exceedance in 50 years)
SsD	1.5	Factored deterministic acceleration value (0.2s)
S1RT	0.072	Probabilistic risk-targeted ground motion (1.0s)
S1UH	0.079	Factored uniform-hazard spectral acceleration (2% probability of exceedance in 50 years)
S1D	0.6	Factored deterministic acceleration value (1.0s)
PGAd	0.5	Factored deterministic acceleration value (PGA)

Figure A.1. Seismic characteristic of the site (https://hazards.atcouncil.org/)