A COMPARATIVE STUDY ON ALTERNATIVE STRUCTURAL SYSTEM LAYOUTS OF TWISTED TALL BUILDINGS

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A COMPARATIVE STUDY ON ALTERNATIVE STRUCTURAL SYSTEM LAYOUTS OF TWISTED TALL BUILDINGS

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ABSTRACT

A COMPARATIVE STUDY ON ALTERNATIVE STRUCTURAL SYSTEM LAYOUTS OF TWISTED TALL BUILDINGS

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Tall buildings are seen as icons in their environment and they have a strong impact on the silhouette of the cities. The form of a tall building is critical to define an iconic expression and control their impact on the city silhouette in an aesthetically desired way. In this respect, designers are searching for diversity and uniqueness in the form of tall buildings. Twisted forms are one of the answers for this quest. However, the inherent complexity of twisted tall buildings can pose adverse design features. This study aims to evaluate the challenges of twisted forms in terms of architectural and structural design. First, architectural and structural features of existing examples of twisted tall buildings are examined in terms of their plan layouts, modelling and constructing process, aerodynamic performance, lateral stiffness and torsional demands. Then, generic twisted tall building models are created. The height, structural system and angle of twist of these models are defined such that, the resulting configurations represent the existing buildings as much as possible and provide the opportunity to analyze effect of these features on architectural and structural design in a controlled way. In this study, mainly two alternative structural system layouts called as "adap-

tive” and “non-adaptive” are compared. Besides, a third case named "adaptive-inside" is examined only once. In non-adaptive case, columns stand parallel to the gravitational acceleration as in the case of conventional structures. To create the twisted form, the floors are rotating around the center of the mass by a certain angle on each level but the columns aren’t. In the structurally adaptive case on the other hand, both the structural system and the floors are rotating with the same twist angle which make the columns be leaned to some extent. Adaptive-inside case has a twisted structural system similar with adaptive case but the structural depth of the system is equal to the non-adaptive case’s structural depth. Computer models are created and structural analyses and design checks are performed in ETABS software. Top displacement and structural member forces are of primary concerns in this study where base reactions and modal characteristics have been investigated as well. The results are compared and discussed to evaluate the effects of building height, structural system and angle of twist on the efficiency of adaptive and non-adaptive structural system layouts.

Keywords: Twisted tall buildings, structural system, height, angle of twist, adaptive and non adaptive layout

ÖZ

BURGULU YÜKSEK YAPILARDA FARKLI TAŞIYICI SİSTEM ŞEMALARI ÜZERİNE KARŞILAŞTIRMALI BİR ÇALIŞMA

Taşkın, Gökçe Nihan
Yüksek Lisans, Yapı Bilimleri, Mimarlık Bölümü
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Yüksek binalar bulundukları çevrenin simgeleri olarak görülür ve şehirlerin siluetini güçlü şekilde etkiler. Yüksek bir binanın formu, bu ikonik ifadeyi iyi tanımlamak ve binanın şehir silueti üzerindeki etkisini estetik açıdan kontrol etmek için kritik bir öneme sahiptir. Bu bağlamda, tasarımcılar yüksek binaların formunda çeşitlilik ve özgünlüğü araştırmaktadır. Burgulu formlar bu araştırmanın vardığı sonuçlardan biridir. Fakat, burgulu yüksek binaların karmaşık yapısı, tasarımda zorluklara sebep olabilir. Bu çalışma, burgulu formların mimari ve yapısal tasarım açısından zorluklarını değerlendirmeyi amaçlamaktadır. İlk olarak, burgulu yüksek binaların mevcut örnekleri mimari ve yapısal açıdan incelenmiştir. Daha sonra, kapsamlı burgulu yüksek bina modelleri oluşturulmuştur. Bu modellerin yüksekliği, yapısal sistemi ve burgu açısı, mevcut binaları mümkün olduğu kadar iyi temsil edecek şekilde ve bu özelliklerin mimari ve yapısal tasarım üzerindeki etkilerini kontrollü olarak analiz etme imkânı sağlayacak bir biçimde tanımlanmıştır. Bu çalışmada, “dönmeyle uyumlu” ve “dönmeden bağımsız” olarak adlandırılan iki alternatif taşıyıcı sistem düzeni karşılaştırılmıştır. Bunların yanı sıra, "dönmeyle uyumlu iç sistem" olarak adlandırılan

üçüncü bir alternatif sistem de bir kereye mahsus olmak üzere incelenmiştir. Dönmeden bağımsız taşıyıcı sistemli düzen, kolonların alışılagelmiş şekilde, yerçekimi ivmesine paralel olarak yerleştirildiği düzendir. Burgulu formu oluşturmak için, katlar her seviyede kütle merkezi etrafında belirli bir açıyla döner, ancak kolonlar sabit kalır. Yapısal olarak dönmeyle uyumlu düzende ise, hem taşıyıcı elemanlar hem de katlar, aynı bükülme açısı ile dönmektedir ve bu durum kolonların eğilmesine sebep olur. Dönmeyle uyumlu iç sistemde taşıyıcı elemanlar dönmeyle uyumlu alternatifte olduğu gibi burgulu yapıdadır fakat sistemin etkin derinliği dönmeden bağımsız alternatifteki derinlikle eşittir. ETABS yazılımında bilgisayar modelleri oluşturulmuş, yapısal analizler ve tasarım kontrolleri yapılmıştır. Tepe deplasmanı ve taşıyıcı elemanlar üzerinde oluşan yükler, araştırmanın öncelikli olarak incelediği sonuçlardır. Bunların yanı sıra, taban tepki kuvvetleri ve modal özellikler de incelenmiştir. Sonuçlar, bina yüksekliğin, taşıyıcı sistem seçimin ve dönme açısının, dömeden bağımsız ve dönmeyle uyumlu taşıyıcı sistemlerin performansı üzerine etkilerini göstermek üzere karşılaştırılmış ve tartışılmıştır.

Anahtar Kelimeler: Burgulu yüksek yapılar, taşıyıcı sistem, yükseklik, dönme açısı, dönmeyle uyumlu ve dönmeden bağımsız taşıyıcı sistem düzeni

to the memory of

Ahmet Necati Çakırca, Halit Vedat Çakırca

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To be "with you" or not to be, Fatih Demirel. That is "out of" question. Deepest gratitudes of mine are reserved for you.

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OF	Outriggered Frame
FT	Frame Tube
A	Adaptive
NA	Non-adaptive
CTBUH	Council of Tall Buildings and Urban Habitat
ASCE	American Society of Civil Engineering
ACI	American Concrete Institute
CFD	Computational Fluid Dynamics
3D	Three Dimensional

CHAPTER 1

INTRODUCTION

In his book, A Pattern Language, Christopher Alexander suggested that buildings should have four stories or less. He named this rule “four-story limits” and criticized high buildings as follows (1977);

> High buildings have no genuine advantages, except in speculative gains for banks and land owners. They are not cheaper, they do not help create open space, they destroy the townscape, they destroy social life, they promote crime, they make life difficult for children, they are expensive to maintain, they wreck the open spaces near them, and they damage light and air and view. But quite apart from all of this, which shows that they aren’t very sensible, empirical evidence shows that they can actually damage people’s mind and feeling. (p. 115)

Despite the criticism of Alexander and others, tall buildings are a part of the architecture and structural engineering since the nineteenth century. With their unique qualities, they are differentiated from other building types and create a new study area for both architecture and structural engineering.

In this chapter, a brief background information about the selected study area will be given. The problem definition will be explained and the aim of the study will be described. The possible contributions of this study to the area is defined and in the disposition part the overall work is outlined.

1.1 Background Information

It is hard to make an absolute definition of tall buildings. However, there are several criteria to determine what a tall building is and what are the features that make us define a building as “tall”. According to CTBUH (Council of Tall Buildings and Urban Habitat), fourteen floors or fifty meters height can be accepted as a threshold for tall buildings, yet it is also noted that such limitations are poor indicators. A building that is shorter than 50 meters can still be classified as a tall building if it is distinctly taller than other buildings in the surrounding. On the other hand, a building higher than 50 meters can be excluded from the definition of tall buildings if its slenderness ratio is not adequate. (*CTBUH Height Criteria*, 2019)

Tall buildings are different from other type of buildings. They introduce new aspects to architecture and structural engineering. A few concerns that are valid specifically for tall buildings can be described as follows;

- Buildings should be in harmony with their surroundings, urban environment. For tall buildings, it is a challenging matter. They are inevitably distinguished from the rest of the built environment and have a bold impact on cities’ silhouette. This impact that tall buildings create on the urban scale should be controlled in an aesthetically desired way by designing the form of the building carefully.
- Because of their slender form, plan dimensions are limited in tall buildings. Therefore, plan area is limited. Since they have large number of occupants, vertical transportation should be sufficient enough to serve a large number of users, so an imported percentage of plan area is occupied by vertical transportation. Relatively large dimensioned structural members also occupy space and divide the plan area into zones. Therefore, plan area which is already limited is further reduced by vertical transportation system and structural system. Designing the plan layout becomes a challenging task.
- Similarly, because of their slender form, tall buildings are vulnerable to the lateral loads, particularly wind load. Wind load may not be critical for a conventional building, however; it creates a crucial effect on tall buildings. Structural system should be designed in a way to overcome this effect.

Because of the aforementioned concerns and many others, tall building design is a delicate trade off process in which each parameter may be affected from one another.

As a consequence, it is hard to create balance between architecture and structural performance.

The tall building concept, possibilities and limitations of tall building design and motivations for designing them have constantly changed throughout history.

The first skyscraper, Home Insurance Building, was built in 1885, which has 55 m. height. (Harbert, 2002). Home Insurance Building is accepted as the first skyscraper because of its "steel skeleton structural system". Masonry load bearing walls were not suitable for high-rise buildings because of their insufficient load bearing capacities and limited adaptations for openings or unconventional forms. With the use of rigid frames made of steel, the structural system became lightweight and more flexible. Therefore, this building with its skeleton system initiated a starting point of possibilities for improvement in the structural design of tall building. (Smith & Coull, 1991)

New structural systems have been developed for tall buildings since then. With the help of the improvements in the material qualities, the height limit for building has been constantly extended and the developments in the construction techniques followed this process. Also the improvements in the elevator systems play crucial role in tall building design. Early studies on structural systems of tall buildings are done by Bungale Taranath in 1988, who classified tall building structural systems and described their different behaviors. Similar studies are done by Stafford Smith and Alex Coull in 1991, which developed the classification further. In 2014, Mehmet Halis Günel and Emre Ilgın come up with a classification of structural systems for tall buildings which displayed a more refined approach.

Today, in 2019, the highest completed building of the world is Burj Khalifa with its 828 meters height (Baker, Korista, & Novak, 2008). According to CTBUH, there are forty vision projects that are proposed to be higher than Burj Khalifa and rise more than a thousand meters. Two of these projects, Nakheel Tower and Sky City have never been completed. Nakheel Tower started to get constructed in 2008 and stopped in 2009, it was supposed to be higher than a thousand meters. Sky City started in 2013 and it was supposed to be 838 meters height; however, like Nakheel Tower, it has never been completed. (*https://www.skyscrapercenter.com/*,). Jeddah Tower (or

Kingdom Tower) is still under construction and supposed to be higher than a thousand meters when it will be completed (Weismantle & Stochetti, 2015).

At the end of the 19th century, the fundamental causes of designing tall buildings were population growth in cities and increasing land values (Günel & Ilgin, 2014). They were designed with the aim of benefiting from the land as much as possible. However; over time, the rationale behind constructing tall buildings has changed. Since the population growth in the cities is still a valid concern, it can be accepted that buildings must be tall enough to deal with the population density of the cities. Nevertheless; today, tall buildings do not meet this need. Their heights are far more than what is necessarily needed. Also the increasing land values can be seen as a fact in certain cities, but the budgets that are devoted to the tall building projects show that this is not a concern behind shaping tall building design either.

Today, at the beginning of the 21st century, there are novel reasons to design tall buildings. As a result of all these development process, designers have started to question the limits of the height. Aiming to design the tallest become a challenge. As well as height, designers started to question the form too. Tall buildings, are obviously the dominant elements of a city's silhouette and their forms are important because of the bold effect they have. Therefore, it become a constant desire to design a tall building which is taller than previous projects or which has an outstanding new form, or both.

With these concerns, tall buildings have become a tool for prestige, a way to draw attention to a city. Thus, they become iconic landmarks. Despite their challenging budgets, they are preferred since they are seen as an investment on the prestige of a specific area. Technological developments trigger designers for innovative projects and innovative ideas trigger improvements in structural design. As a result, tall buildings are open to a continuous progress.

Because of the iconic effect that tall buildings create and designers' quest for pluralism and innovation, form has become an important factor in tall buildings design.

Forms that are observed in existing tall buildings can be classified into seven main groups; prismatic forms, tilted/leaning forms, tapered forms, setback forms, free forms and twisted forms (Ilgın, Ay, & Günel, In Review). In this study, twisted tall buildings will be investigated.

1.2 Problem Definition

Twisted form is one of the forms that are preferred in tall buildings design because of its aesthetic. It creates a visual effect when it is applied on tall buildings.

Aerodynamic performance is another reason why twisted form is preferred. As discussed previously, tall buildings are vulnerable to the impact of lateral loads. One of these lateral loads is wind load. Twisted form's aerodynamic performance is better than other forms (Bilgen, Ay, Sezer, & Orbay, 2018), which means the form itself can reduce the wind load effect on the structural system. Since wind load is the governing factor in tall building design, twisted form creates benefits in terms of structural design of the building which will be discussed in details in following chapters.

While twisted form is preferred due to aforementioned advantages, it also creates challenges and concerns in design process. As it has been discussed, tall building design is a delicate balance between structural limitations and architectural necessities and having a twisted form can make the design process even more challenging (Baker, 2010). Besides the potentials of twisted forms, new concerns occur to be dealt with.

Twisted form can be obtained by rotation of the floors and a façade that is adapted to this rotation. For the structural system, there are two options. It may follow the twisted movement of the form. In this case, structural members have irregular forms and leaned geometries. The other option is having a structural system that is not affected by the twisted form of the building. These two options are named "adaptive" and "non-adaptive" respectively. They both correspond to different potentials and problems in the design process. Comparing them is one of the motivations of this study. There are other parameters that may affect the design process of a tall building such as height, total twist angle and structural system. This study also covers their effect together with the adaptive and non-adaptive approaches.

1.3 Aim and Objectives

The main aim of this study is to investigate the tradeoff between the potentials and limitations of twisted tall buildings concerning structural and architectural design. The objectives of the research can be listed as follows:

- Existing examples of twisted tall buildings and the literature will be investigated to understand potentials and limitations of twisted form in terms of architectural design.
- The methods that have been used so far in order to design twisted tall buildings will be defined. These methods correspond to different concerns in terms of architecture and structural design. To understand their differences, these methods will be evaluated separately and then will be compared.
- Structure of twisted tall buildings will be analyzed for their performances. Analyses will be done in the computational environment by selected software.
- Analysis will be made for different design approaches, structural systems, heights and twisting angles so as to understand the effects of these parameters on twisted tall buildings.
- Structural performance results will be compared and discussed in groups to illustrate the effects of different parameters separately.

1.4 Contribution

There are several studies that evaluate structural performance of twisted tall buildings. However, these studies are done only for specific types of structural systems and limited variability of parameters. There are two different approaches to design a twisted tall building which are adaptive and non-adaptive cases, as mentioned previously. Existing studies do not include a clear comparison between these approaches.

It is not possible to evaluate twisted tall buildings by only investigating the existing projects. Twisted tall building are unique and most of the time their designs include case specific solutions, it is not possible to compare them with one another. The aspects about architectural design are more suitable to generalize. However, the aspects about the structural design are not so. Existing buildings may have different structural systems. They may also have different additional members like outriggers and dampers and it is not easy to estimate their effect on the overall structural systems in term of quantitative manners. There is general knowledge about the effect of the twisted forms both on the impact of lateral loads and on the response of the structural members to the loads. However, it is not possible to relate this knowledge with the specific qualities of a project and estimate results.

In this study it is intended to define a generalized methodology and to have controlled results that show the effects of twisted forms to structural systems and tall building design. Results will show the performance difference between adaptive, non-adaptive and adaptive -inside cases. Besides, they also demonstrate the effect of different structural systems, heights and total twist angles on the twisted tall buildings.

1.5 Disposition

This thesis consists of five chapters. In the first chapter, the background information about the study area is given. The problem definition, aim and objectives and the contribution of the study are described.

In the second chapter literature review is outlined. Definition of the twisted tall building is provided. The architectural and structural aspects of the area are explained separately. The case studies are given with the information that are specific for these projects. Finally critical evaluation of the literature is presented.

The third chapter describes the material and the methodology of the research. First, the criteria for material selection of the study is explained. The references for creating generic models are given. Then the simulation method and analyses are described.

In the fourth chapter, obtained quantitative results are evaluated and compared with the information gathered in the literature review.

Finally, in the conclusion chapter, the summary of the research is given. Besides, main outcomes are listed. Limitations of the study are explained and suggestions for further studies are provided.

CHAPTER 2

LITERATURE REVIEW

In this chapter, literature survey about the twisted tall buildings is presented in five sections. Firstly, the definition of a twisted tall building is given from two different sources. Then the subjects are categorized into two as architectural design and the structural design issues. In the second section, the architectural design concerns such as the overall form of the buildings, modelling and construction process and the plan layouts are discussed. In the third section, the structural design concerns such as the wind load response, lateral stiffness of the twisted tall buildings and the inherent torsion effect are discussed. In the fourth section, the existing examples of the twisted tall buildings are investigated and solutions that are specific for these projects are given. Finally, in the critical evaluation section, the given information evaluated with a holistic manner.

2.1 Definition

CTBUH made the definition of twisted building (it can also be named as twisting building) as, “A twisting building is one that progressively rotates its floor plates or its façade as it gains height” (CTBUH, 2016). According to Sev and Başarır (2011), twisting buildings are the ones that their floors are rotating horizontally with respect to a vertical axis.

2.2 Evaluation of the Twisted Tall Buildings in terms of Architectural Design

In this chapter, the limitations and potentials that twisted forms bring to the tall buildings are discussed in terms of general form of the building, process of modelling and constructing and plan layout.

2.2.1 Diversity in Form

In the area of the tall building design, there is a tendency to create twisted forms, as it has been discussed earlier. As a part of the architectural design process, there is a quest for different forms and twisted form is one of the ways to create diversity.

Moon (2014) argued that pluralism affects architecture in general, and it affects design approaches for tall buildings too. Early examples of tall buildings had rectangular prismatic forms. However, with the desire to create variations in form, complex-shaped tall buildings were started to be designed and twisted form is an example of these complex shapes.

Sev and Başarır (2011) had a similar point of view with Moon (2014). They emphasized the desire to create 'iconic' tall buildings and said that designers have the tendency to develop extraordinary forms to have that iconic impression. With this motivation, tall buildings which have non-orthogonal complex forms, e.g. twisted forms, are emerging worldwide.

Figure 2.1 shows the eight highest examples of twisted tall buildings, including Shanghai Tower (Shanghai, China) designed by Gensler, Diamond Tower (Jeddah, Saudi Arabia) designed by Buruoj Engineering Consultant, Cayan Tower (Dubai, UAE) designed by Skidmore, Owings & Merrill LLP, Evolution Tower (Moscow, Russia) designed by Gorproject, F&F Tower (Panama City, Panama) designed by Pinzon Lozano & Associated Architects, Al Tijaria Tower (Kuwait City, Kuwait) designed by Al Jazera Consultants, United Tower (Manama, Bahrain) designed by Aref Sadeq Design Consultants, and Turning Torso (Malmo, Sweden) designed by Santiago Calatrava Architects & Engineers.

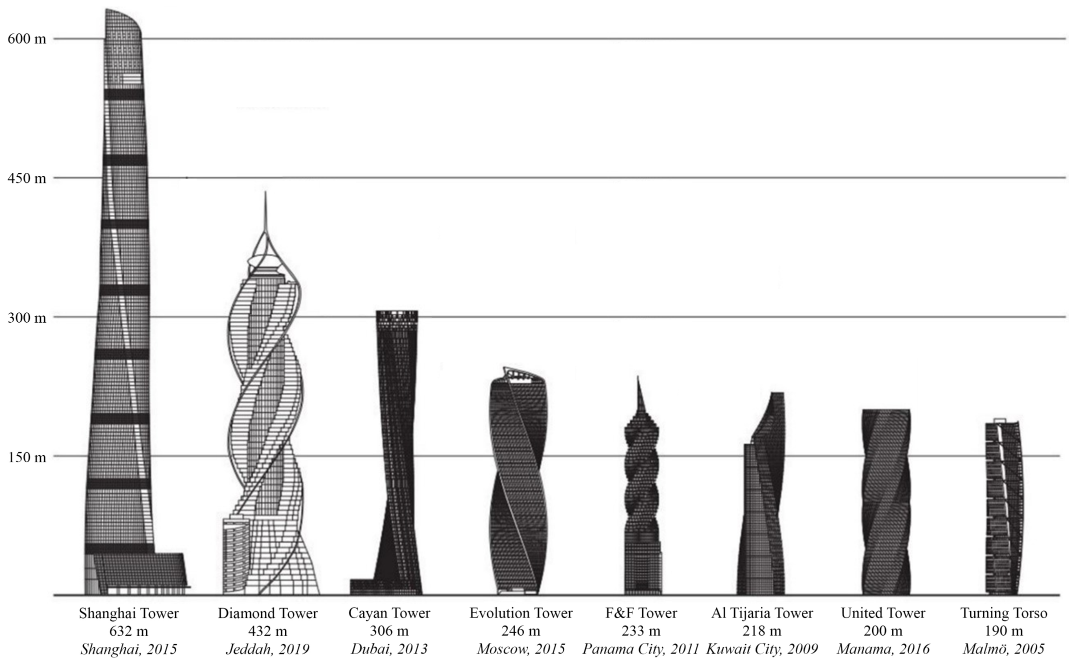


Figure 2.1: The highest eight twisted tall buildings (CTBUH, 2016).

2.2.2 Modelling and Constructing

Tall buildings are large-scale projects. They require long term designing and constructing process and designing a tall building in a twisted form extends this process even more.

Sev and Başarır, (2011), acknowledged that producing a twisted form for design and analyzing process is a challenging task which requires parametric modeling. Parametric modelling means longer design process which will cause financial disadvantages. They also noted that, twisted buildings have complex shaped façade surfaces. The complex form of the façade requires unique façade elements. Because of this, mass production of these elements is not possible, thus the production and application of the façade elements become a challenge. All these difficulties can make twisted buildings non-economic projects.

Scott, Farnsworth, Jackson and Clark (2007) have a similar point of view with Sev and Başarır (2011). In their study, it is noted that twisted forms create drawbacks in design and construction. Scott *et al.* (2007) described the construction of non-prismatic members as a challenging process and mentioned issues in the construction sequence and composition of overall structural system due to the uncertainties in estimating creep and shrinkage of non-prismatic members. When these values cannot be estimated properly, it may result in an unbalance state and extra torsional forces on the system.

2.2.3 Plan Layout

Designing the plan layout and circulation is a challenging task for tall buildings. Because of their slenderness and relatively large areas devoted to structural members, the net floor areas are limited. Also because of the large occupant numbers, especially in office and multi-use buildings, an important percentage of the plan area has to be reserved for the vertical circulation. When the building has a twisted form these considerations become more challenging.

In twisted tall buildings, the relationship between structural elements and floor layout is changed in every floor level. In each floor, spaces differentiate from one another. It makes interiors and circulation hard to design. James (2017) argued that in most of the twisted tall buildings, structural core is not twisted, stands perpendicular for practical reasons. If other structural members are twisted throughout the height of the building, the relation between the core and other structural members change constantly. In that case, space utilization become a challenge.

In most cases, structure has a central mega core. This mega core is designed in a circular form, so that, the moment of inertia of the core is the same in all directions and no torsion effect occurs in the core itself. Also, in most of the examples, the mechanical service core and circulation of the building is located inside the core. When the floors rotate, the intersection of the core and plan layout changes in every level so arranging circulation becomes problematic. Having a circular core can be beneficial in that manner too. A ring corridor around the core can solve the circulation problem (Scott et al., 2007).

Figure 2.2 shows three dimensional form and plan schemes from different stories. Spaces differentiate from one another with varying twist angle, as it can be observed by the colored areas on the plans.

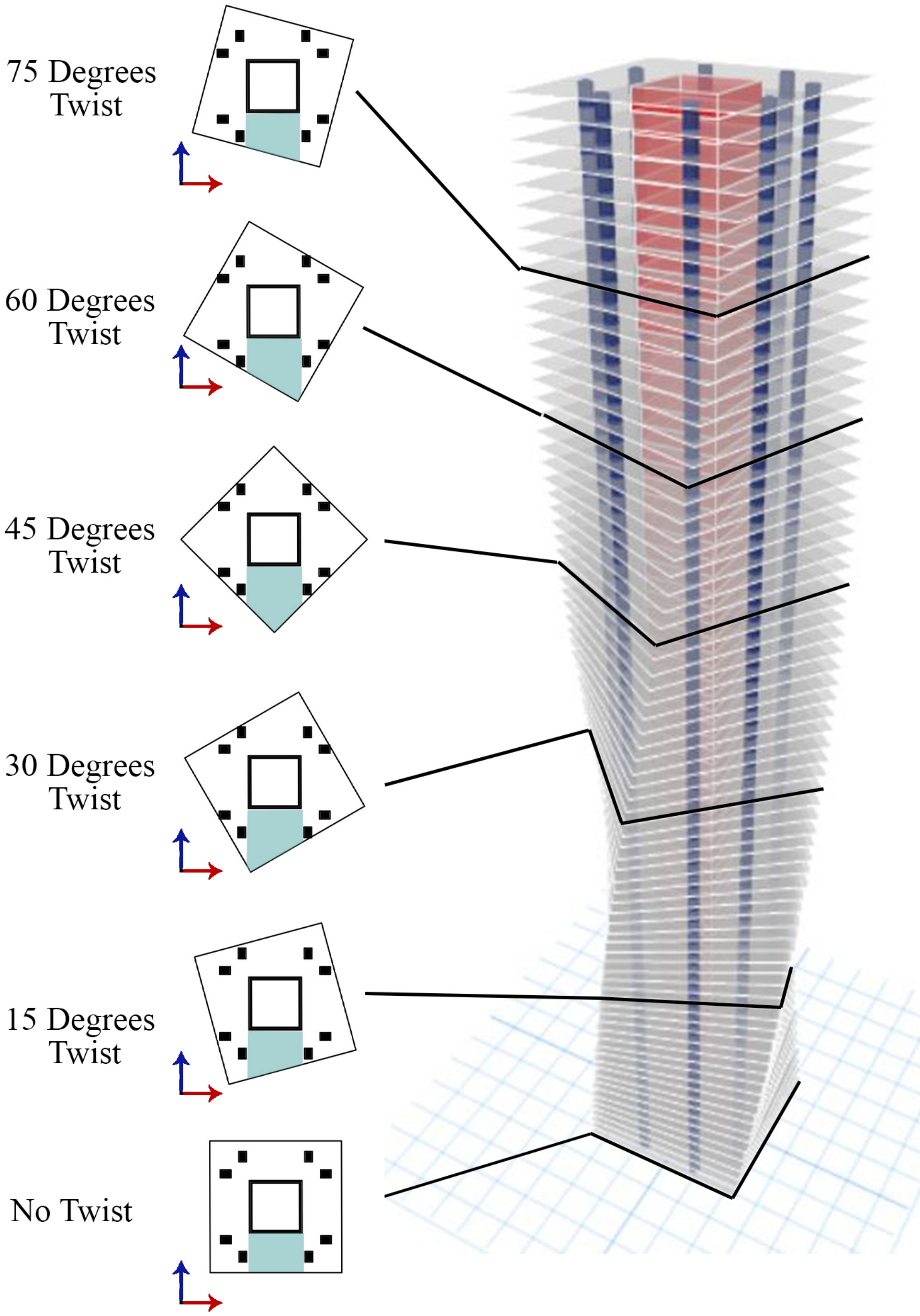


Figure 2.2: An example of twisted tall building with plan schemes

2.3 Evaluation of the Twisted Tall Buildings in terms of Structural Design

Structural design of a tall building has lots of critical parameters to deal with. Twisting forms can have both advantages and disadvantages in terms of structural design. In this part, the effect of the twisted form to the wind response of the system is discussed. Lateral stiffness of the twisted structures are compared with the prismatic ones. The additional torsion effect that occurred because of the twisted form is explained.

2.3.1 Wind Response

It is possible to say that; tall buildings can be defined as the buildings whose structural design is governed by the lateral loads. Because of their form, slenderness and height; tall buildings have sensitivity to lateral loads so they are dominant factors for tall buildings design. Wind load is critical for tall buildings because the effect of the wind increases as the height increases and the lateral stiffness of the buildings gets smaller as they become taller. The wind speed and pressure increases parabolically as the height increases, therefore; the loading effect also increases parabolically as the building become taller. Also the lateral stiffness is critical for wind response. Tall buildings have slender forms and their aspect ratios are usually more than six. As a result, wind response is a critical parameter for structural design of the tall buildings. (Günel & Ilgin, 2014)

Wind load creates 3 modes of action in tall buildings which are, along wind motion, across wind motion and torsional motion. Along wind motion occurs in the same direction with the main wind due to the pressure fluctuations on windward face which is the face that wind hits and leeward face that is the opposite of windward face. Across wind motion occurs in the direction that is perpendicular to the wind direction. In tall buildings, across wind response is usually the most critical factor that governs the design (Günel & Ilgin, 2007). Figure 2.3 shows three different motions' directions.

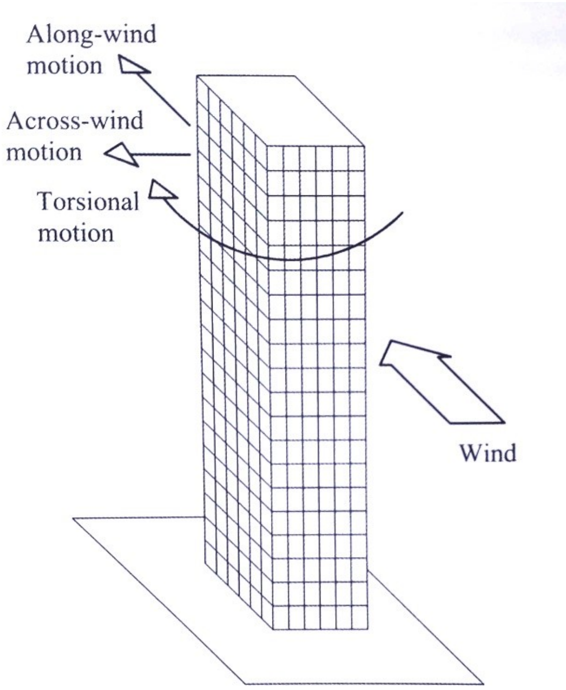


Figure 2.3: Three motions with directions (Günel & Ilgin, 2014)

When a wind flow hits a building, wind steam lines which are originally parallel to the wind direction become disoriented on the two sides of the building and create forces that are called vortices (Günel & Ilgin, 2007) Figure 2.4 shows vortex effect. At low wind speeds, vortices do not create vibration. However, at high wind speeds strong vortices occur on two sides of the building. These vortices create alternating impulses which cause vibration on across wind direction. This phenomenon is called “vortex-shedding” (Taranath, 1998).

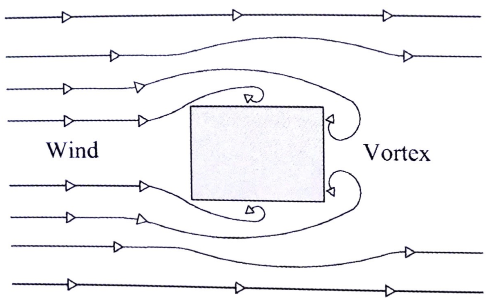


Figure 2.4: Vortex effect (Günel & Ilgin, 2014)

Aminmansour and Moon (2010) stated that, irregular forms create complicated design analysis and construction process when they applied on tall building projects. However, they perform better than prismatic forms in terms of response to dynamic wind forces. If building has a rectangular box form, wind steam lines create vortexes. Organized vortexes create serious vibration problems in the across wind direction. In order to prevent these vibration problems, wind flow should be "confused". If the building has an irregular form rather than a rectangular box form, wind cannot create organized vortexes and thus irregular forms face relatively less vibration demands.

Similar with Aminmansour and Moon, Mara (2015) stated that, if a correlated vortex-shedding occurs along the height of the building, it results in an excessive across wind response. Changing the cross-section of the building along the height of the mass interrupts the correlation of vortices. Therefore, the effect of vortex-shedding is decreased which eliminates vibration concerns.

Twisting form is one of the irregular forms that are mentioned by Aminmansour and Moon. It creates an alternating cross-section in the buildings form as suggested by Mara. Alaghmandan and Elnimeiri (2013), defined strategies that reduce impact of the wind on tall buildings. These strategies are divided into two categories: structural strategies and architectural strategies. Structural strategies increase the structural stiffness and use damping sources. Architectural strategies form modifications by using porosities or openings and corner modifications. In their study, twisted form is discussed as an aerodynamic modification in architectural design. They stated that, twisting form raises concerns about structural design of the building, yet it is an effective form to reduce vortex-shedding effect.

2.3.2 Wind Tunnel and CFD Tests

To estimate the wind response of a twisted tall building, it is important to understand the aerodynamic performance of the twisted form. There are two main ways to test the aerodynamic performance of the buildings. The first way is the wind tunnel test. In the wind tunnel test the solid model of the building is created with a certain scale. On the faces of the model receptors that get the pressure value are settled. The model located on the closed tunnel and the artificial wind effect is applied throughout the tunnel. With the information that compiled by the receptors, the wind pressure on the faces of the model is obtained. The second way is computer-based simulations. The form of the building and the wind tunnel are defined in the software environment and similarly the wind pressure on the faces of the model can be obtained. Using the wind tunnel itself creates more accurate results, however, it is an expensive and time consuming way of testing when it is compared with the computer-based tests.

A wind tunnel test study was done by Tanaka *et al.* (2013) to investigate aerodynamic characteristics of different forms that are applied to tall buildings. In this study, 31 different three dimensional models are created. The models represent 400 meters height tall buildings whose aspect ratios are eight. Models have different forms including straight, tapered, tilted, perforated forms and twisted forms with six different configurations. Test results showed that, twisted forms were exposed almost similar or slightly less wind force on the along wind direction, but in the across wind direction they were exposed less wind force than straight ones (Tanaka et al, 2013). If a building has a twisted form, wind flows around the building are get confused. Therefore, organization of the wind forces is eliminated and the vortex-shading is reduced. Overall results of the study showed that twisted forms are better than other tested forms which are straight, tapered, tilted and perforated forms, in terms of aerodynamic performance. Figure 2.5 shows the wind pressure distribution on the façades of straight, 90 degrees twisted and 180 degrees twisted forms.

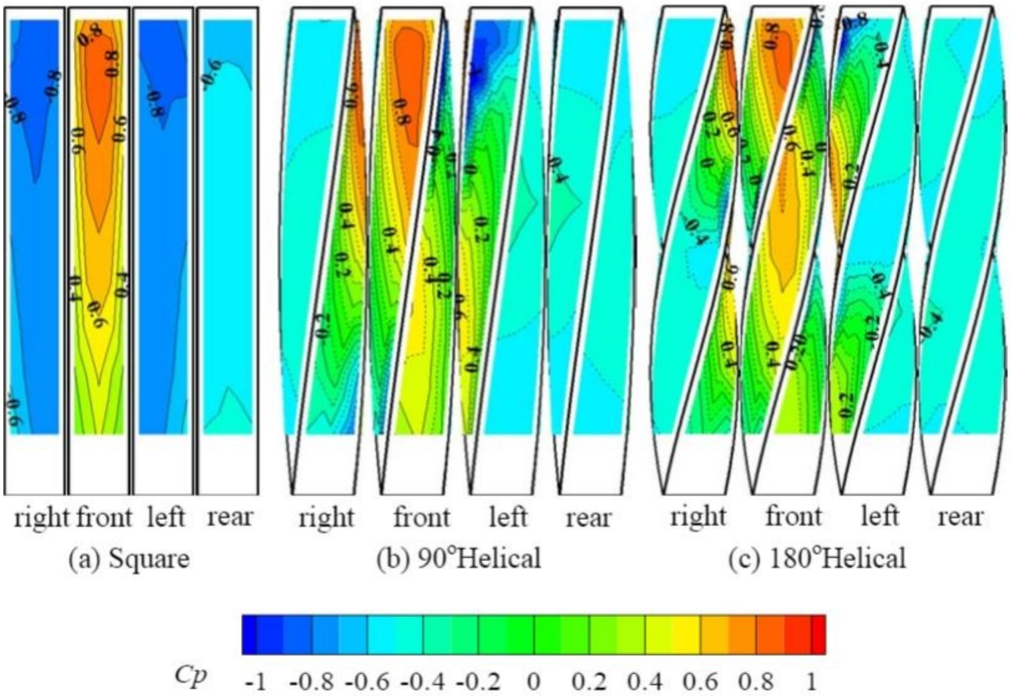


Figure 2.5: Wind pressure distribution on the façade of straight and twisted models (Tanaka et al., 2013)

Another study about wind effect on twisted tall buildings which is based on computer simulations was done by Tang, Xie, Felicetti, Tu and Li (2014). Calculating the effect of wind loads on a building is possible by wind tunnel test. However, as they mentioned in their paper, wind tunnel test is expensive and requires a long working process. In their study, wind effect was calculated on a software environment by using computational fluid dynamics (CFD) technique. Based on the idea that twisted forms are less affected by the wind loads, one straight and three twisted forms, which have different rotation angle as 60º, 120º and 180º, were created for CFD test. Test results showed that, twisted forms have less wind drag effect than straight form and the efficiency of wind drag reduction depends on the angle of twist. It is also noted that, on the along wind direction the greatest wind drag reduction achieved by twisted forms is 6% compared with the straight form. Twisted forms are advantageous for wind drag and confusing wind load but do not have a significant effect.

2.3.3 Lateral Stiffness

Tall buildings have slender forms, which reduce their lateral stiffness. Having a twisted form reduces the lateral stiffness more.

Twisted tall buildings are effective in terms of aerodynamic response, particularly in across-wind direction since vortex-shedding effect is reduced in twisting forms. However, twisted forms are not advantageous statically. The moment of inertia of the plan is the same for a straight and a twisted structure given that they have same plan geometry. However, twisted structural systems or members are not as strong as straight ones in terms of lateral stiffness (Ali & Moon, 2007).

To compare the lateral stiffness of the twisted tall buildings, a simulation based study is done by Moon (2014). In this study, three different structural systems are evaluated which are diagrid system, braced tube and outriggered system. To have comparative results, four different models are created for each structural system. The first model has no twist, second one has 1 degree twist per each floor, third one has 2 degree twist and fourth one has 3 degree twist. For all different twisting angles there are three models which are 60 story height, 80 story height and 100 story height. All these models are analyzed with the help of the software SAP2000 by applying the same loading cases and earthquake conditions. In the results, it is seen that, twisted forms have less lateral stiffness than the prismatic forms and the reduction of lateral stiffness increases when the angle of the twist increases. The height of the building is also important for lateral stiffness. As the height increases, the top deflection also increases. Moreover, as the building becomes higher, the reduction in the lateral stiffness is affected more by the increasing twist angle. These results are fairly similar for all of the three structural systems. For the brace tube and diagrid system, the reduction in lateral stiffness is similar and higher than outriggered system. According to the study of Moon (2014), outriggered system has better results for twisted form among these three structural systems.

Based on the findings of Moon (2014), Figure 2.6 shows how top deflection values change in relation to the twist angle. Figure 2.7 shows the results of 60 and 90 story models which indicate the effect of the height on the results.

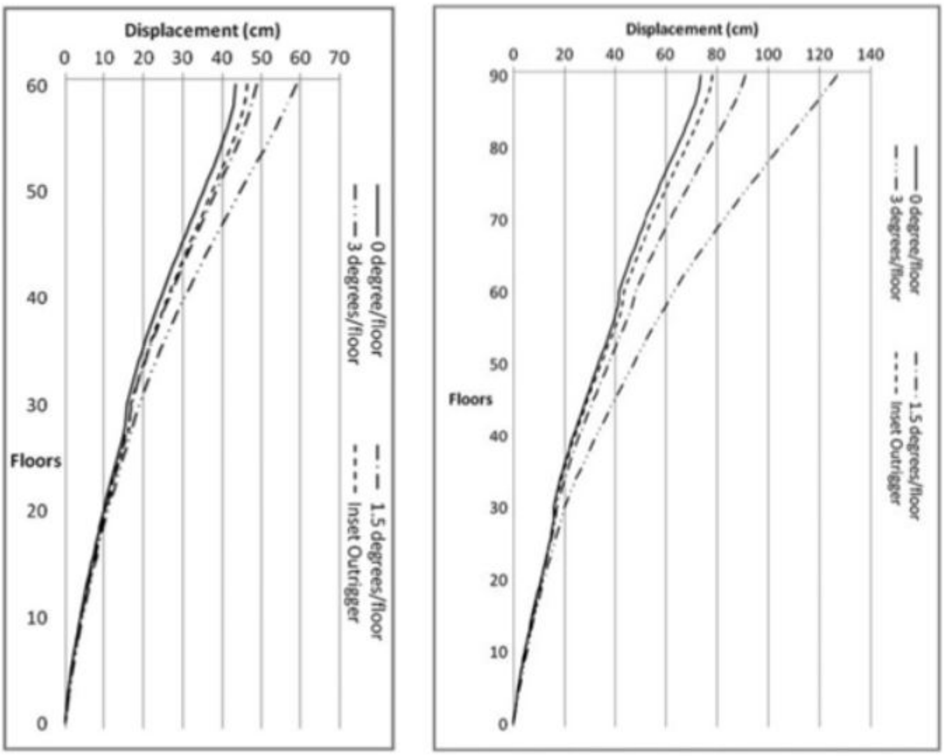


Figure 2.6: Top deflections for 60 and 90 story height outriggered frame system models (Moon, 2014)

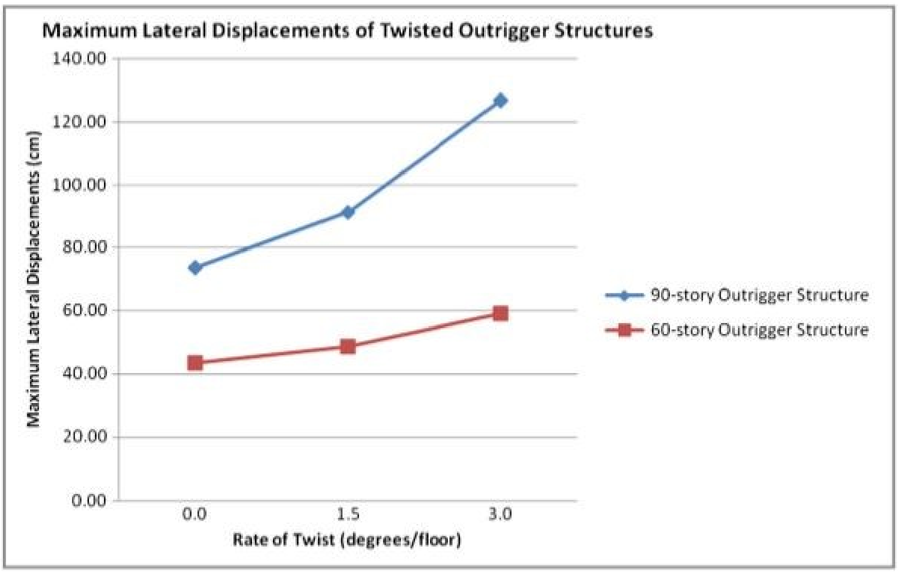


Figure 2.7: Maximum lateral displacements for 60 and 90 story height outriggered structures (Moon, 2014)

2.3.4 Torsion Effect

Tall buildings face large amount of lateral loading due to their form. Structural systems of tall buildings are designed to respond the need for lateral stiffness. In some twisted tall buildings, structural elements are also twisted as building rises. In straight prismatic buildings, structural system primarily carries axial load of the building and lateral loads. In these buildings torsion is a secondary effect of discontinuities of lateral load carrying system which is somehow exceptional in tall building design. However, if the building has twisted structural elements, torsion effect is occurred inherently and the system also has to carry the significant amount of torsion force. Structural design against torsion is a difficult task due to uncertainties in estimation of both the demand and capacity which is much more problematic in tall building design. The core systems that are designed to carry significant amount of lateral loads also have to carry that torsion force, which creates unpractical sized load carrying elements (Ceng & Pe, 2010).

In their study about structural challenges of twisted towers, DeSimone, Ramirez and Mohammad (2015) explained that in twisted structural systems the columns are leaned. Due to their geometry, the gravity loads also has a transverse component which does not occur in the prismatic system. This additional force creates torsion in the overall system. This torsion is transferred to the core and required dimensions for core walls become larger and unfeasible in some cases. One suggested solution to cope with torsion is a system which is called “hat truss”. Hat truss consists of shear wall or shear truss members that connect the core and the perimeter columns. By the help of these members, the torsion force that occurs in the columns is transferred to the core as a lateral force. Dealing with lateral force instead of torsion, eliminates the core wall dimensions to become impractical.

Another way to eliminate torsion effect is suggested by Scott, Farnsworth, Jackson, and Clark (2007). They argued that, the twisted form can be obtained by leaned structural elements. If these elements are leaned in a proper plane that does not create any eccentric layout according to the center, twisted form can be obtained without torsion effect. Furthermore, they also suggested that, torsion effect can be balanced with counter torsion force. Overall structural system can be designed in a way that summation of the torsion forces is neutral with respect to the center. Figure 2.8 shows the diagram of their proposal. First image shows an example of twisted tall building with perimeter columns. Second and third images indicate the axes of the columns and last two images show the proposed column application that neutralize the torsion forces. (Scott et al., 2007)

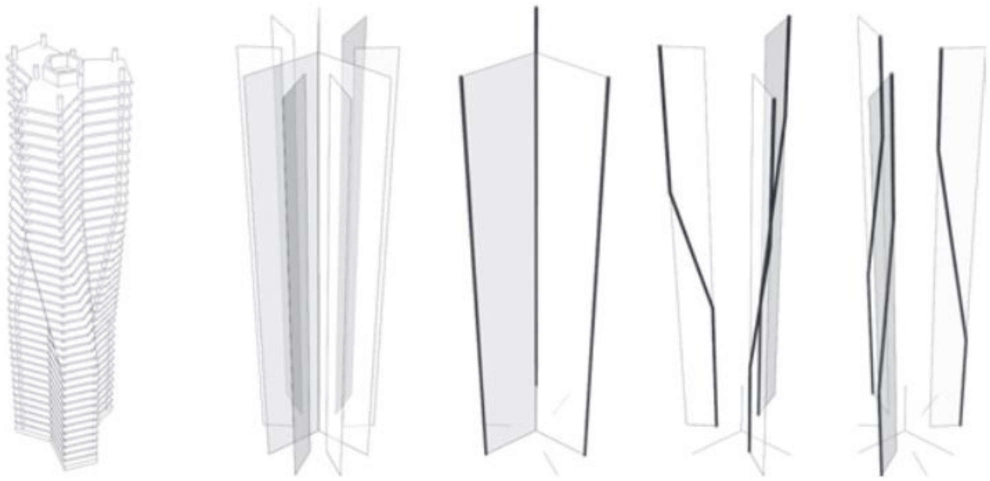


Figure 2.8: A proposed design of a twisted tall building that eliminates torsion on the core (Scott et al., 2007)

2.4 Structural Systems for Tall Buildings

Structural systems of tall buildings are investigated and classified by Khan (1969), Schueller (1977), Smith and Coull (1991), Taranath (1998), Günel and Ilgın (2014) and Ilgın et al. (In Review). Among these studies, Günel and Ilgın (2014) defined 9 major systems as; rigid frame, flat plate, core, shear wall, shear-frame, mega column, mega core, outriggered frame and tube systems. Later, Ilgın et al. (In Review) further modifies structural system classification of Günel and Ilgın (2014) by adding buttressed core system which is relatively new and still rare. Figure 2.9 shows the structural systems for tall buildings and supertall buildings.

Structural Systems for **Tall Buildings**

- Rigid Frame System
- Flat Plate/Slab System
- Core Systems
- Shear Wall Systems
- Shear-Frame Systems
  - Shear Trussed Frame (Braced Frame) Systems
  - Shear Walled Frame Systems
- Mega Column (Mega Frame, Spae Truss) Systems
- Mega Core Systems
- Outriggered Frame Systems
- Tube Systems
  - Framed-Tube Systems
  - Trussed-Tube Systems
  - Bundled-Tube Systems

Structural Systems for **Supertall Buildings**

Figure 2.9: Structural systems for tall buildings (Günel & Ilgin, 2014)

To satisfy structural safety and occupancy comfort in tall buildings, maximum lateral drift is limited to approximately 1/500 of the building height. In supertall buildings, rigid frame, flat plate, core and shear wall systems are not feasible enough to satisfy this maximum lateral drift. Therefore, these four structural systems are not preferable for supertall buildings. In this study, outriggered frame system and frame tube system are investigated which are two mostly used structural systems among supertall buildings (Ilgın et al., In Review)

2.4.1 Outriggered Frame System

In outriggered frame systems, shear truss or shear wall members, namely outriggers are used to connect structural core and perimeter columns at one or more levels. Mostly, they are at least one story height members, located on the mechanical floor in most of the cases in order not to interrupt interiors at occupied floors. Connecting the core with the perimeter columns increases structural depth of the building and decreases the lateral drift. At the outrigger levels, perimeter columns are connected by belt trusses to improve the efficiency of the system (Günel & Ilgin, 2014)

Figure 2.10 shows 3D model of an outriggered frame system (right panel) and section and plan drawings of the given model (left panel)

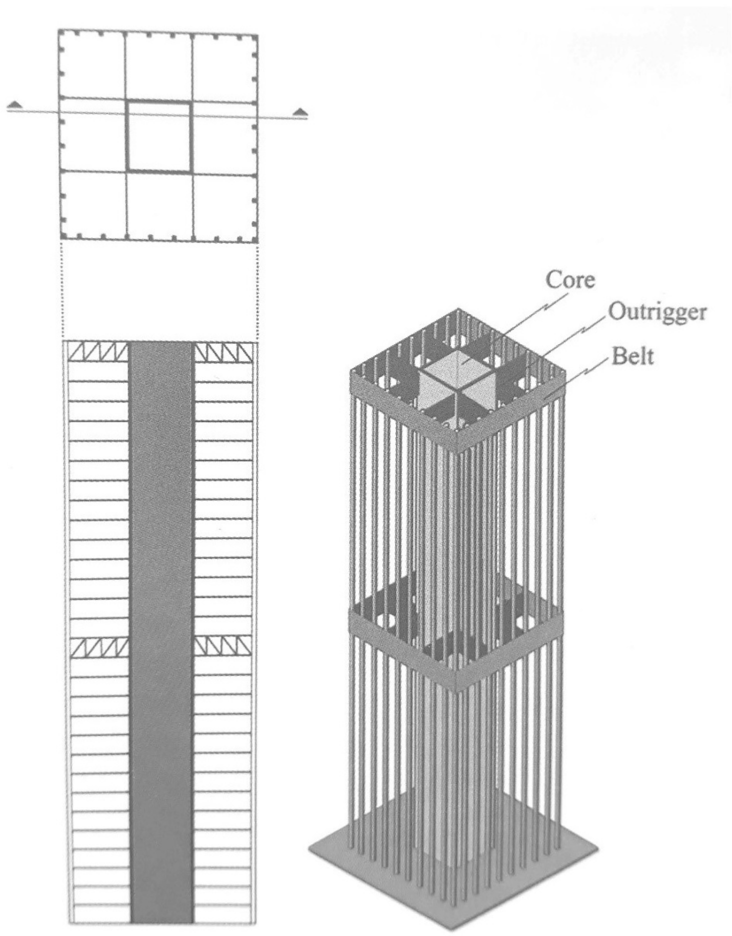


Figure 2.10: Outriggered frame system, 3D model and drawings (Günel & Ilgin, 2014)

Outriggers combine structural core with perimeter columns to make them work as a whole against lateral forces. Normally beams are used for this purpose. However, in tall buildings span between core and perimeter columns is relatively large. For that reason, it is hard to design beams in a way that is stiff enough to combine core and perimeter columns. Instead, outriggers are preferred. (G. Ho, 2016)

Since columns work together with the structural core against lateral forces, moment on the core is reduced on the outrigger levels. Figure 2.11 shows deflected shape of an outriggered frame system and moment diagram of the core. Tension occurs on the windward columns and compression occurs on leeward columns. In the right panel, moment distribution without outrigger system is shown with dashed line. As seen in the figure, moment decreased on every outrigger level. (Taranath, 1998)

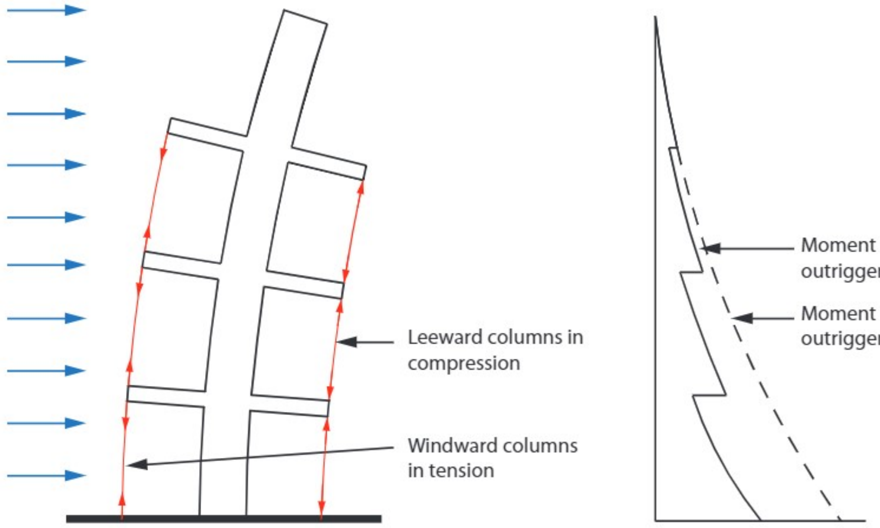


Figure 2.11: Deflected shape of outriggered system and moment graph of the core (Taranath, 1998)

Depending on the height of the building, there may be one or more levels of outrigger on a tall building. Although outriggers are mostly placed on the mechanical floors not to disturb occupied levels, there are optimum levels to place them in order to reach maximum structural performance. According to Smith and Coull (1991), if there is "n" number of outriggers, optimum levels for outriggers can be calculated approximately by the following formula: 1/(n+1), 2/(n+1) … n/(n+1). By making several assumptions such as uniformly distributed wind load and simplified analytical model, Günel and Ilgın (2014), calculated optimum location of one and two levels of outriggers. They have found that, if there is one outrigger level in a building and building's height equals to L, the optimum location of outrigger is 0.455L distance from the top of the building. For two levels of outriggers, (again building's height is accepted as L) optimum locations of outrigger levels are calculated as 0.31L and

0.69L from the top of the building.

2.4.2 Frame Tube System

Tube system was invented by Fazlur Rahman Khan in the early 1960s. There are three different types of tube system which are frame tube, trussed tube and bundled tube systems. Frame tube system includes closely spaced columns on the façade of the building and deep spandrel beams that connect columns. All the primary structural members are located on the perimeter of the building and form a tube. Exterior members in the frame tube system resist lateral loads as a whole. Vertical loads are also supposed to be carried by the tube; however, there might be additional structural members in the interior of the building that carry some part of the vertical loads and reduce the span. Since all the primary structural members are located on the exterior of the building, frame tube system creates flexible, undisturbed interior spaces. Nevertheless, in all tall buildings, whether tube or not, a service core is mandatory that hosts elevators, staircases, etc. This service core is customarily made as a structural core also in frame tube systems as a supplementary element of the exterior system. Frame tube systems are stiff enough to be used in buildings more than 40 story (Günel & Ilgin, 2014) Figure 2.12 shows an example of frame tube system.

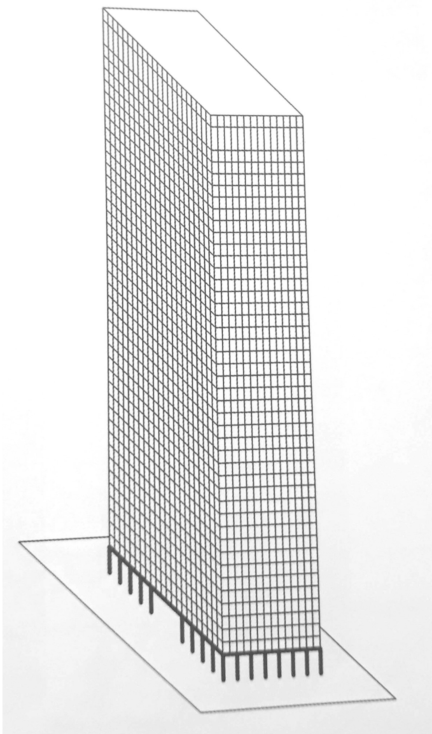


Figure 2.12: 3D representation of frame tube system (Günel & Ilgin, 2014)

2.5 Case Studies

According to the statistics published on 2016 by CTBUH, there are 28 examples of twisted tall buildings (CTBUH, 2016), 22 of them are completed whereas 6 of them are still under construction by the year 2019. The highest twisted tall building, Shanghai Tower (Shanghai, China) is the second highest completed tall building of the world which is 632 meters tall. Figure 2.13 shows heights of these 28 twisted tall buildings and the number of the buildings at each hundred-meter interval. It should be noted that, only one of them is mega tall (higher than 600 meters) and five of them are supertall. Figure 2.14 shows the total twist angles of these 28 twisted tall buildings. Diamond Tower (Jeddah, Saudi Arabia) has the maximum total twist angle which is 360 degrees. Five of the buildings have 90-degree twist. In figure 2.15, heights and twist angles of the existing twisted tall buildings are shown on the same graph. Detailed information about the existing twisted tall buildings is given in the appendix A.

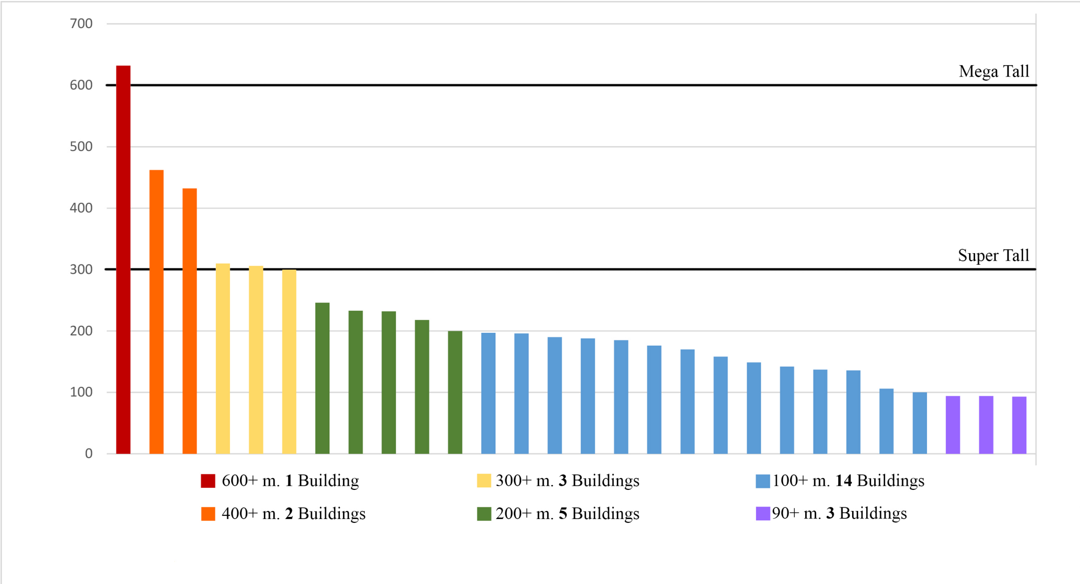


Figure 2.13: Height of the 28 twisted tall buildings in meters (CTBUH, 2016)

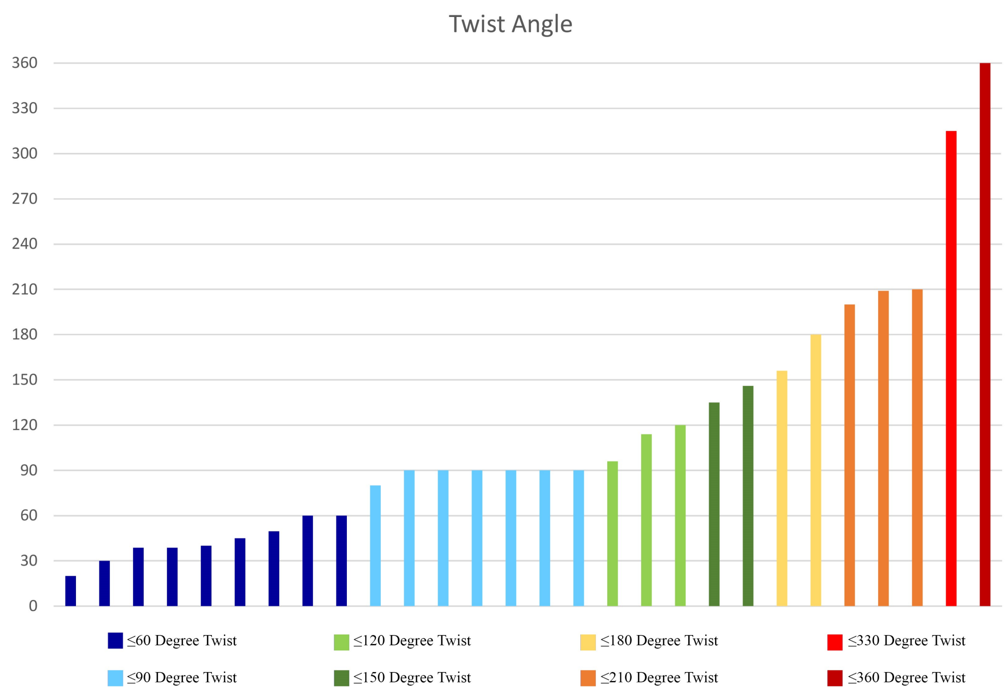


Figure 2.14: Twist of angle of the 28 twisted tall buildings (CTBUH, 2016)

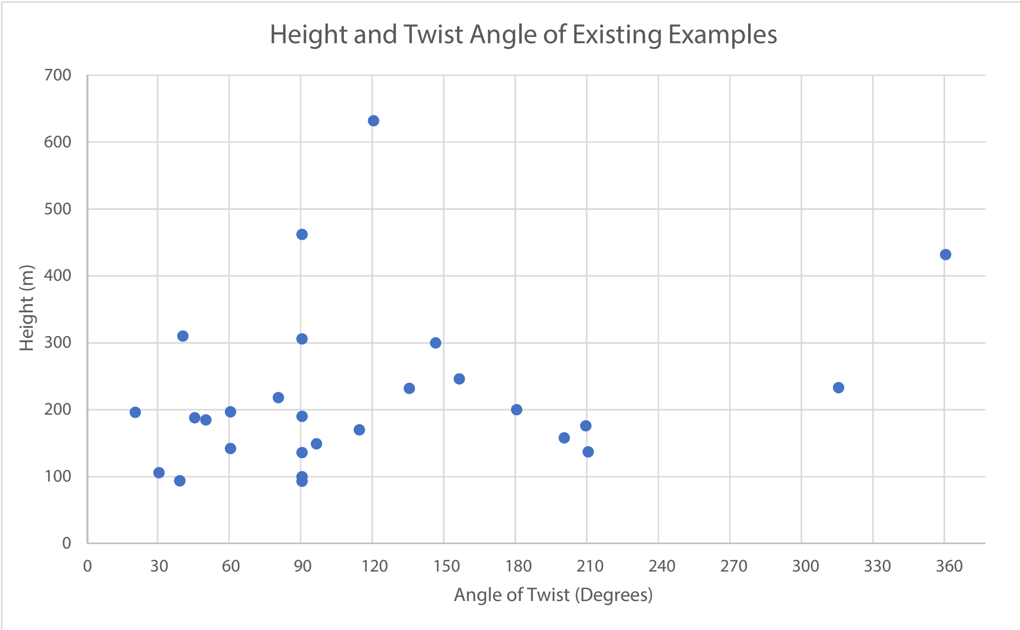


Figure 2.15: Height and twist angles of the existing twisted tall buildings (CTBUH, 2016)

In this part, the existing examples of the twisted tall buildings are examined in terms of height, twist angle, structural system etc. Moreover, project-specific solutions and qualities are presented. Information about their design and construction process is given. Examined buildings include; Shanghai Tower (Shanghai, China), Lakhta Center (St. Petersburg, Russia), Cayan Tower (Dubai, UAE), Evolution Tower (Moscow, Russia), Turning Torso (Malmo, Sweden) and the Grove at Grand Bay Tower (Miami, USA)

2.5.1 Shanghai Tower

Shanghai Tower, built in Shanghai, China, is 632 meters tall, the second tallest building in the world and the highest twisted tall building by year of 2019. The rotation angle of its each floor is 0.9 degree which results in a 120 degrees twist at total. Structural system of the building is outriggered frame system. The twisting form of the tower is obtained by rotation and the geometry of the floors. The conventional structural system is not rotating with the building but cantilever slabs are located in a twisting way around the central core. (Zhu, Poon, & Velivasakis, 2012).

Zhaoa, Ding and Sun (2011) explains the aerodynamic modification process of the Shanghai Tower's form. Like all tall buildings, it is exposed to excessive wind load and because of its close location to the sea it is also exposed to typhoon effect. To deal with these lateral loads, aerodynamic design is considered in detail. The main parameters that enable designers to reach aerodynamic optimization are the twist angle, building orientation and the shrink ratio of the building plan as the building rises. For the beginning a rectangular sectioned straight form is created with the same shrink ratios on the plans. Then the models with twist angle of 100, 110, 120, and 180 degrees are created. These models are oriented on the site with 0, 30 and 40 degrees and evaluated by the high-frequency force-balance wind tunnel test. The base reactions for all models and orientation angles are compared and it is seen that the optimum result is the 120 degrees twisted form with the 40-degree orientation angle. When it is compared with the initial rectangular sectioned model, the base reaction is reduced by 33% in the optimum solution. These tests are done at the beginning of the process and the overall form is defined by the aerodynamic performance. Throughout the process, the design is also tested by other wind tunnel test method such as high frequency pressure integration method, aeroelastic model test and high Reynolds number test.

Figure 2.16 shows image of the Shanghai tower (left panel), its plan drawing and partial 3D model of structural members (right panel). 3D model of structural system shows the core inside (red), mega columns (light blue), outrigger trusses (dark blue), belt truss (green) and radial truss to support exterior façade and framing (purple).

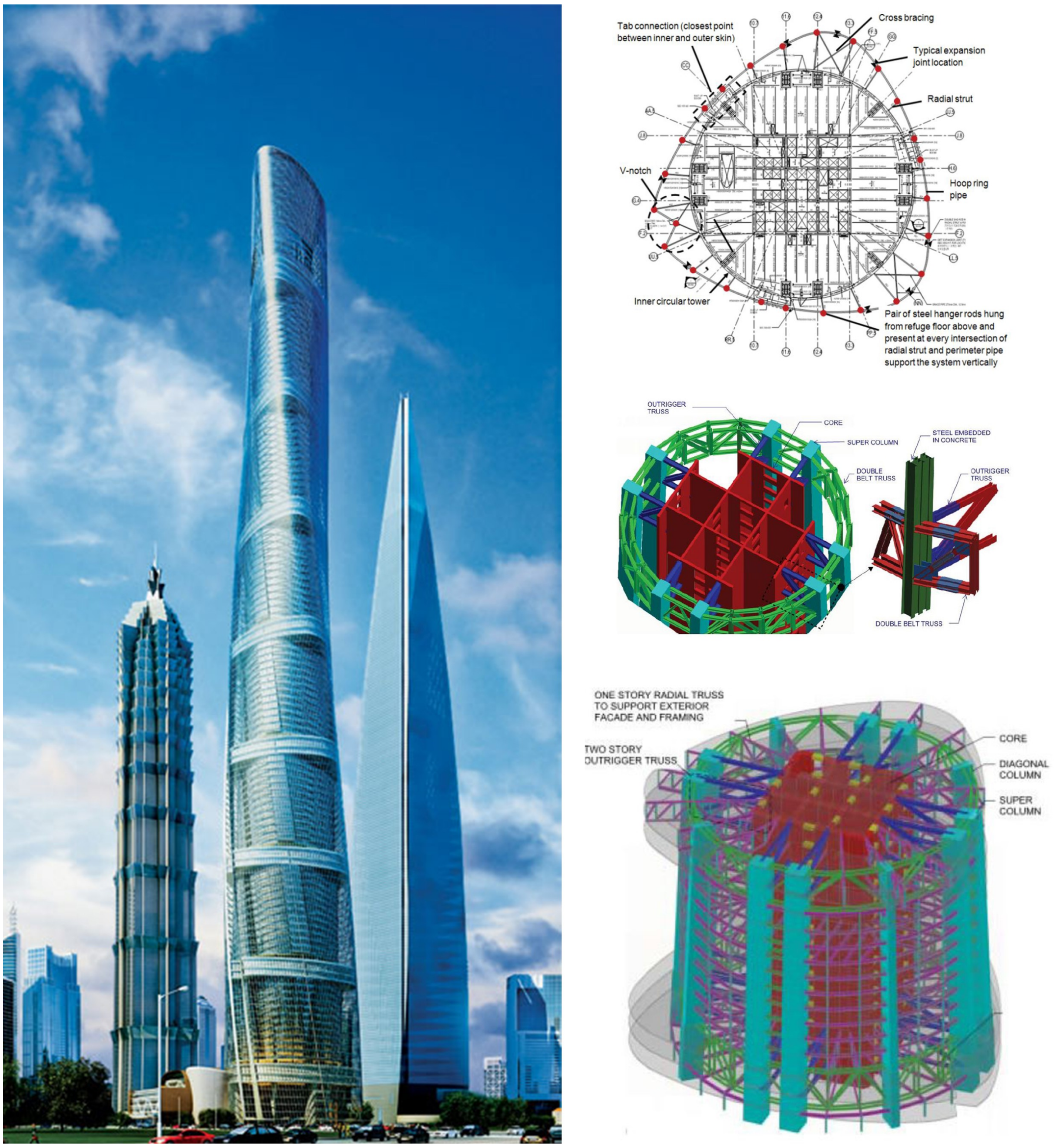


Figure 2.16: Shanghai Tower, its plan and structural system in 3D (Katz et al., 2008)

2.5.2 Lakhta Center

Lakhta Center is 462 meters tall and has 90 degrees twist angle at total. Rotation for each floor is 1 degree. It has a circular form in the center and five additional tapered volumes surround that central form with a spiral movement. Overall it has a five corner star like floor layout and a tapered twisted form. Its tapered form contributes to its aerodynamic performance in a positive manner and the twisted form reduces the wind loading on the structure (Askarinejad, 2014)

Outriggered frame structural system of the Lakhta Center consists of a central mega core and ten twisting mega columns. The central mega core is not capable of carrying all lateral loads. To increase the lateral stiffness of the overall system and reduce the loading effect on the core, mega columns are connected to the core with outrigged members on four levels. However, the connection of the outriggers to the core and columns become problematic. Since the mega columns twist as the building rises, they have a leaned geometry which makes the connection challenging. Also because of the twisting movement of the columns, in each of the four outrigger levels the outriggers are connected to the core at different points. This alternating connection creates additional torsion effect on the core. Meanwhile, the twisted movement of the columns also creates a torsion effect on the overall system because of the inclined component of columns' self-weight. The geometry of the columns affected the construction process and the construction sequence is arranged in a way that it minimizes the torsion and creep effect. (Askarinejad, 2014)

Figure 2.17 shows the image of Lakhta Center (left panel), its plan drawing and partial 3D model of the structural members (right panel). 3D models show mega core, columns and outriggers. It can be observed that columns have a leaned geometry because they are also twisted with the form of the building. Outriggers are connected to the core by sharing a linear edge. Since columns are leaned, it may be problematic to connect columns and outriggers in the same way. Instead, outriggers have triangular form on the column end and connected to the mega columns with a point.

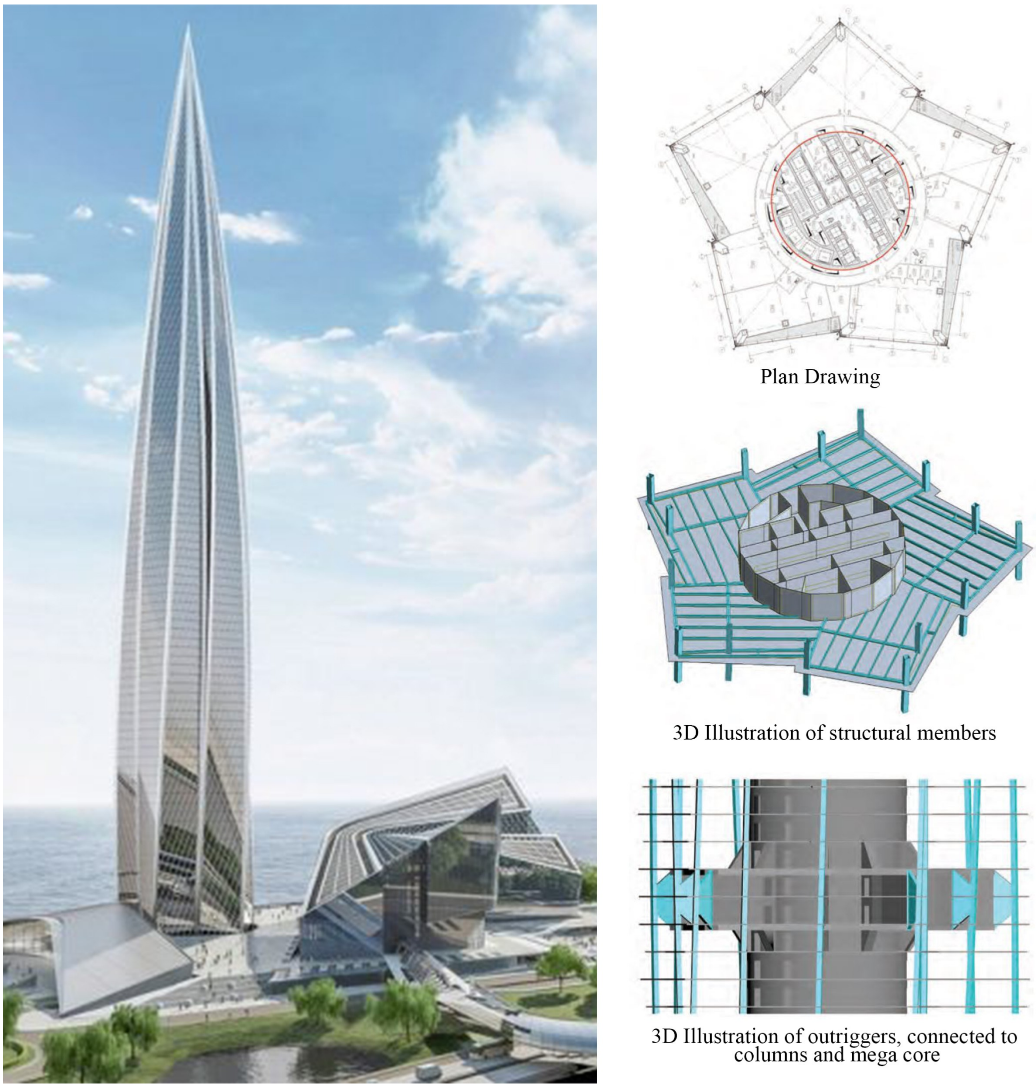


Figure 2.17: Laktha Tower, its plan and structural system in 3D (Askarinejad, 2014)

2.5.3 Cayan Tower

Cayan tower (or Infinity Tower), has 305-meter height and rotates 90 degrees at total. Structural system of the tower consists of reinforced concrete perimeter tube, a central core and six twisting internal columns that are used to reduce the span of the slab. The tube system and the central core are connected by the concrete flat slabs which act as diaphragms. The tube system on the façade consists of frequently placed columns. These columns are placed in a way that they follow the twisted form of the building. However, these columns are not fully sloped, rather they are offset with a certain distance at every floor level. This movement of the columns fits the twisted form of the building and creates a continuous visual effect. The beams between two neighboring columns are proportioned in a way that the axial load transfer does not create a significant torsion effect. By this method, the openings on the façade and the interior partitions are rotating with the movement of the columns, however; the plan layout is the same regardless of orientation angle. Floor plans become identical and also instead of leaned, unique structural or non-structural members, this project has typical members. Therefore, the modelling and construction process does not become a challenge. The core has a circular geometry so it is also not affected by the twisted form in terms of stiffness. The form is evaluated by the wind tunnel tests. For comparison, another model that rises straight is tested and it is seen that, the twisting form of Cayan Tower decreases the across-wind force by 25% (Baker et al., 2010)

Figure 2.18 shows the image of Cayan Tower (left panel), its plan drawing and column layout scheme (right panel). Central core, interior columns and framed tube system can be seen on the plan drawing. Columns of the frame tube system are located in a stepped way which is illustrated on the figure.

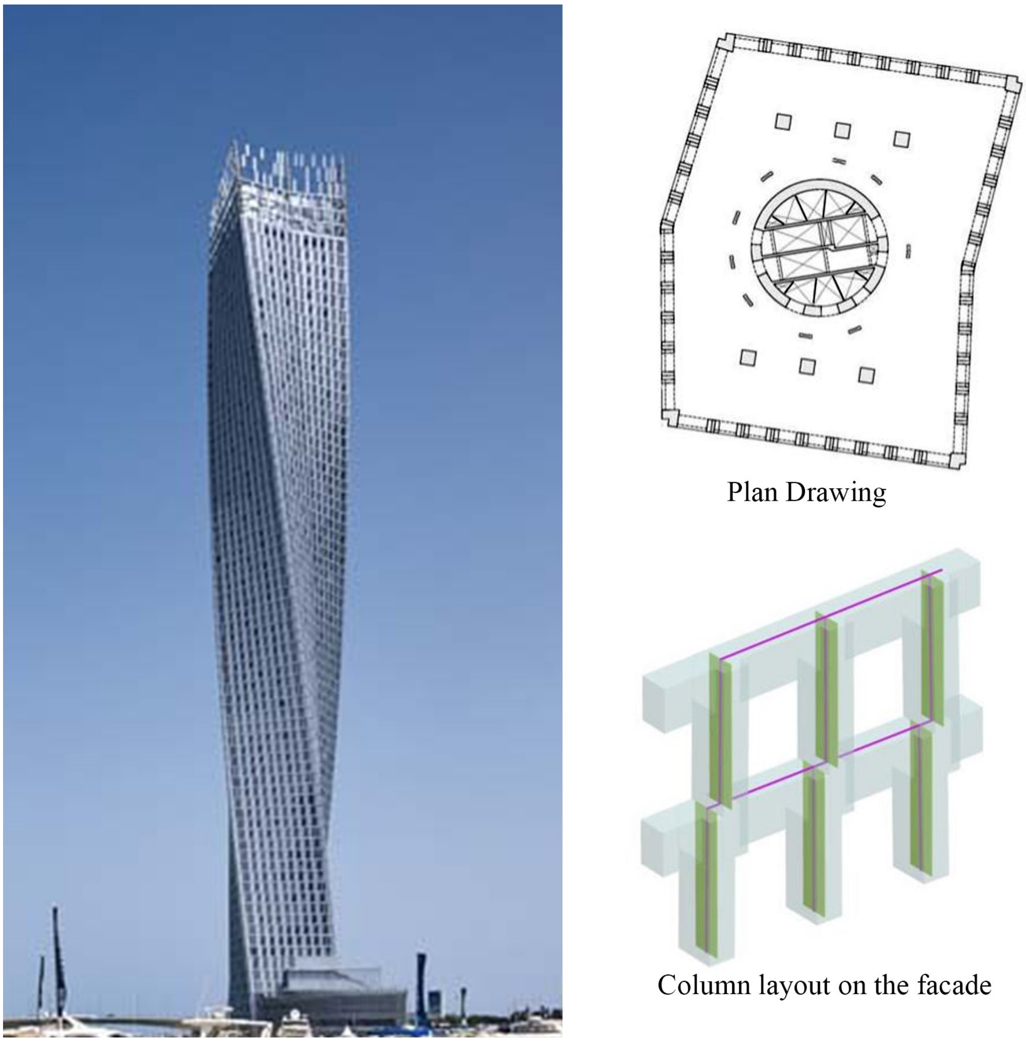


Figure 2.18: Cayan Tower, its plan and column layout on the façade (Baker et al., 2010)

2.5.4 Evolution Tower

Evolution Tower is a 246 meters tall building. It has 156-degree rotation at total (2.8-degree rotation for each floor). The shear walled frame system of Evolution Tower consists of a circular core at the center and eight mega columns around the core. On each corner of the tower, there are gravity columns, rotating with the form of the tower. Except from these outer corner columns, inner structure does not twist. Instead, square floor slabs rotate around the circular core. Since the mega columns are not twisted but straight, they are not at perimeter and thus there are cantilever beams and slabs. To decrease the deflection at the corners of the slab, corner columns are located. Having the structural system perpendicular and rotating only the floors eliminates outriggers, additional torsion effect and rather large dimensioned structural members. However, in every level the structural system intersects with the floor layout at different points. Since there is no typical plan, creating formwork for the construction become time consuming and challenging. To eliminate this problem a special formwork is applied that consists of three parts and enable pouring the slab and the core at once. Even though the construction difficulties are tackled, having different plan layouts for every floor raises concerns about architectural design. (Nikandrov, 2016)

Figure 2.19 shows the image of Evolution Tower (left panel) and 3D model of its structural members (right panel). From the 3D model, it can be observed that the inner columns stand in a perpendicular way while floors rotate as the buildings rises. Four corner columns that rotate with the twist angle of the floors can be seen on the exterior edges of the model.

Figure 2.19: Evolution Tower and 3D model of structural members. (Nikandrov, 2016)

2.5.5 Turning Torso

Turning Torso (official name is HSB Turning Torso) is a 190 meters tall twisted building located in Malmö, Sweden. It is designed by Santiago Calatrava. Its structural system is mega core system and it is a reinforced concrete building. In the design process, Calatrava was inspired from the human body. Early sketches of the project depict a rotating human torso and the spine. The building is carried by a central mega core. The spine on the exterior of the building which is rotating with the form of the building is to support cantilevered slabs. There are 5 story height 9 modules. In every module, building rotates 10 degrees and there is 90-degree twist at total. (Günel & Ilgin, 2014) Figure 2.20 shows plan drawing and rotation of 9 modules and 3D representation of structural system.

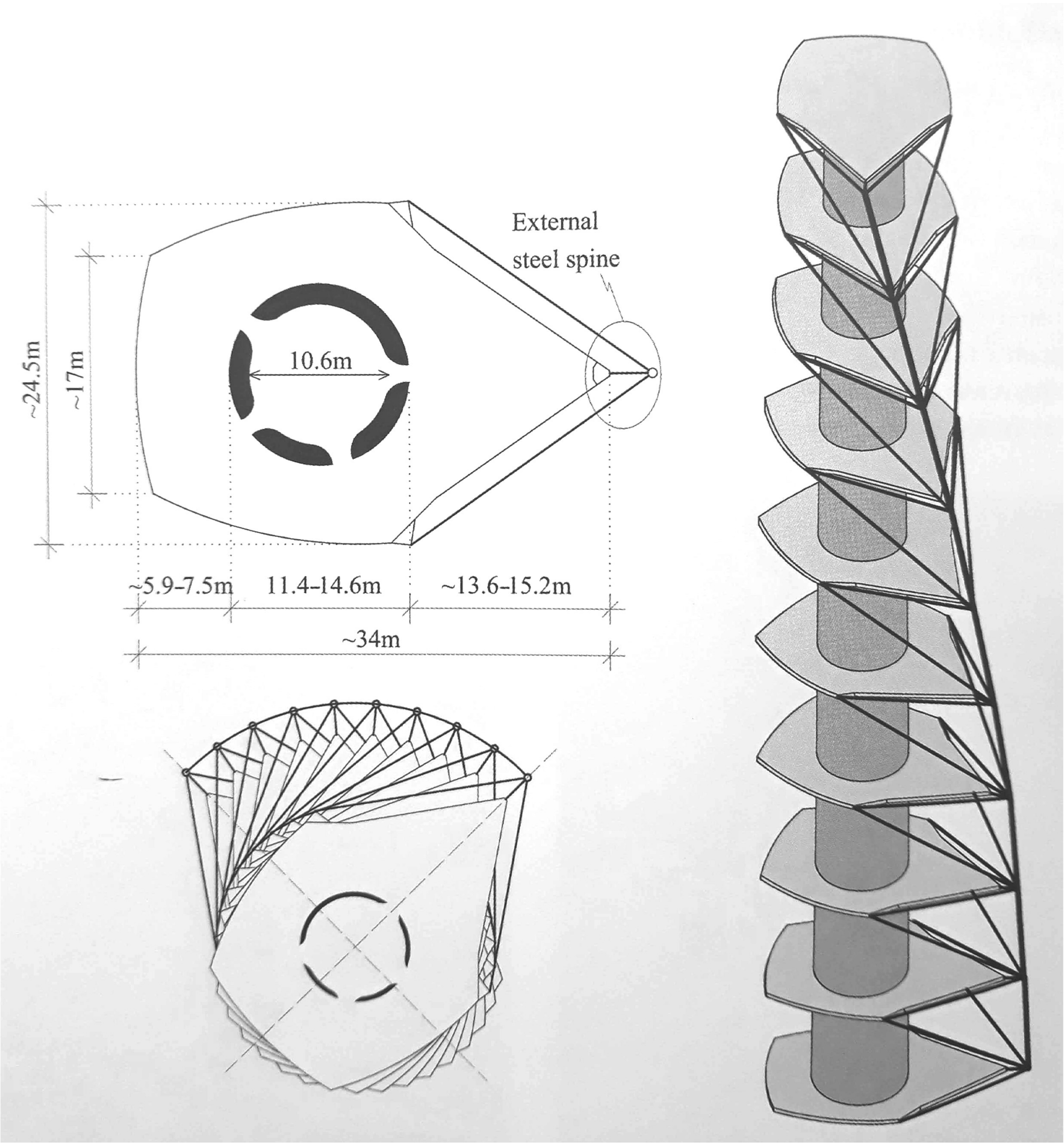


Figure 2.20: Structural system of Turning Torso (Günel & Ilgin, 2014)

2.5.6 The Grove at Grand Bay Tower

The Grove at Grand Bay Tower is a 94-meter height residential building. It rotates 38 degrees at total which corresponds a 1.8-degree rotation on each floor. It has a rectangular central core, columns and rotating rectangular slabs. The core does not twist but the rigid frame system twists as the building rises. The rotation of the columns creates torsion which is carried by the core. To reduce that torsion effect, hat truss is located at the top of the structural system. This hat truss partially converts torsion effect to lateral force which reduces the required dimensions of the mega core. (Desimone et al., 2015)

Figure 2.21 shows the image of Grove and Grand Bay Towers. Figure 2.22 shows the structural system of the building in 3D model. Rectangular core of the building can be observed in figure 2.22. It does not twist with the form of the building. But floors and the columns twist as the building rises.

Figure 2.21: The Grove at Grand Bay Tower (Desimone et al., 2015)

Figure 2.22: Structural system of the Grove at Grand Bay Tower (Desimone et al., 2015)

2.6 Critical Evaluation of the Literature

The tendency to use twisted form in tall buildings emerged from the search for pluralism in architectural design. Twisted form fulfills the demand to create iconic and unique expression. In that sense, it contributes to the architectural quality of the projects. However, it also creates concerns for both architectural and structural design.

For design and analysis of the twisted forms, parametric modelling may be required which makes the process longer. Instead of conventional structural members, twisted structural system can have unique members which is a drawback for the construction. These delays because of the parametric modelling and construction difficulties make twisted tall buildings economically challenging projects. Twisted form also creates difficulties for designing the plan layout. Therefore, in terms of architectural design, twisted form has both advantages and disadvantages.

Lateral load response is one of the most critical concerns for structural design of a tall building. The wind load effect and the aerodynamic quality of the building is important in that sense. When they are compared with the other forms, twisted forms have a better aerodynamic performance. For the same wind conditions, a twisted tall building are exposed to less wind load, particularly in across wind direction, than a prismatic one, which makes twisted tall buildings advantageous in terms of structural demands. However, rising with a twisted structural system reduces the lateral stiffness of the building and creates additional torsion effect. In other words, twisted form reduces the load demand on the system but it also reduces the capacity of the system. From the existing studies it is not possible to see exact relationship between these two phenomena and decide whether twisted forms are advantageous or not in terms of structural design.

Advantages and disadvantages of twisted forms can vary with regard to the architectural and structural design projects. It can be observed from the existing projects that, there are two main ways to construct a twisted tall building. The first way is having the structure stand perpendicular and only rotating the floors with respect to the center point. This approach is called as non-adaptive system in this study. The second way is constructing the structural system with the same twisting movement of the form. This approach is called as adaptive case in this study. These two ways of structural system correspond to different potentials and problems for both architectural and structural design and their differences are not clearly studied in the existing literature.

Most of the time, tall buildings have unique qualities. Existing examples of twisted tall buildings are unique projects too. They are located on different geographies of the world so the earthquake and wind loading are different for every project. Since they are located in different countries, the design code also varies between different projects. The parameters like structural system, height, twist angle, aspect ratio and etc. are not the same. Also, in most of the projects there are case specific solutions. Therefore, it is not fair to compare these projects and understand the effect of the twisted form clearly. In this study, it is aimed to contribute to this study area by creating a refined data set about the potentials and problems of twisted tall buildings.

CHAPTER 3

MATERIAL AND METHODOLOGY

Twisted forms affect structural performance of tall buildings. This study aims to examine and compare the structural performance of twisted tall buildings with adaptive and non-adaptive design (also adaptive-inside design for only two models) and different height, twist angle and structural system. In the procedure of the study, hypothetical structural system models for twisted tall buildings are created and analyzed by using a software for the structural analysis and design of building type structures. In material part, structural models that are used in the study are explained. Selected variables that are used to create structural models are described in detail. Preferred software are introduced. In the methodology part, the analysis procedure is explained.

3.1 Material of the Research

The existing examples of twisted tall buildings differ from each other in terms of parameters such as height, structural system, twist angle, aspect ratio and etc. All of these parameters affect the overall system and it is not possible to evaluate the effects of these variables separately by comparing existing projects. Similarly, understanding the effect of the twisted form in a controlled way is not possible. Therefore, hypothetical design cases are created which make a controlled analysis process possible. Results that are apart from the project-specific qualities are obtained.

3.1.1 Initial Models

In the model creation process, firstly the parameters that will be evaluated in the scope of this study are determined which are height, structural system and twist angle.

For the first models 300-meter height is selected, because it is the limit of supertall buildings according to CTBUH. For supertall buildings there are five different structural systems classified by Günel and Ilgın (2014) In this study, outriggered frame (OF) system and framed tube (FT) system are chosen to be investigated. Twist angle is selected as 90 degrees since 6 of 28 existing examples have 90-degree twist and also previous studies about aerodynamic performance of the forms are mostly focused on 90, 120 and 180 degrees. Aspect ratio is set as 6. Square plan is preferred for the models. Since the height and the aspect ratio are selected as 300 meters and 6, respectively, plan dimensions are set as 50x50 meters.

There are two different ways to design a twisted tall building, as it has been discussed in the literature review. First one is adaptive case, which is the case that structural system members rotates with the floors as the building rises. Second one is non-adaptive case in which structural system stands perpendicular while floors rotate as the building rises. For initial models, OF system and FT system are selected. For each of these structural systems, 2 models are created; an adaptive model and a non-adaptive model. Therefore 4 models are created at first which are adaptive OF system, non-adaptive OF system, adaptive FT system and non-adaptive FT system. Then, two additional models are added which are adaptive-inside models.

3.1.1.1 Outriggered Frame System Models

Existing tall buildings that have OF system are investigated and it is seen that there are some common applications in their structural system layout. One of these common applications is, having a central core and eight mega columns at perimeter. Guangzhou CTF Finance Center (I. Ho, Yuk, Lo, & Ming, 2014), Taipei 101 (Poon, Shieh, Joseph, & Chang, 2004), Shanghai Word Finance Center (Katz et al., 2008), Ping An Finance Center, International Commerce Center (Klemperer et al., 2016), Jin Mao Building and Two International Finance Center (Günel & Ilgin, 2014) are examples of this application. Figure 3.1 shows plan drawings (left) and outrigger applications (right) of Two International Finance Center, Jin Mao Building, International Commerce Center and Taipei 101 respectively. Considering the frequency of this layout, OF system cases are comprised with a central core and eight mega columns.

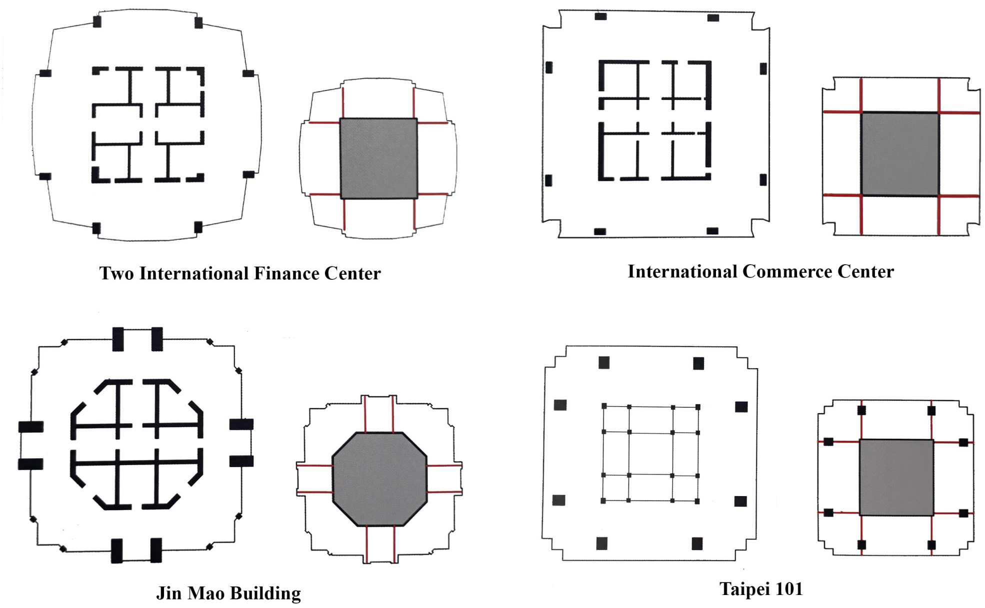


Figure 3.1: Plan drawings and outrigger applications (Günel & Ilgin, 2014)

In the given OF building examples, columns are mostly located on the perimeter. When the outriggers connect the columns and core, they work together against lateral forces. Locating columns as close as possible to the edge of the floor increases distance between core and columns. Therefore, structural depth of the building increases. All of these mentioned examples are prismatic buildings. In a prismatic building it is possible to locate columns on the edge of the floor. However, for the twisted tall buildings it may not be possible.

In a twisted tall building, building's sections that are parallel to each other change constantly. If we accept a twisted tall building's form as a solid mass, there is a prismatic cylindrical volume at the center and an irregular mass wrap around this cylinder. In adaptive case, columns have the same twisted movement with the form and wrap around the building. Therefore, they can be located on the edges of the floor. On the other hand, in non-adaptive case, columns stand in perpendicular and prismatic way. Therefore, they have to be within the cylindrical volume at the center. Figure 3.2 shows the square ground floor plan and the projections of the upper rotated floors. The circular area that remains the same throughout the height of the building is shown with grey color.

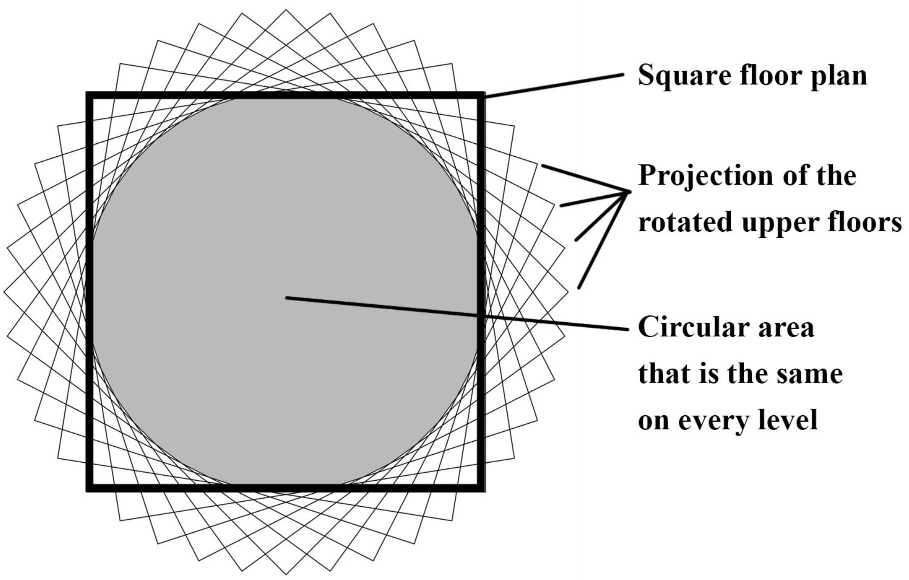


Figure 3.2: Plan projections of twisted floors

Because of different projections created by twisted form, column axes are passing through different locations in non-adaptive and adaptive cases. In the adaptive case columns are on the edge of the plan, in non-adaptive case they are inside the marked circular area. Since there are two columns on each side of the plan, columns are located in a way that they divide the building width into approximately equal tree zones.

Circular cross-section is used for the columns. Therefore, their moment of inertia is the same for every direction. This is important especially for adaptive cases. Despite turning movement of the columns, moment of inertia of the columns stays constant in the analysis and does not cause a variation in the results. Similarly, mega core of the models has a circular tube section. James (2017) noted that in twisted tall buildings, even if the structural system has the same twisted movement with the form of the building, core should stay prismatic. The core is used for vertical transportation and shafts. Twisted form creates inconvenience to locate these functions inside the core. The adaptive case is defined as the case that the structural system also rotates with the floors which means the core rotates too. If the core has a section that is not a circular geometry, its overall form cannot be prismatic after the twisting movement but a circular form creates a prismatic cylinder with the rotation movement. Another benefit of having a circular core was explained by Scott *et al.* (2007) as, with a ring corridor around it, circular core will create a practical circulation for twisting floors.

Dimensions of columns and core are determined by an iterative process. For the first model, which is a non-adaptive case, Evolution Tower's core and columns are taken as a reference. Model is analyzed and modified for several times until the top deflection under code based wind loading reaches 1/500 of the height which is the serviceability limit for tall buildings (Moon, 2014). At the end, diameter of the columns and core become 3.2 meters and 20 meters, respectively. Figure 3.3 shows plan drawing and dimensions of non-adaptive case.

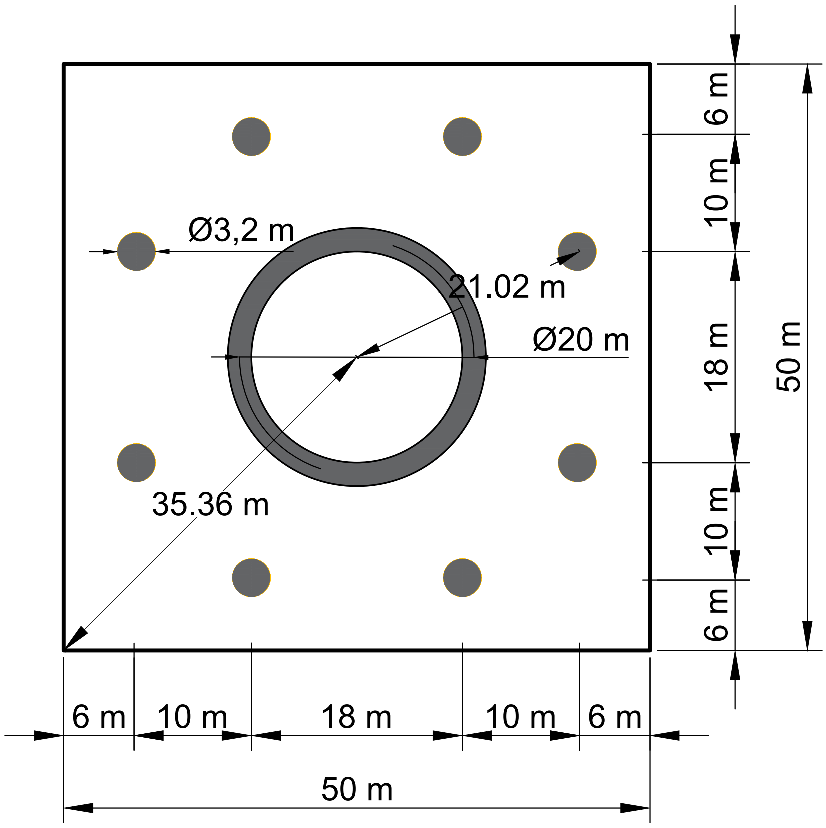


Figure 3.3: Plan drawing and dimension of non-adaptive case

To be able to make comparison between them, dimensions of the core and columns are kept same in adaptive and non-adaptive cases. However, structural axes for columns are different in adaptive case, as it has been discussed. Figure 3.4 shows plan drawing and dimension of adaptive case.

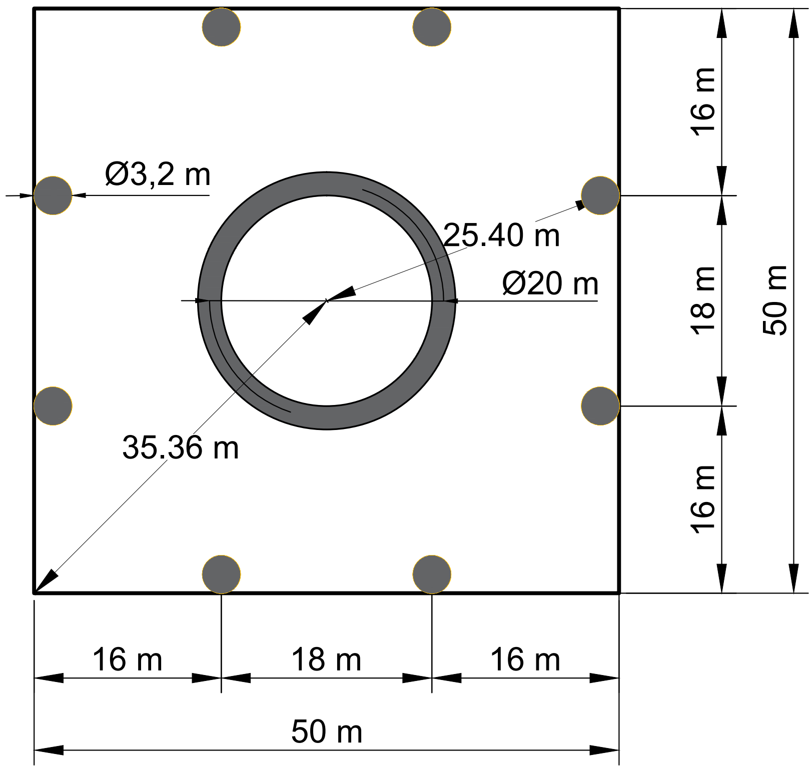


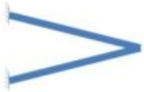
Figure 3.4: Plan drawing and dimension of adaptive case

Story height of the models is set as 4 meters, so there are 75 stories in the models. Slabs are created as 30 cm thick flat plate concrete slabs. Deflection limits of the slabs have been ignored and accepted as the same for all cases. Since total twist angle is 90 degrees, twist per each floor is 1.2 degrees.

For 300 meters outriggered frame models, two levels of outriggers placed. Location of the outrigger floors are determined according to the formula suggested by Smith and Coull (1991). The formula suggests that if there is n number of outrigger levels and the height of the building is h, outriggers should be located on the h/(n+1), 2h/(n+1) … nh/(n+1) of the height. For 2 outrigger locations are 300/3 and 600/3 and they correspond to 25th and 50th floors.

Ho (2016), examined four different outrigger topologies and compared their material amount, stiffness and strength. Table 3.1 shows images of the topologies and comparative results. In this study, topology A is used. Two-story height outrigger levels are located on the floors 24-25 and 50-51. The slab between these levels is removed to make them serve as mechanical floors. For the section of the outrigger, Lotte World Tower (Seoul, South Korea) is taken as a reference. Dimensions of the section is 1600mm x 500mm x 80mm (web) x 20 mm (flange) (Lee, Kim, & Jung, 2014).

Table 3.1: Outrigger topologies (G. Ho, 2016)

Topology	 A	 B	 C	 D
Material	1.00	1.04	1.80	1.49
Stiffness	✓✓	✓	✓✓✓✓	✓✓✓
Strength	✓✓✓✓	✓✓✓	✓	✓✓

Reinforced Concrete (RC) is used as the structural material of the core, columns and slabs. By considering existing supertall buildings, C90/105 RC is used for mega core and mega columns whereas C40 is selected for slabs. Outriggers are made of steel (S355).

Figure 3.5 shows 3 dimensional (3D) structural model of non-adaptive case. On the left panel of the 3D model, plan drawings are put from indicated floors. On the right panel of the 3D model axonometric drawing of outrigger levels and regular levels are depicted. Figure 3.6 represents the same information for adaptive case.

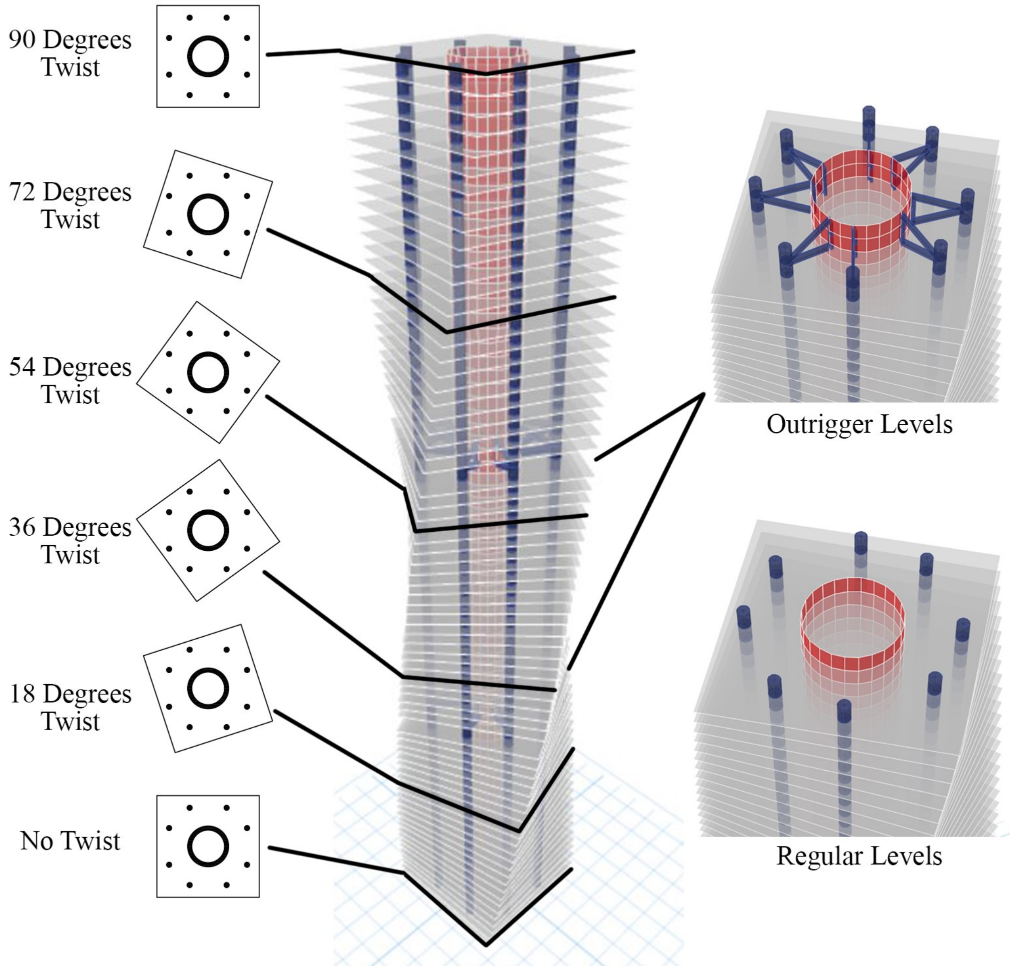


Figure 3.5: 3D structural model of non-adaptive case, plan drawings and axonometric drawings of outrigger floors and regular floors

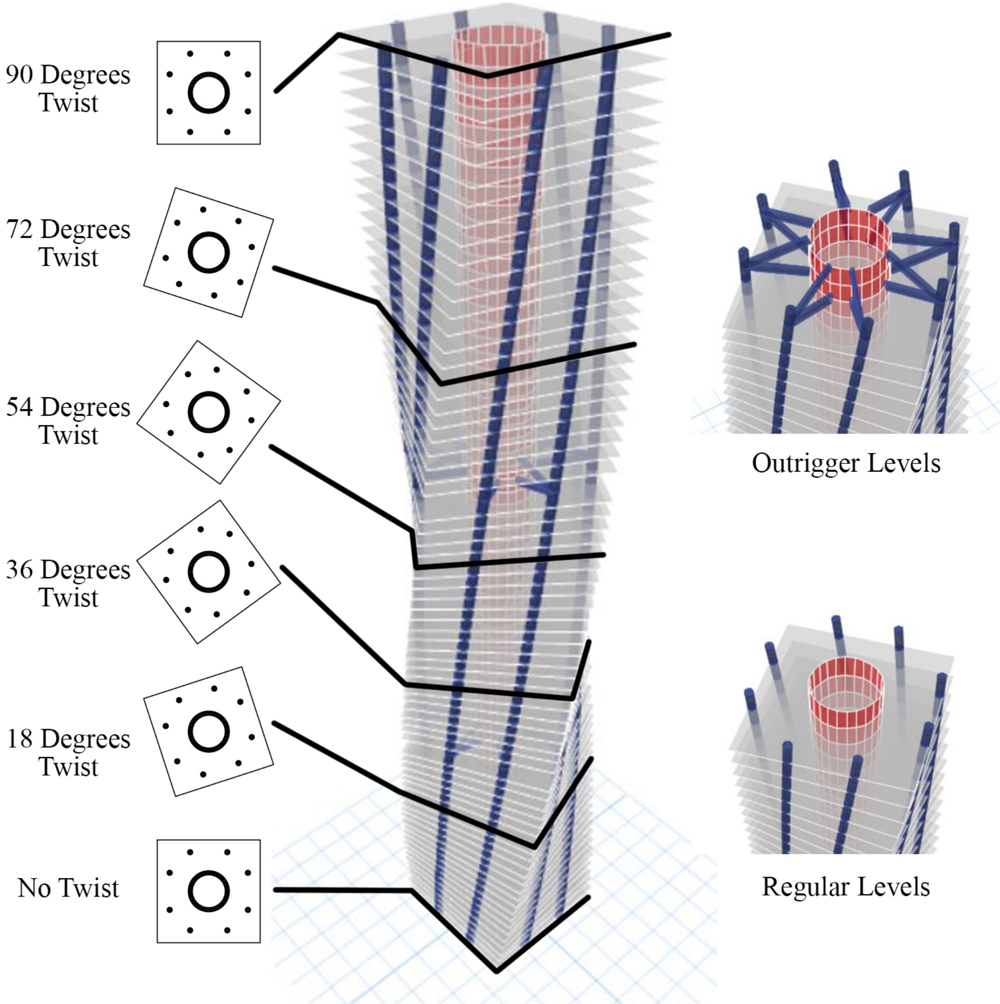


Figure 3.6: 3D structural model of adaptive case, plan drawings and axonometric drawings of outrigger floors and regular floors

For adaptive and non-adaptive cases, structural depths of the system are different, which inevitably affect the results and add a bias to the comparisons. To be able to make a clear comparison between these cases, a third model is created. In this model, columns are located on the same axes with the non-adaptive case, but they rotate as the building rises like adaptive case. This case is named as “adaptive-inside case”. Figure 3.7 shows three models together, non-adaptive (left), adaptive-inside (middle) and adaptive (right), respectively.

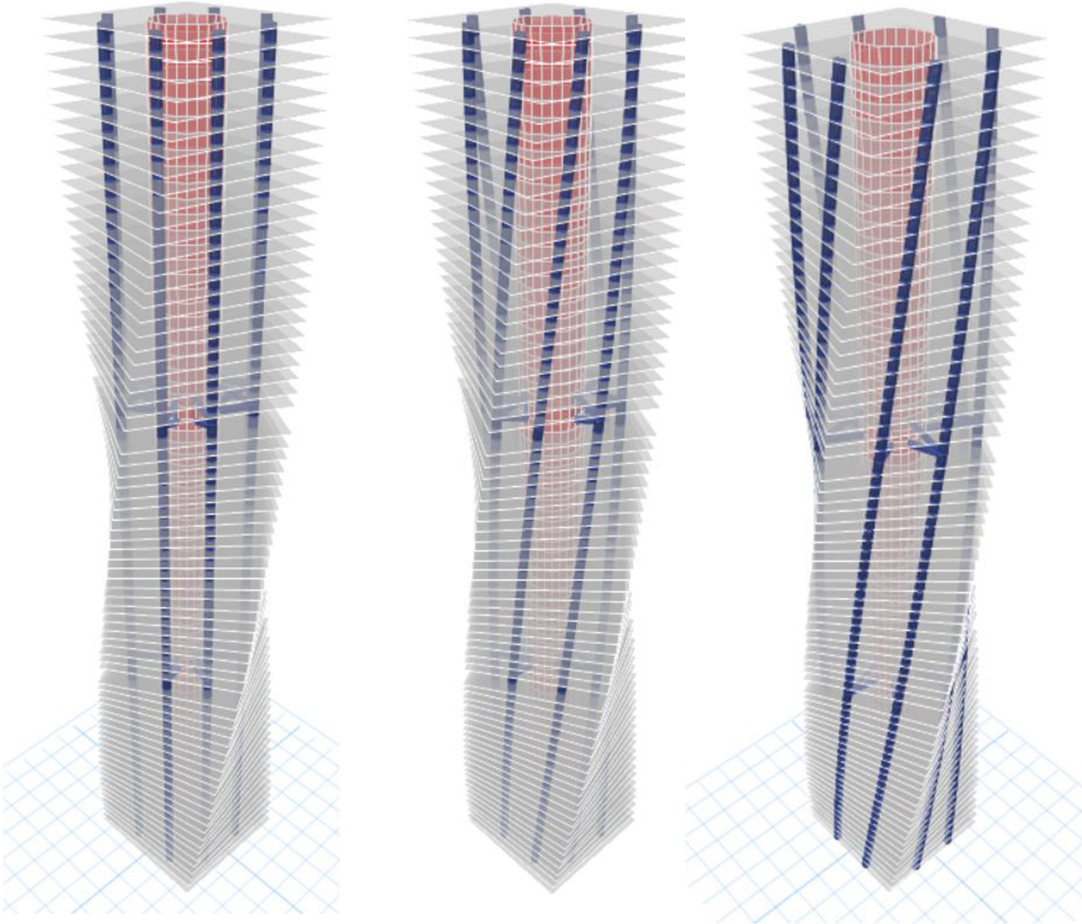


Figure 3.7: Non-adaptive, adaptive-inside and adaptive cases

3.1.1.2 Frame Tube System Models

Framed Tube system is another frequently used structural system for tall buildings. Guangzhou International Finance center, 30 st Mary Axe and John Hancock Center are some examples of tall buildings with FT system. (Günel & Ilgin, 2014)

In tall buildings, an important percentage of the floor area is devoted to vertical transportation and mechanical shafts, as discussed earlier. This area can be called as service core. Locating the service core on the center of the plan is an effective method. From center, it can serve all of the spaces on a floor easily. Also center of the floors are the places that have minimum daylight. It is better to leave these places to elevators and mechanical shafts. Service core's walls are usually load-bearing elements. When it is located on the center of the floor, load-bearing walls of service core creates a structural core for the building. To sum up, having a service core with load-bearing walls, which is more likely located at the center, is inevitable. Therefore, tall buildings mostly have a mega core at the center of the building and this is also valid for the ones designed with FT system. In this study, FT system models have a central mega core. The mega core has a circular form because of the same reasons discussed for the OF models.

Similar with the OF system models, FT models have 4 meters floor-to-floor height and 75 floors. Total twist angle, rotation per floor, plan dimensions and the aspect ratio are same with the OF models. Also for FT system, two generic models are created as adaptive and non-adaptive case.

In adaptive case, FT system consists of 40 columns and deep spandrel beams. Since the columns rotate with the building, it is possible to locate them on the perimeter and have the largest structural depth, like the adaptive OF model.

Dimensions of the columns, spandrel beams and the core are defined in relation to the OF models in order to have comparable results. Thus, it is decided that, total column volume of the OF models should be equal to the total column volume of the FT system models. Summation of core and outrigger volumes in OF models should be equal to the summation of beam and core volumes in the FT models. In OF models, all of these members are made of RC except for outriggers and in FT system models, all members are made of RC. However, outriggers that are made of steel have to be converted into equivalent RC members. Thus, a replica of non-adaptive OF model is created where steel outriggers are replaced with RC outriggers. With an iterative analyses and design process, the dimensions of RC outrigger that gives the same top deflection value with the steel outrigger is found. Volumes are calculated with this equivalent RC outrigger's dimensions.

Circular columns with a diameter of 1.45 meters have been used in FT models. 1m x 1m square spandrel beams with a length of 3.81m have been used in non-adaptive case. The core wall thickness of the non-adaptive FT model is 1.28 meters. Figure

3.8 shows the plan drawing and dimensions of the non-adaptive FT model.

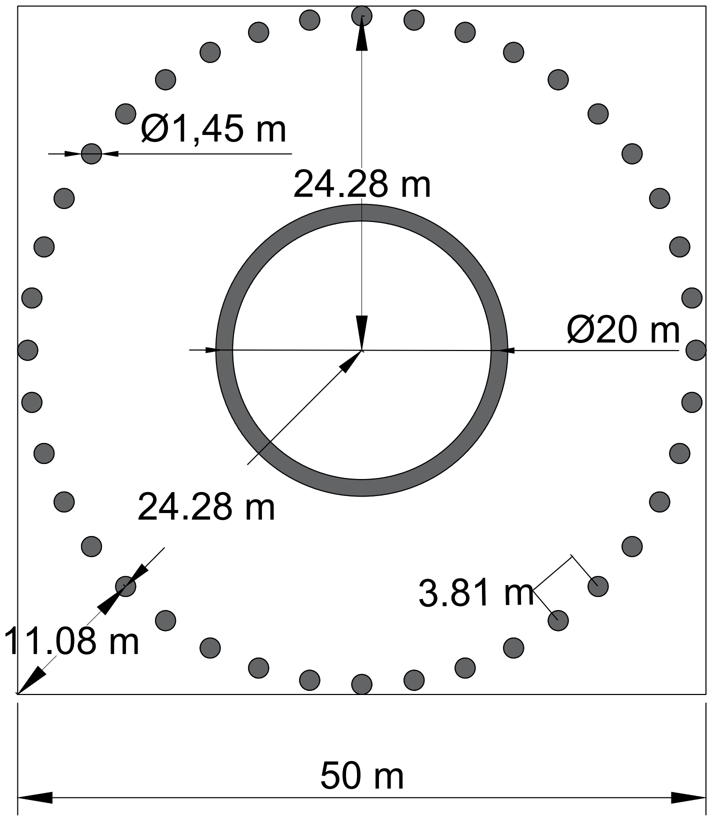


Figure 3.8: Plan drawing and dimensions of the non-adaptive tube model

Existing examples of tall buildings with FT system are designed with adaptive approach. Framed tube system covers the faces of the building so the system should be twisted with the form of the building. Still, non-adaptive FT system is examined in this study to be consistent and to be able to compare OF system results with FT system results.

In non-adaptive FT model, columns and beams cannot be located on the edges of the floor, for the same reason with the non-adaptive OF model. They should be located on the face of cylindrical volume that stands constant throughout the height of the building.

In adaptive FT model, columns are the same with the non-adaptive FT model. Beam cross section is also same but the length of beams is longer, 4.89 meters. Since the beams have more volume than the previous model, the core has a smaller volume and has 1.22 thickness. Figure 3.9 shows plan drawing and dimensions of the adaptive FT model.

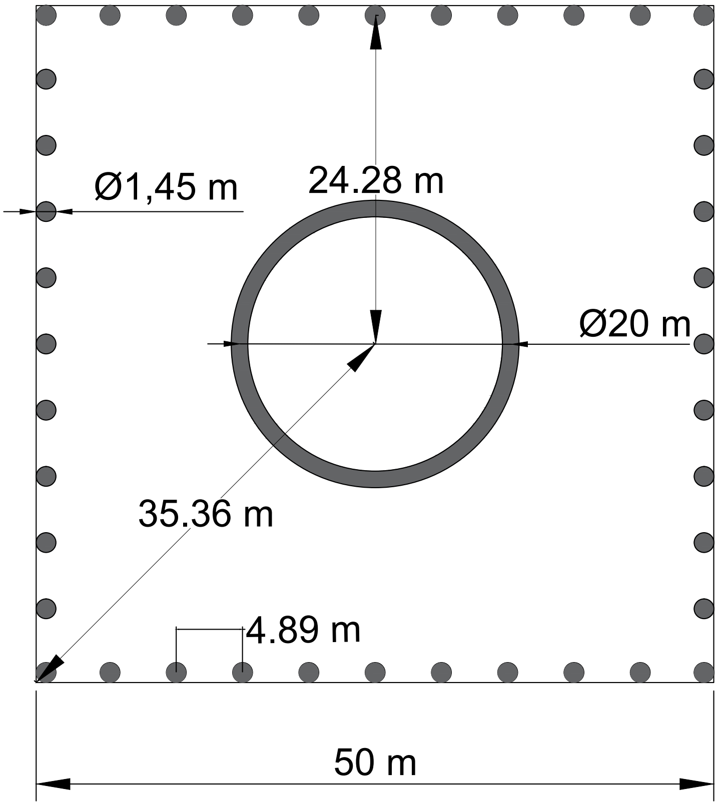


Figure 3.9: Plan drawing and dimensions of the non-adaptive tube model

For both adaptive and non-adaptive FT models slabs are made of C40 RC and columns, beams and core are made of C90/105 RC. Figure 3.10 shows the 3D model of non-adaptive FT model. On the left panel of the 3D model, plan drawings are put from indicated floors. Figure 3.11 shows the 3D model of adaptive FT model. On the left panel of the 3D model, plan drawings are put from indicated floors.

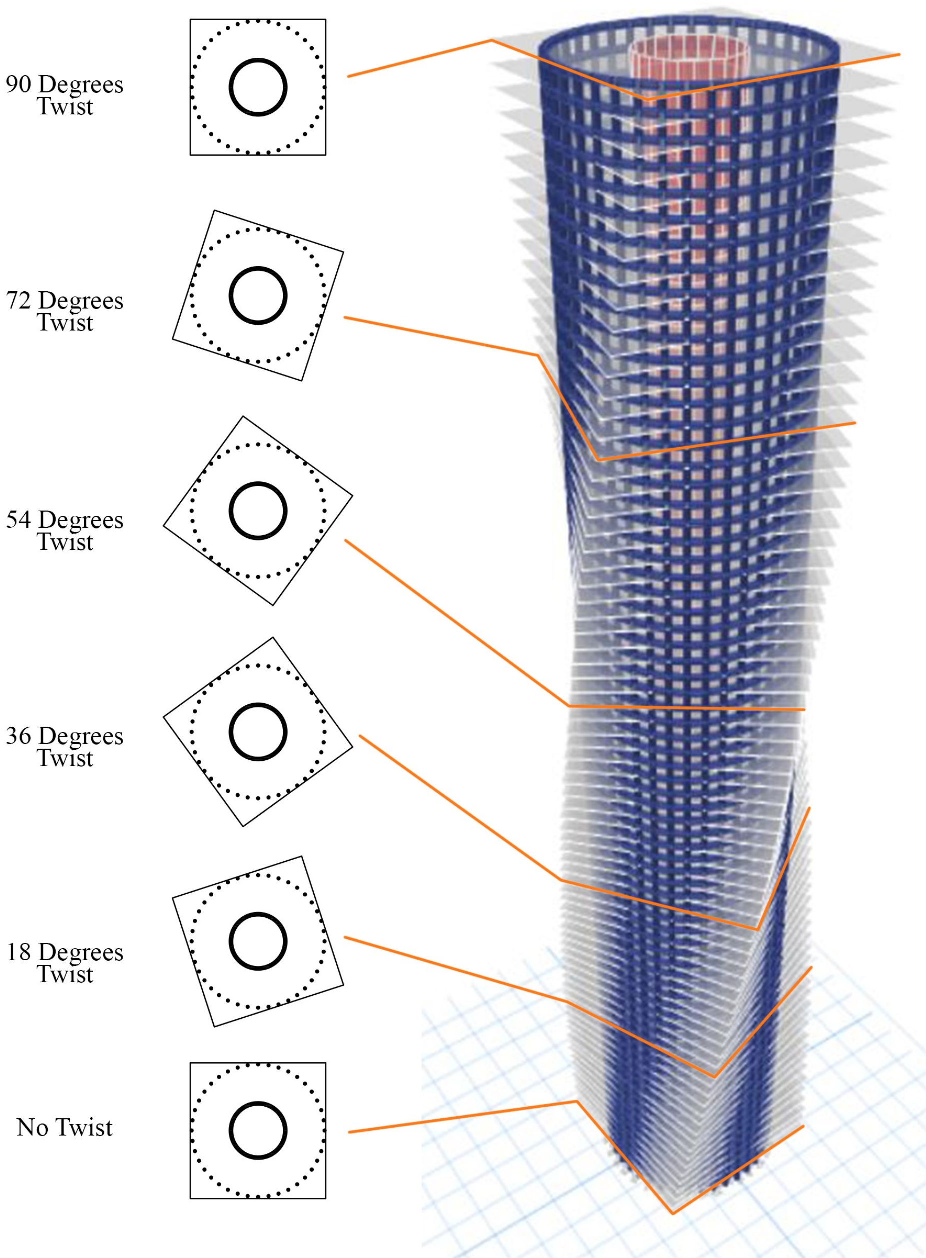


Figure 3.10: 3D structural model of non-adaptive case and plan drawings

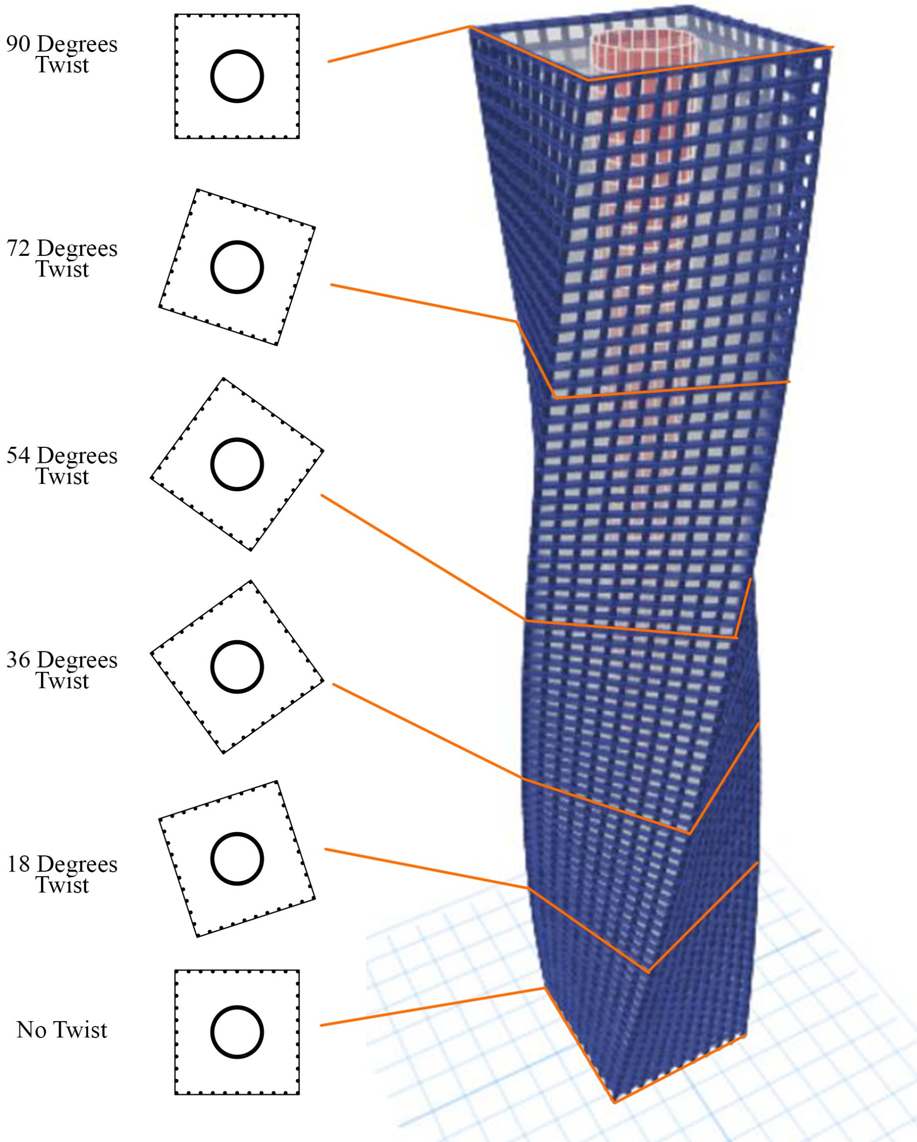


Figure 3.11: 3D structural model of adaptive case and plan drawings

Like OF system, another FT model (adaptive-inside case) is created in which structural system is adaptive but located on the same axes with the non-adaptive case. Figure 3.12 shows non-adaptive, adaptive-inside and adaptive FT models respectively.

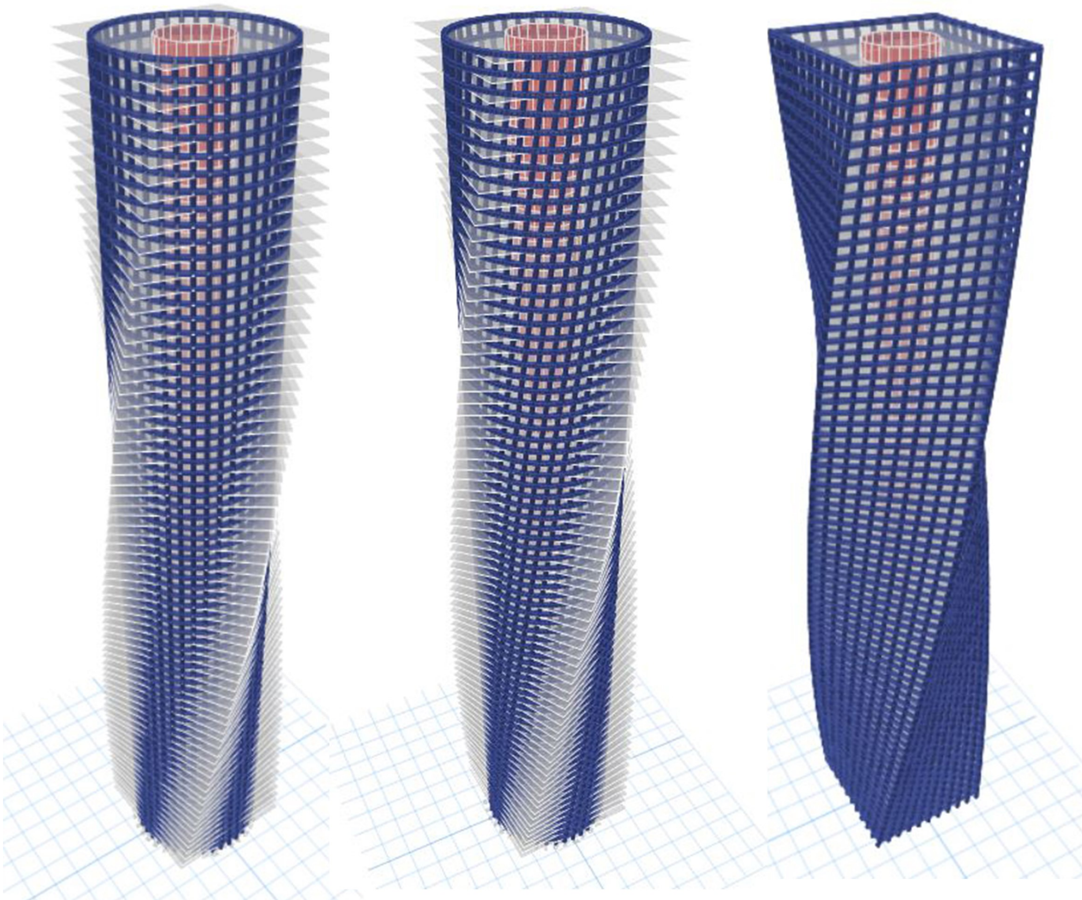


Figure 3.12: Non-adaptive, adaptive-inside and adaptive cases

Adaptive inside case is not a realistic design. Structural depths of adaptive and non-adaptive cases are different and adaptive inside case is created just for eliminating the bias of this difference on the results. Therefore, it is not produced for all of the cases, it is only created for 300-meter height models with 90 degree twist. Since there are two different structural systems, two adaptive inside models are created, one with OF system, one with FT system.

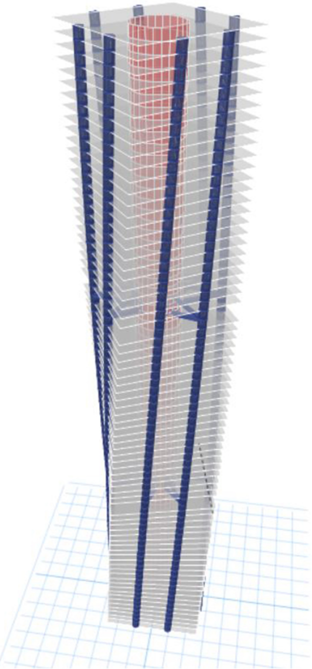
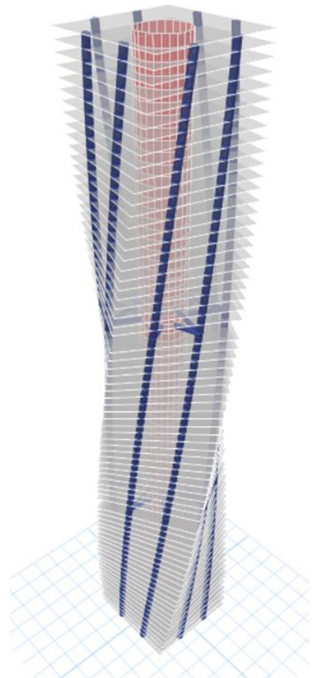
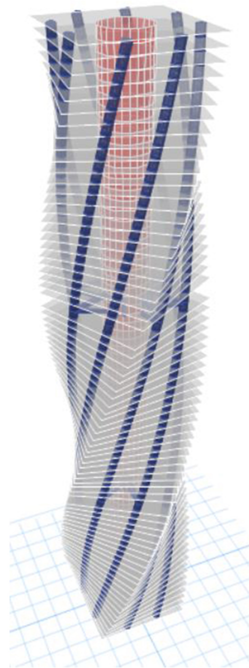
3.1.2 Variations of the Initial Models with Different Twist Angle and Height Values

In addition to alternative structural systems which are outriggered frame and framed tube, the effect of primary design parameters of adaptive and non-adaptive twisted tall buildings have been investigated to generalize the observations of this study. Other than the models that have 300meter height and 90 degrees total twist angle, alternative models are created with different twist angles and height. In these models, material qualities of the structural members are kept same.

In terms of angle of twist, 45 degrees and 180 degrees twisted models are created. Since 8 of the 28 existing twisted tall buildings have a total twist angle equal to or less than 60 degrees, 45 degrees total twist angle is chosen to represent this group of twisted buildings. There are two examples that have 330 and 360 degrees total twist which are clearly distinguished from the rest. Other than these two buildings, 10 of 28 existing examples have total twist angle between 90 and 210 degrees. To represent these 10 buildings, 180 degrees total twist angle is selected. 180 degrees is also an angle that is tested in the wind response studies. In the 90 degrees twisted models, the rotation angle per story is 1.2 degrees. For 45 and 180 degrees twisted models it is 0.6 and 2.4 respectively.

In the non-adaptive models, changing the twist angle does not affect the structural system. Only the rotation angle of the floors is changed. However, in the adaptive cases, layout of the columns is changed to adjust new twist angles. Table 3.2 shows axonometric views of the adaptive case models designed with OF and FT systems for 45, 90 and 180 degrees total twist angles.

Table 3.2: Axonometric views of the adaptive case models designed with OF and FT systems for 45, 90 and 180 degrees total twist angles

	45 Degrees Twist	90 Degrees Twist	180 Degrees Twist
Outriggered Frame System Models			
Frame Tube System Models			

To investigate the effect of building height on structural system performance of adaptive and non-adaptive twisted buildings, 200 and 400 meters high versions are created in addition to the 90 degrees twisted 300 meters tall ones.

In terms of height, 22 of 28 existing twisted tall buildings are lower than 300 meters. To represent these buildings 200 meters height is selected. On the other hand, there are only 3 twisted tall buildings higher than 300m. Among these, only Shanghai Tower is taller than 600 meters which is the limit of mega tall buildings. Thus, to represent three existing examples that are taller than 300 meters, 400 meters height is selected.

Other than height and angle of twist, the aspect ratio which is an important design parameter that inevitably affects the structural performance of adaptive and non-adaptive models is kept same as 6 for all of the models to scrutinize the effect of height in an unbiased way. As a result of this, plan dimensions of the 200 and 400 meters models are different than 300 meters height models. In 200 meters tall models it is 33.3x33.3 meters and in 400 meters models it is 66.7x66.7 meters. To be able to make comparison between these models, diameter of the core and distance between axes of the structural members are scaled according to the plan dimensions. Like 300 meters high models, 200 and 400 meters high models have a circular core at the center and perimeter columns.

Story height is kept the same for all models which is 4 meters. Therefore, in the 200 meters models there are 50 story and in 400 meters models there are 100 story. Total twist angle is kept the same which is 90 degrees. Therefore, twist per each story is different, it is 1.8 degrees in 200 meters models, 1.2 degrees in 300 meters models and 0.9 degree in 400 meters models.

To define dimensions of the structural members, the same methodology applied in the 300 meters models is used for 200 and 400 meters models. Firstly, non-adaptive OF model is designed in a way that its top deflection will be approximately 1/500 of the height of the building. To be able to make comparison between models with different heights, ratios of the shear force that is carried by core and columns are used. The ratios are kept approximately the same for three different heights.

In 200 meters OF models, the column diameter is estimated as 1.5 meters. Diameter of the core and corresponding wall thickness are taken as 13.33 meters and 1.1 meters, respectively. Figure 3.13 shows plan drawing and dimensions of 200 meters non-adaptive OF system model whereas Figure 3.14 depicts the same information for adaptive OF system model.

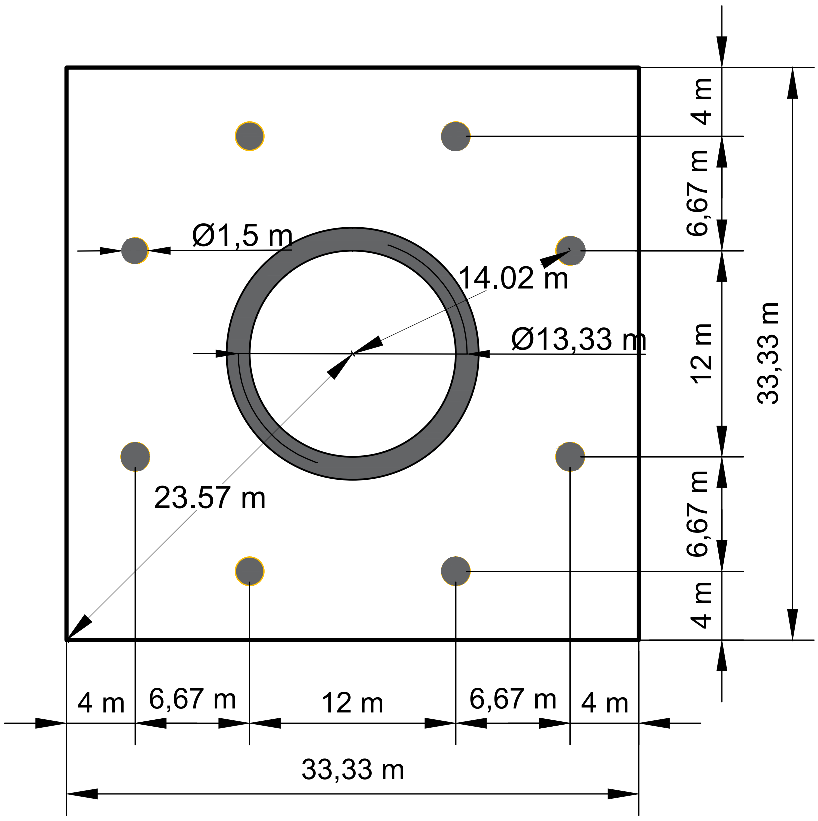


Figure 3.13: Plan drawing of 200 meters non-adaptive OF system model

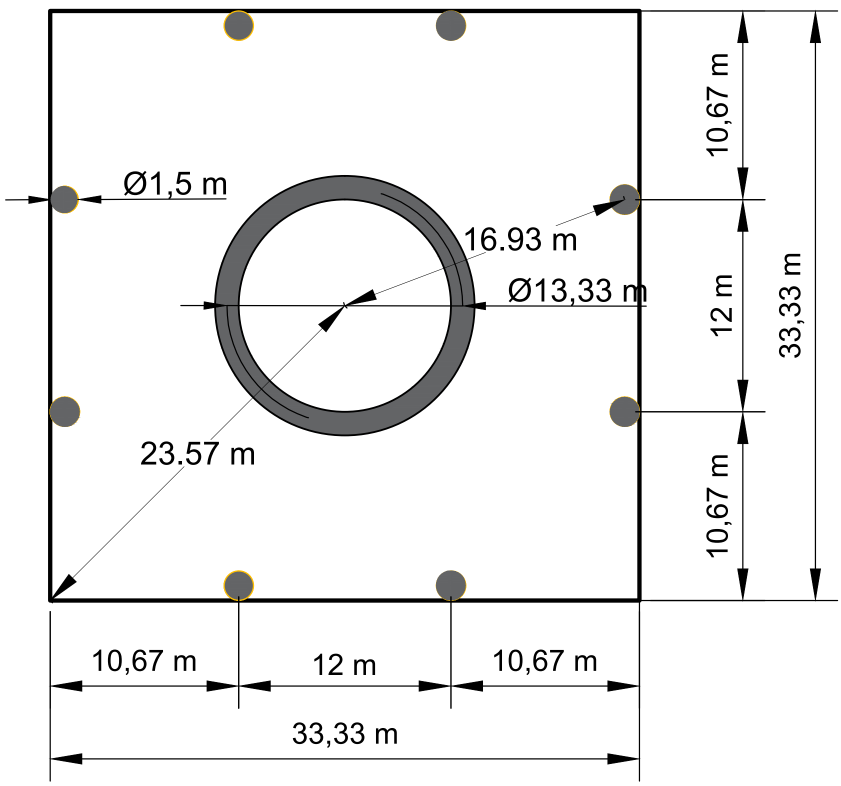


Figure 3.14: Plan drawing of 200 meters adaptive OF system model

In 400 meters OF models, column diameter is 5 meters. Diameter of the core is 26.67 meters and core wall thickness is 4 meters. Figure 3.15 and 3.16 show plan drawing and dimensions of 400 meters non-adaptive and adaptive OF system models, respectively.

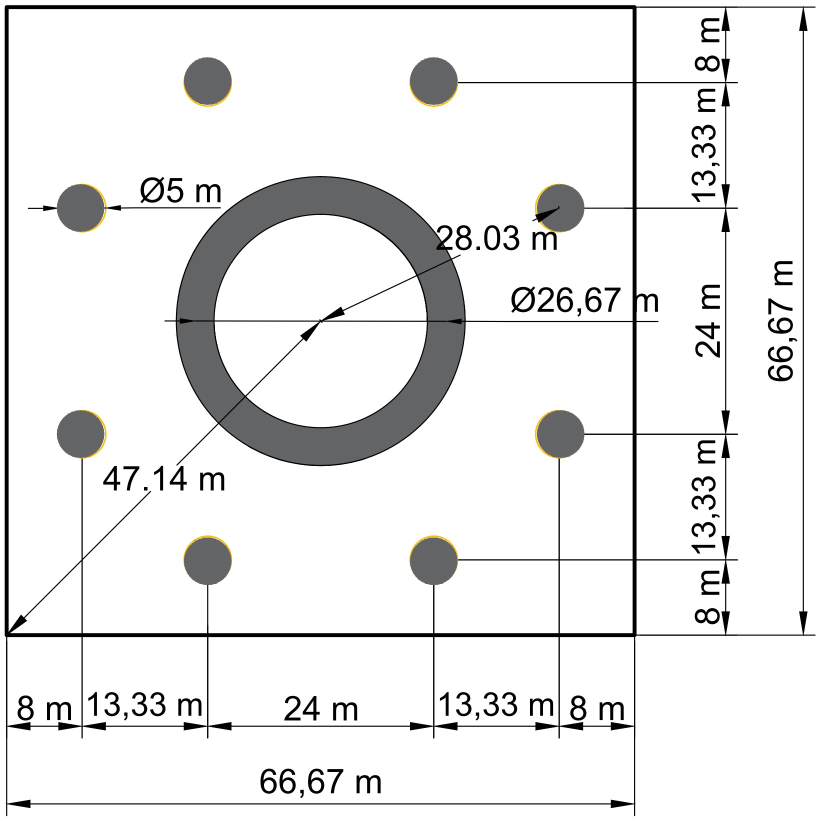


Figure 3.15: Plan drawing of 400 meters non-adaptive OF system model

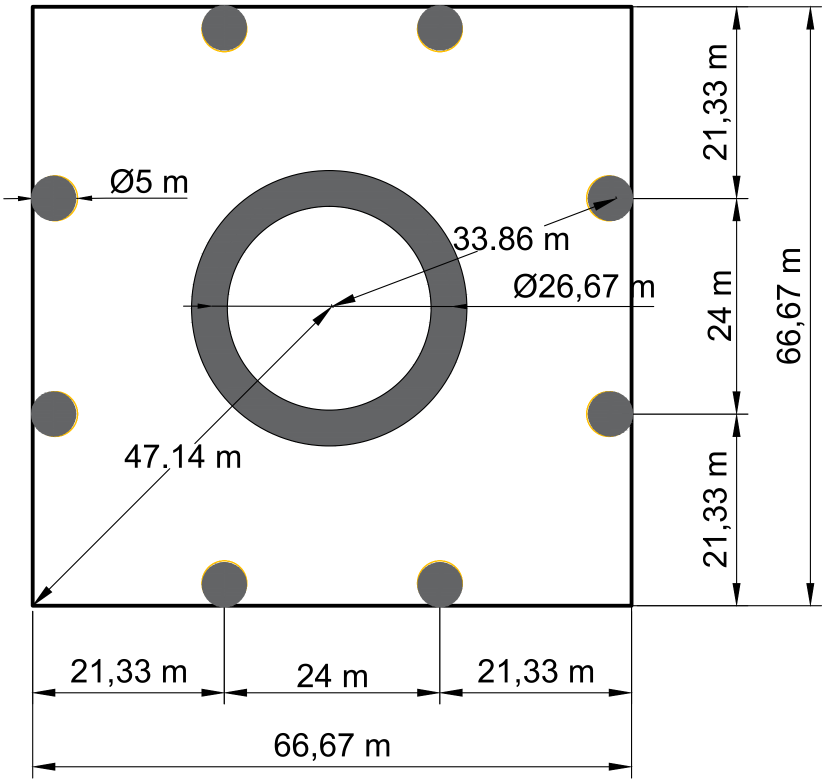


Figure 3.16: Plan drawing of 400 meters adaptive OF system model

In 300 meters models, there are 2 outriggers located on 100 and 200 meters height. In 200 meters models, one outrigger level is located on the 100 meters height whereas three outrigger levels are located on the 100, 200 and 300 meters height in 400 meters models. These outriggers connect the 8 columns and the core. Geometry, material quality and section properties of the outriggers are the same with the ones in the 300 meters models. Figure 3.17 shows 200, 300 and 400 meters adaptive OF system models to illustrate the height relation and outrigger levels.

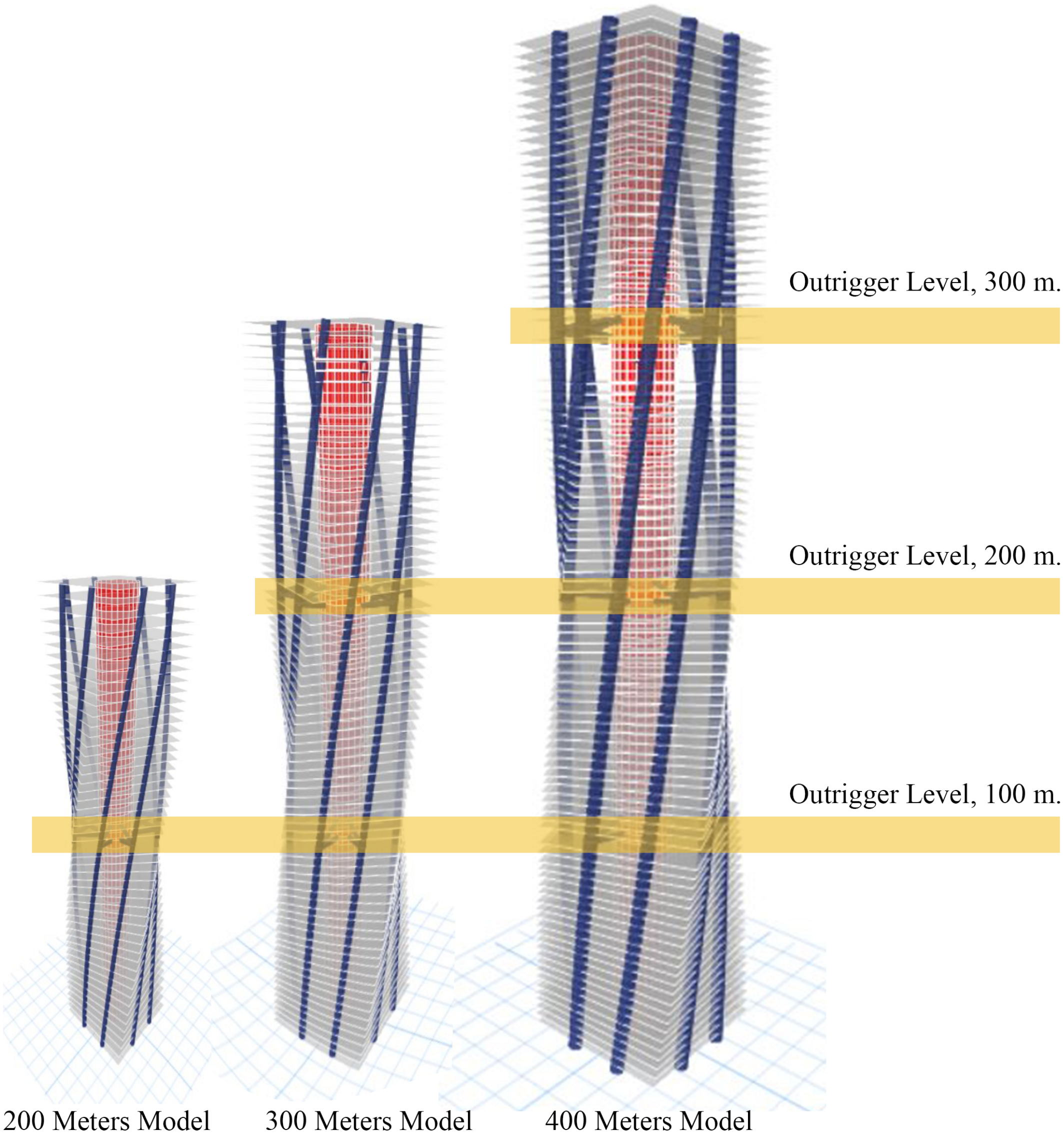


Figure 3.17: 200, 300 and 400 meters adaptive OF system models

FT system models that are 200 and 400 meters height are created with the same method applied to 300 meters high models. Total concrete volume of columns in OF system models is accepted to be equal to total concrete volume of columns in the FT system models. Then, total concrete volume of core walls and volume of equivalent concrete outriggers of OF models are equalized to the summation of core walls' volume and beams' volume in the FT models. According to this methodology, column diameter of the 200 meters FT models is found as 0.9 meter. To have a similar column to column distance with the 300 meters models, 8 columns are located on each façade of adaptive case which makes 28 columns in total. Core wall thickness is taken as 0.95 meter and section of beams is used as 0.8x0.8 meter. Figure 3.18 shows plan drawing and dimensions of 200 meters non-adaptive FT system model. Figure 3.19 illustrates plan drawing and dimensions of 200 meters adaptive FT system model.

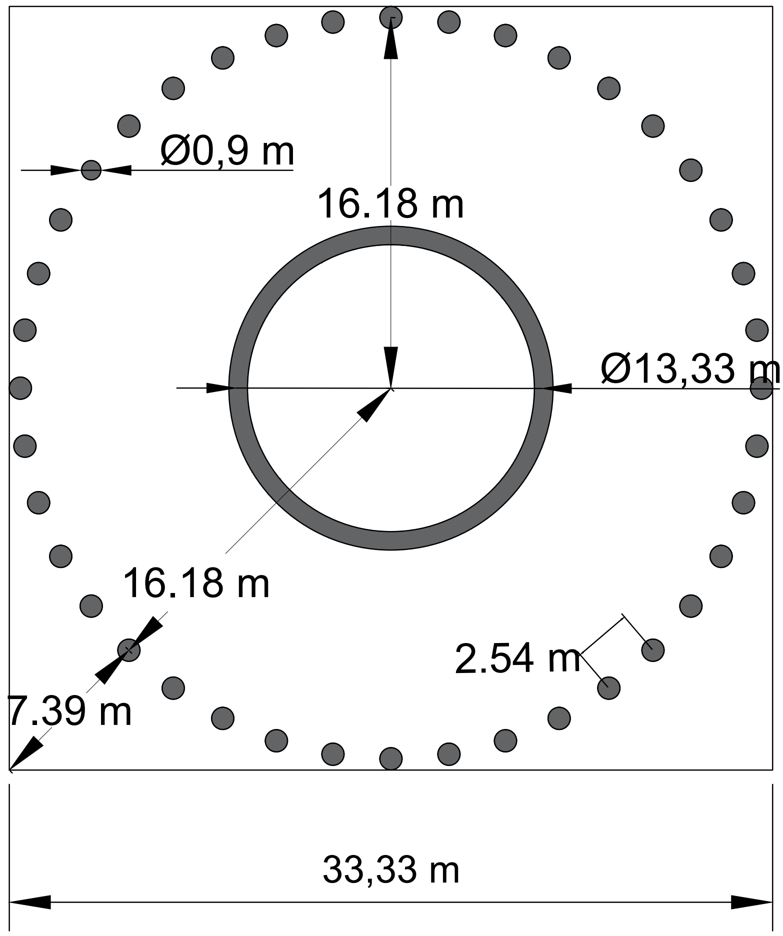


Figure 3.18: Plan drawing of 200 meters non-adaptive FT system model

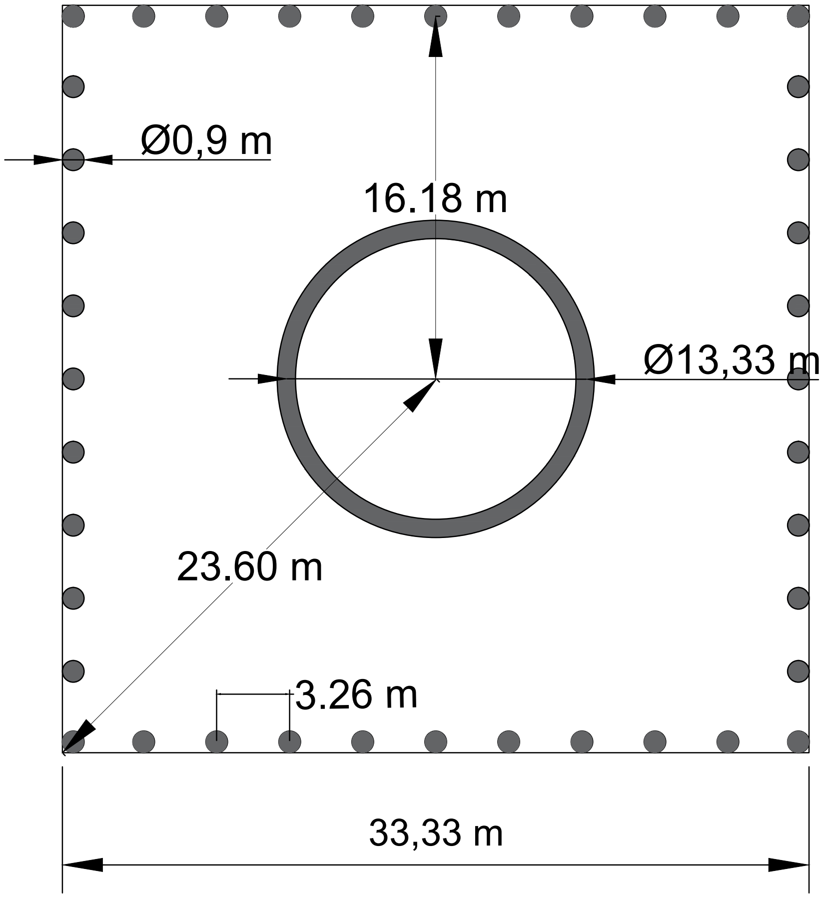


Figure 3.19: Plan drawing of 200 meters adaptive FT system model

For 400 meters FT models, column diameter is calculated as 1.9 meter. Again, to have similar column to column distance with the 300 meters models, 14 columns are located on each façade of adaptive case which makes 52 columns at total. Core wall thickness is 2 meters and section of beams is 1.5x1.5 meter. Figure 3.20 and 3.21 depict plan drawing and dimensions of 400 meters non-adaptive and adaptive FT system models, respectively.

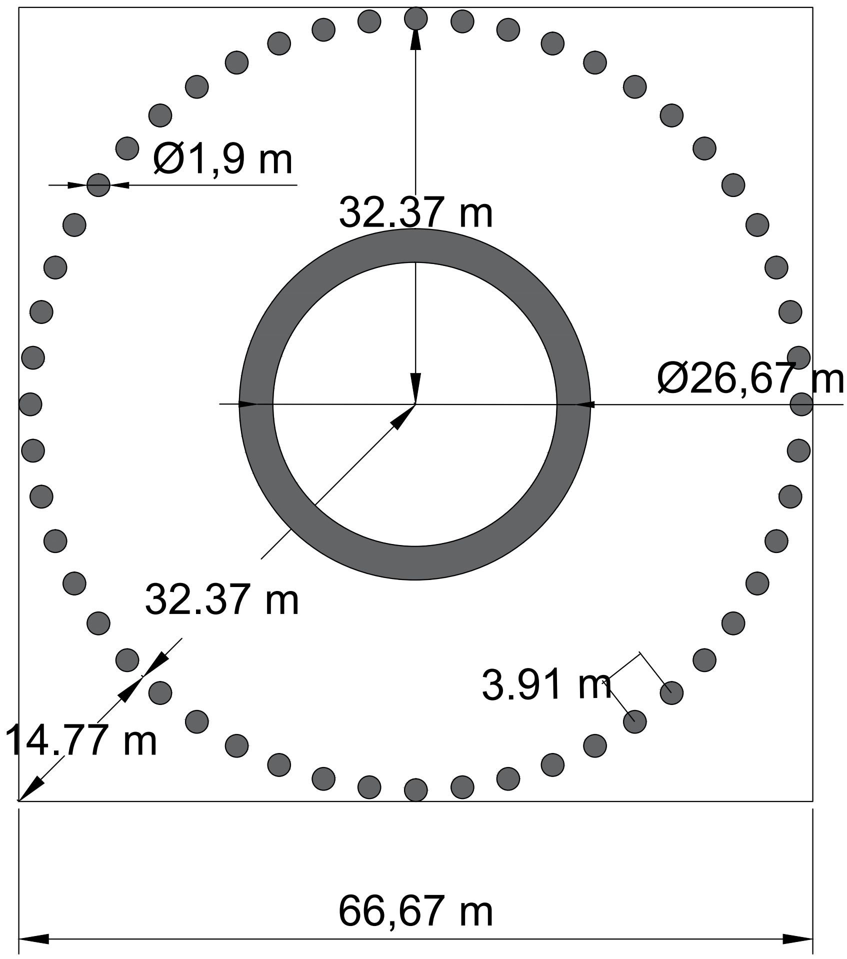


Figure 3.20: Plan drawing of 400 meters non-adaptive FT system model

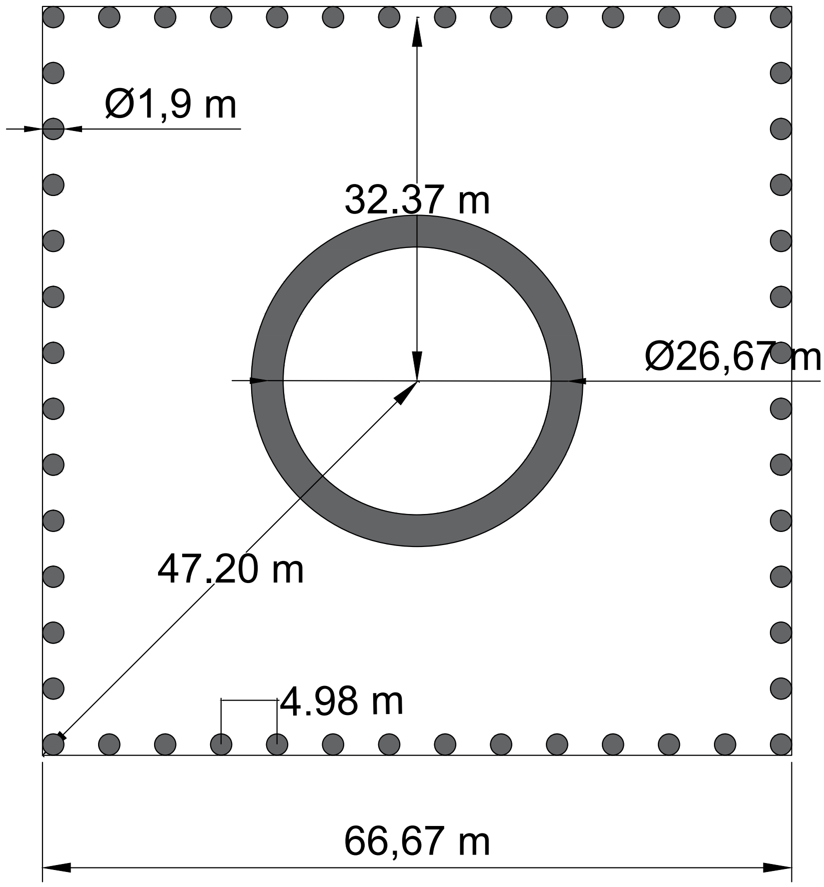
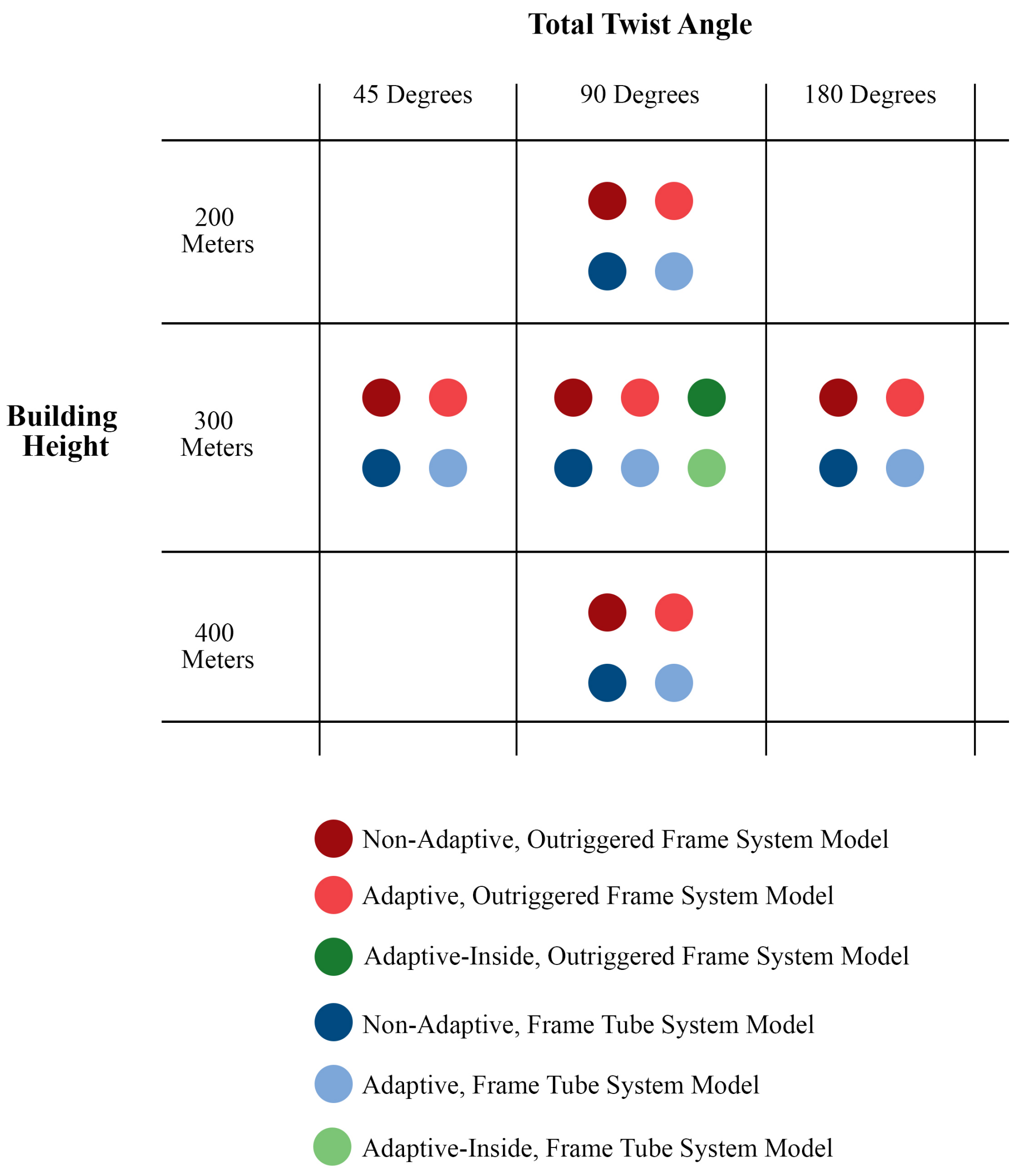


Figure 3.21: Plan drawing of 400 meters adaptive FT system model

At total, there are 22 models that are analyzed in this study. Table 3.3 shows the overall layout of the models.

Table 3.3: Overall layout of the models



3.1.3 Software Preferences

In this study, building models are analyzed by the software ETABS (version 16.2.1). It is a software similar to SAP2000. Their difference is, ETABS has been produced specifically for building type structures. In ETABS, it is possible to create 3D models of buildings, perform structural analysis and obtain results. Several design codes, such as ASCE 7-10 (ASCE, 2013), are embedded in the program. Thus, code-based loads can easily be applied and design checks of frame members can be performed. Although ETABS has its own modelling tools, it is also possible to import CAD or DXF files into ETABS. Adaptive models are created with the help of the software Rhinoceros 5.0. It is a 3D modelling software with various tools. The reason why Rhinoceros is preferred is that it has more sophisticated tools for modelling that expedite the model production process. In adaptive models all of the columns are leaned and their location is changed on each floor. In Rhinoceros, it possible to array objects not only on the xy plane but also on the z axis. After drawing the lines that represent the columns or beams of one floor, they can be copied to the other floors with respect to the twisted form of the building at once easily. For non-adaptive cases, models are created in the ETABS.

3.2 Methodology

22 models, which are described in detail in the material part, are analyzed by ETABS software (version 16.2.1). Modal and linear static analyses of the models have been conducted in this study.

In this part, assigned loads are given and the method to assign wind load is described. Stiffness modifiers of each type of structural member, are given as defined in ASCE 7-10 (ASCE, 2013). Gust factor is explained. Calculation method of gust factor and its effect on the analysis process is described.

3.2.1 Assigned Loads

Gravity loads that are applied on the models are live load, dead load and super dead load. Mass source of the models are defined as the summation of dead load, super dead load and 30 percent of live load.

2 kN/m uniformly distributed live load is applied on the slabs which is similar to the value defined in ASCE 7-10 code for office and residential buildings (ASCE, 2013).

Also 3.5 kN/m super dead load is applied on the slabs.

Code-based wind force is applied. In ETABS, semi-rigid diaphragms are defined to the slabs and "expose wind to the extensions of the diaphragms" option is used in order to apply the wind load. Wind velocity is set as 115 mph (185 km/h). Wind force is applied on only one direction which is parallel to the x since the aim of the study is to make a comparison of different models. As long as the same wind condition is applied, wind on different directions is not necessary.

3.2.2 Stiffness Modifiers

For reinforced concrete structural walls, diaphragms, beams and columns, stiffness modifiers for moment and shear are defined. Modifiers are taken from the code ACI318-14 (ACI, 2015). Table 3.4 shows the modifier values for different members.

Table 3.4: Stiffness modifiers

	Moment	Shear
Structural Walls	0.75 Ig	1 Ag
Diaphragms	0.5 Ig	0.8 Ag
Beam	0.7 Ig	1 Ag
Column	0.9 Ig	1 Ag

Ig: moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement
Ag: gross area of section

3.2.3 Gust Factor

To make analysis for the wind load, it is required to determine the gust factor values of the models. "Gust factor (GF) is defined as the ratio between the peak wind gust of a specific duration to the mean wind speed for a period of time." (Paulsen & Schroeder, 2005)(p.270). According to the ASCE 7-10 (ASCE, 2013), gust factor of the rigid buildings can be taken as 0.85, however; for the flexible buildings gust factor should be calculated according to the section 26.9.5 of ASCE 7-10 code. Slender buildings or the buildings with natural frequencies that are less than 1 Hz are defined as flexible buildings by ASCE 7-10 (ASCE, 2013). In this study, all of the models are in the category of flexible buildings. Therefore, gust factor of each model is calculated for analyses. Gust factor depends on the period and aspect ratio of the building. For gust factor calculation; modal analyses have been performed to have the period values and then, analytical models are analyzed with the correct gust factor values to have structural response.

CHAPTER 4

RESULTS AND DISCUSSION

Results of the conducted analyses are compared and discussed in this chapter. Linear static analyses give the results of base shear values, top displacements and member forces via defined section cuts and groups. Modal analyses give the period values of the models and modal participating mass ratios.

Structural system, twist angle and height are the three parameters that are used in the process of creating study models which are applied twice, once for adaptive case and once for non-adaptive case. To demonstrate the effects of each parameter, the results of alternative models are compared in groups.

First, outriggered frame and framed tube models that have 300 meters height and 90 degrees twisting angle are compared in terms of their modal analysis results, base reactions, top displacement values, and section cut forces.

Then, the angle-of-twist of 300-meter high models has been changed to scrutinize the effect of the twisting angle on structural demand and response parameters.

Finally, to demonstrate the effect of height, 90 degrees twisted models that have different heights are compared in terms of top displacement and modal frequencies.

4.1 Comparison of adaptive, adaptive-inside and non-adaptive cases

Results of six models are compared (non-adaptive, adaptive-inside and adaptive versions of OF and FT systems). All of the 6 models have 300 meters height, 90 degrees total twist angle and 50x50m plan dimensions.

Structural depth is an important factor that affects both the top displacement and leasable span. Left panel of Figure 4.1 shows the structural depth of non-adaptive OF models whereas right panel shows the same information for non-adaptive OF model. Structural depth of OF and FT models are 38m and 47.5m, respectively.

Figure 4.2 shows the structural depth of non-adaptive and adaptive FT models, where it is 48.9 meters for both cases.

Adaptive-inside cases of OF and FT models have always the same structural depth with the corresponding non-adaptive case.

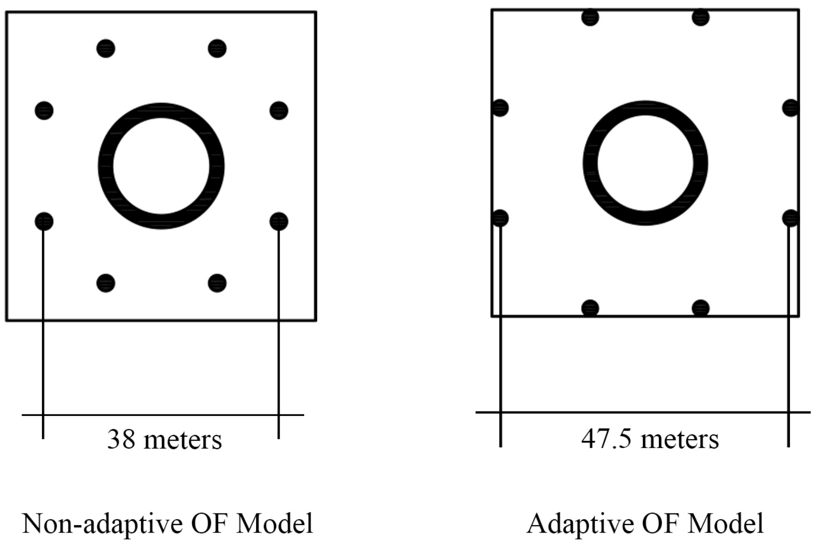


Figure 4.1: Structural depth of non-adaptive and adaptive OF models

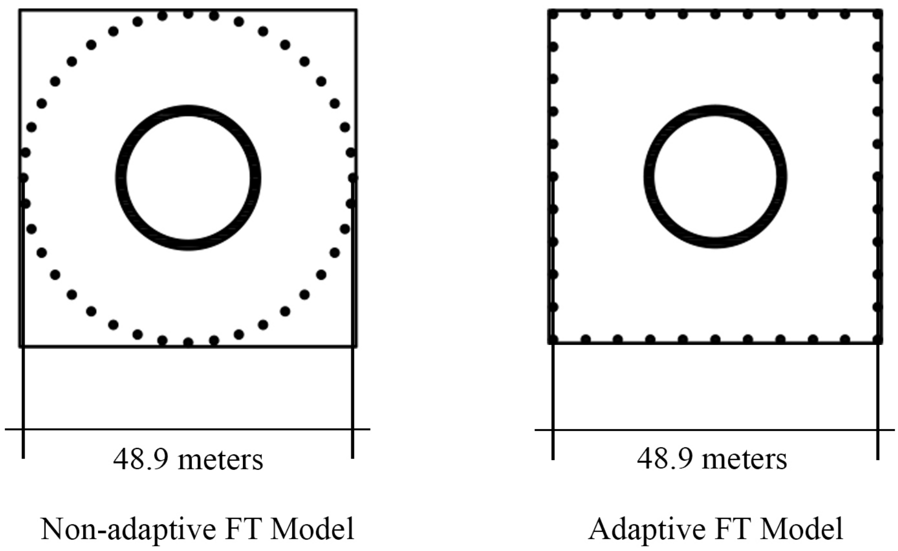


Figure 4.2: Structural depth of non-adaptive and adaptive FT models

Figure 4.3 shows the story displacement values of three OF and three FT models. In OF models, top displacement values are approximately 590 mm for non-adaptive case, 730 mm for adaptive case and 630 mm for adaptive-inside case. In FT models, top deflection values are 393 mm for non-adaptive case, 486 mm for adaptive case and 460 mm for adaptive-inside case.

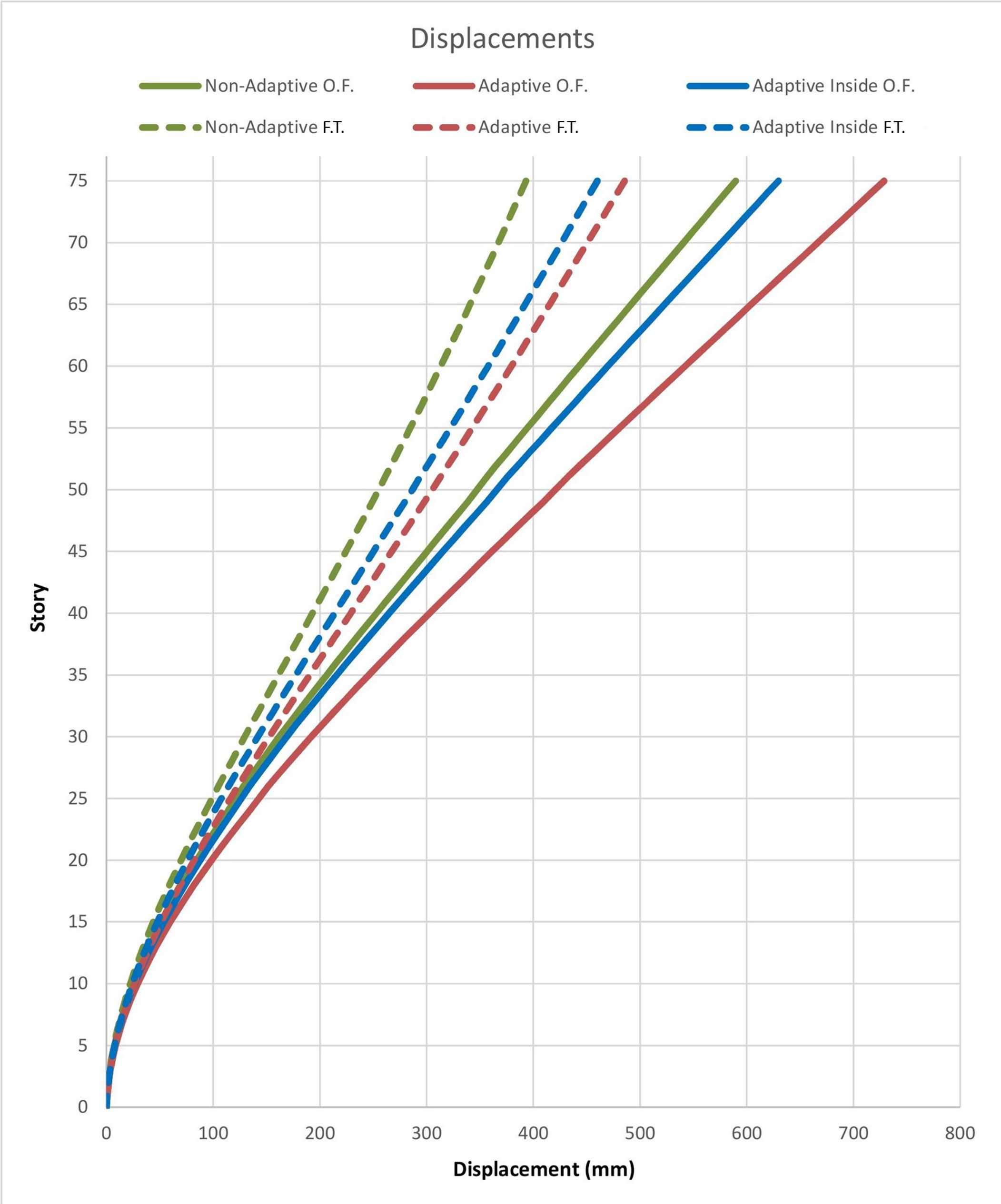


Figure 4.3: Story displacement values of non-adaptive, adaptive-inside and adaptive models for OF and FT systems

For both OF and FT models, the same relation is observed. In terms of top displacement of a given structural system, non-adaptive case has the best performance and adaptive inside case is in between the adaptive and non-adaptive cases.

Comparing the top displacement of adaptive and non-adaptive cases has revealed the fact that overall stiffness of the adaptive case is less than non-adaptive case. In other words, the twisting movement of columns cause a considerable reduction on the lateral stiffness of adaptive structural system. It should be noted that adaptive case has larger structural depth than the non-adaptive case. Nevertheless, non-adaptive case has smaller top deflection which means that the reduction on the lateral stiffness created by the twisting movement is more critical than the effect of larger structural depth.

To remove the effect of structural depth from the results and scrutinize the influence of twisting movement in an unbiased way, adaptive inside case models which have the same structural depth with non-adaptive case have been used. Compared to non-adaptive case results, larger top deflection of adaptive inside model has revealed the negative effect of leaned geometry on columns on the lateral stiffness of the structural system.

When adaptive and adaptive-inside cases are compared, it is seen that adaptive case has larger top deflection. In adaptive case, as the structural depth increases, the inclination angle of columns becomes larger. Thus, comparisons between adaptive and adaptive-inside cases further reinforce the fact that, the twisting movement of the columns is the major factor affecting the lateral drift resistance of the structural system.

According to the presented results, non-adaptive case is better than adaptive case in terms of lateral stiffness. However, for some other aspects, adaptive case is better than non-adaptive case. In adaptive case, columns do not interrupt the space. It is especially critical for FT models. Non-adaptive FT model has the highest lateral stiffness but this layout generates the most challenging plan area among other options. In non-adaptive OF model, arranging the plan layout in harmony with the columns may be easier than FT model, but in this case plan scheme is different on every level. This forces the designer to create unique plan solution for each floor where there may be 100 floors. Consequently, when the structural performance of the twisting tall building is of primary concern, non-adaptive case is better whereas this layout can bring significant difficulties to the architectural design phase of the design process.

4.2 Results of 300 Meters Models

For two different structural systems, three different twisting angles (45, 90 and 180 degrees) and two options which are adaptive and non-adaptive cases, there are 12 models that have 300 meters height. Modal analysis results, base shear forces, lateral displacements and section cut forces of these 12 models are compared and discussed in this section.

4.2.1 Modal Analysis Results

By modal analyses, free-vibration periods and modal participating mass ratios are found. Modal participating mass ratios give the percentages of the mass that contributes translational or rotational movements on the x y or z directions.

Table 4.1 shows periods and modal participating mass ratios for 300-meter high and 90 degrees twisted non-adaptive and adaptive OF models whereas Table 4.2 presents the same information FT models. Modal analysis results of 45 degrees and 180 degrees twisted models are given in the Appendix B.

Table 4.3 summarizes period values in second for 45 degrees twisted models and indicates translational and rotational modes whereas Table 4.4 and 4.5 reveal the same information for 90 degrees twisted models and 180 degrees twisted models, respectively.

Table 4.4 shows that, in the 90 degrees twisted adaptive and non-adaptive OF models, first four modes are translational and the fifth mode is rotational. Similar results are also observed in the 45 degrees and 180 degrees twisted OF models (Table 4.3 and 4.5, respectively). On the other hand, in the 90 degrees twisted adaptive and non-adaptive FT models, first two modes are translational and the third mode is rotational as given in Table 4.4. The same results are observed in Table 4.3 for 45 degrees twisted FT models. However, in 180 degrees twisted FT models first four modes are translational and the fifth mode is rotational like OF models (Table 4.5).

Table 4.1: Periods and model participating mass ratio values for 90 degrees twisted non-adaptive and adaptive OF system models

Modal Participating Mass Ratios - Non-Adaptive Case

Case	Mode	Period sec	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
Modal	1	9.04	0.03	0.60	0	0.03	0.60	0	0.35	0.02	0	0.35	0.02	0
Modal	2	9.04	0.60	0.03	0	0.63	0.63	0	0.02	0.35	0	0.37	0.37	0
Modal	3	1.89	0	0.18	0	0.63	0.81	0	0.21	0	0	0.58	0.37	0
Modal	4	1.89	0.18	0	0	0.81	0.81	0	0	0.21	0	0.58	0.58	0
Modal	5	1.58	0	0	0	0.81	0.81	0	0	0	0.80	0.58	0.58	0.80
Modal	6	0.74	0	0.06	0	0.81	0.87	0	0.11	0	0	0.69	0.58	0.80
Modal	7	0.74	0.06	0	0	0.87	0.87	0	0	0.11	0	0.69	0.69	0.80
Modal	8	0.54	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.89
Modal	9	0.40	0.03	0.01	0	0.90	0.88	0	0.01	0.06	0	0.70	0.75	0.89
Modal	10	0.40	0.01	0.03	0	0.91	0.91	0	0.06	0.01	0	0.76	0.76	0.89
Modal	11	0.34	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.26	0.01	0.01	0	0.91	0.92	0	0.03	0.02	0	0.80	0.78	0.93

Modal Participating Mass Ratios - Adaptive Case

Case	Mode	Period sec	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
Modal	1	9.72	0.62	0	0	0.62	0	0	0	0.37	0	0	0.37	0
Modal	2	9.71	0	0.62	0	0.62	0.62	0	0.37	0	0	0.37	0.37	0
Modal	3	1.86	0.10	0.09	0	0.72	0.71	0	0.08	0.12	0	0.45	0.49	0
Modal	4	1.86	0.09	0.10	0	0.81	0.81	0	0.12	0.08	0	0.57	0.57	0
Modal	5	1.56	0	0	0	0.81	0.81	0	0	0	0.80	0.57	0.57	0.80
Modal	6	0.72	0.07	0	0	0.87	0.81	0	0	0.12	0	0.57	0.69	0.80
Modal	7	0.72	0	0.07	0	0.87	0.87	0	0.12	0	0	0.69	0.69	0.80
Modal	8	0.53	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.89
Modal	9	0.39	0.02	0.01	0	0.90	0.88	0	0.02	0.05	0	0.71	0.74	0.89
Modal	10	0.39	0.01	0.02	0	0.91	0.91	0	0.05	0.02	0	0.76	0.76	0.89
Modal	11	0.33	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.26	0.01	0.01	0	0.92	0.91	0	0.02	0.03	0	0.78	0.79	0.93

Table 4.2: Periods and model participating mass ratio values for 90 degrees twisted non-adaptive and adaptive tube system models

Modal Participating Mass Ratios - Non-Adaptive Case

Case	Mode	Period sec	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
Modal	1	7.65	0.33	0.34	0	0.33	0.34	0	0.17	0.16	0	0.17	0.16	0
Modal	2	7.65	0.34	0.33	0	0.66	0.66	0	0.16	0.17	0	0.34	0.34	0
Modal	3	1.95	0	0.00	0	0.66	0.66	0	0	0	0.81	0.34	0.34	0.81
Modal	4	1.84	0	0.16	0	0.67	0.83	0	0.27	0	0	0.60	0.34	0.81
Modal	5	1.84	0.16	0	0	0.83	0.83	0	0	0.27	0	0.61	0.61	0.81
Modal	6	0.79	0.01	0.04	0	0.84	0.87	0	0.08	0.03	0	0.68	0.63	0.81
Modal	7	0.79	0.04	0.01	0	0.89	0.89	0	0.03	0.08	0	0.71	0.71	0.81
Modal	8	0.66	0	0	0	0.89	0.89	0	0	0	0.09	0.71	0.71	0.90
Modal	9	0.46	0	0.03	0	0.89	0.92	0	0.07	0.01	0	0.78	0.72	0.90
Modal	10	0.46	0.03	0	0	0.92	0.92	0	0.01	0.07	0	0.79	0.79	0.90
Modal	11	0.40	0	0	0	0.92	0.92	0	0	0	0.03	0.79	0.79	0.94
Modal	12	0.30	0	0.02	0	0.92	0.94	0	0.05	0	0	0.83	0.79	0.94

Modal Participating Mass Ratios - Adaptive Case

Case	Mode	Period sec	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
Modal	1	8.51	0	0.65	0	0	0.65	0	0.34	0.01	0	0.34	0.01	0
Modal	2	8.51	0.65	0	0	0.65	0.65	0	0.01	0.34	0	0.34	0.34	0
Modal	3	2.18	0	0	0	0.65	0.65	0	0	0	0.81	0.34	0.34	0.81
Modal	4	1.88	0.07	0.10	0	0.72	0.76	0	0.21	0.05	0	0.55	0.39	0.81
Modal	5	1.88	0.10	0.07	0	0.83	0.83	0	0.05	0.21	0	0.60	0.60	0.81
Modal	6	0.84	0.03	0.02	0	0.86	0.85	0	0.04	0.07	0	0.64	0.67	0.81
Modal	7	0.84	0.02	0.03	0	0.89	0.89	0	0.07	0.04	0	0.71	0.71	0.81
Modal	8	0.74	0	0	0	0.89	0.89	0	0	0	0.09	0.71	0.71	0.90
Modal	9	0.48	0.03	0	0	0.92	0.89	0	0	0.07	0	0.71	0.78	0.90
Modal	10	0.48	0	0.03	0	0.92	0.92	0	0.07	0	0	0.78	0.78	0.90
Modal	11	0.45	0	0	0	0.92	0.92	0	0	0	0.03	0.78	0.78	0.94
Modal	12	0.33	0	0	0	0.92	0.92	0	0	0	0.02	0.78	0.78	0.95

Table 4.3: Period values for 45 degrees twisted models and indication of translational and rotational modes

	45 Degree Twist					
	Outriggered Frame			Tube		
Modes	Adaptive	Non-Adaptive		Adaptive	Non-Adaptive	
1	9.773	9.035	Translational	8.108	7.655	Translational
2	9.773	9.035	Translational	8.108	7.654	Translational
3	1.926	1.887	Translational	2.194	1.946	Rotational
4	1.926	1.887	Translational	1.932	1.836	Translational
5	1.655	1.584	Rotational	1.932	1.836	Translational

Table 4.4: Period values for 90 degrees twisted models and indication of translational and rotational modes

	90 Degree Twist					
	Outriggered Frame			Tube		
Modes	Adaptive	Non-Adaptive		Adaptive	Non-Adaptive	
1	9.899	9.035	Translational	8.505	7.654	Translational
2	9.896	9.035	Translational	8.505	7.654	Translational
3	1.908	1.887	Translational	2.176	1.946	Rotational
4	1.908	1.887	Translational	1.878	1.836	Translational
5	1.645	1.584	Rotational	1.878	1.836	Translational

Table 4.5: Period values for 180 degrees twisted models and indication of translational and rotational modes

	180 Degree Twist					
	Outriggered Frame			Tube		
Modes	Adaptive	Non-Adaptive		Adaptive	Non-Adaptive	
1	10.091	9.035	Translational	9.495	7.654	Translational
2	10.091	9.035	Translational	9.494	7.654	Translational
3	1.805	1.849	Translational	1.705	1.744	Translational
4	1.805	1.849	Translational	1.705	1.744	Translational
5	1.518	1.533	Rotational	1.694	1.589	Rotation

Modal analysis results of 300-meter high (75 story) models have shown that first-mode period of FT system models are smaller than corresponding OF system models.

Besides, period values of adaptive cases are always larger than non-adaptive cases. The comparisons among different angle of twist values have showed that this property affects the dynamic vibration characteristics of both adaptive and non-adaptive OF and FT models.

For both OF and FT models, in different twist angles, the first mode vibration periods are different in the adaptive cases but they are the same for non-adaptive cases because in non-adaptive case, structural system is not affected by the twist angle. However, in the adaptive cases, as the twist angle increases, lateral stiffness of the system decreases and the period of the model increases.

4.2.2 Wind loads and Corresponding Base Shear Forces

All of the models are exposed to 115 mph (185 km/h) wind velocity. However, the wind load is different in each model because of changing gust factors and the cross section area of the building. For the latter, when the twist angle changes, the cross-section area of the building that is exposed to the wind changes too. Figure 4.4 shows the façade area of the models for 45, 90 and 180 degree twists.

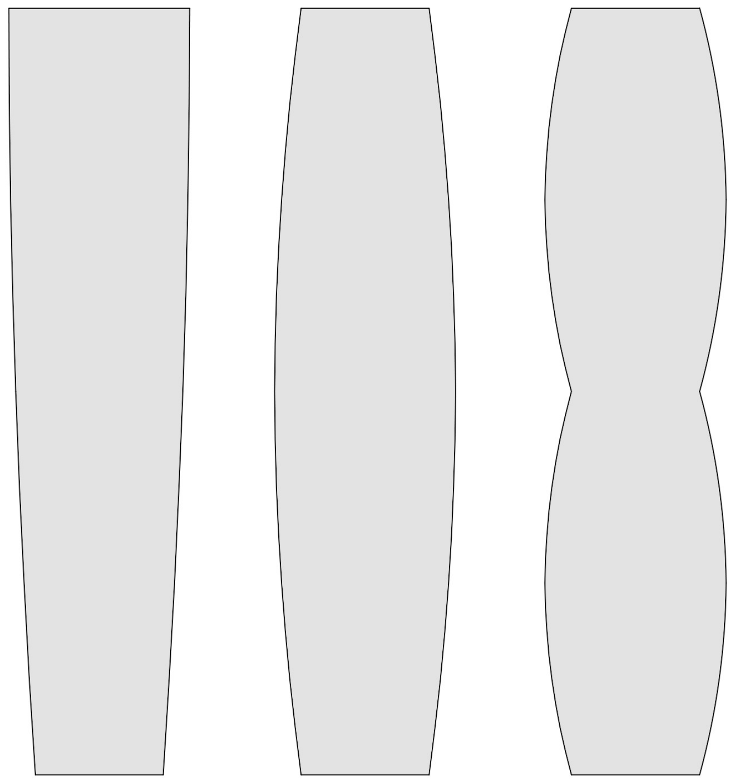


Figure 4.4: Façade area of the models for 45, 90 and 180 degree twist

Table 4.6 shows base shear forces (BS), gust factors (GF) and ratio of them for twelve 300 meters models. Results show that, under the same wind flow the base shear value of the building changes depend on the total twist angle, structural system selection and having an adaptive or non-adaptive structure. Gust factor values are always smaller in the non-adaptive versions of the models when they are compared with the adaptive ones. Similarly, due to their relative lateral rigidity, FT system models have smaller gust factors in comparison with the OF system models.

Table 4.6: Base shear forces (BS), gust factors (GF) and ratio of them for twelve 300 meters high models

		Outrigged Frame		Tube	
		Adaptive	Non-Adaptive	Adaptive	Non-Adaptive
45 Degrees	BS	-66609.512	-64957.7226	-62205.411	-61104.3894
	GF	1.21	1.18	1.13	1.11
	BS/GF	-55049.18347	-55048.91746	-55049.03628	-55048.99946
90 Degrees	BS	-65907.4343	-64273.4645	-62639.3448	-60460.4471
	GF	1.21	1.18	1.15	1.11
	BS/GF	-54468.95397	-54469.03771	-54468.99548	-54468.87126
180 Degrees	BS	-66871.2538	-64153.1999	-63609.5065	-60347.2783
	GF	1.23	1.18	1.17	1.11
	BS/GF	-54366.87301	-54367.11856	-54367.09957	-54366.91739

4.2.3 Top Deflections

Figure 4.3 illustrates that non-adaptive cases have less top displacement than the adaptive cases, both for OF system models and FT system models. Also FT system models have less top displacement than OF system models. The same relation is observed for 45 degrees and 180 degrees twisted models as well. However, the relative difference between adaptive and non-adaptive cases alters depending on the twist angle. Figure 4.5 compares the top displacements of 45, 90 and 180 degrees twisted models.

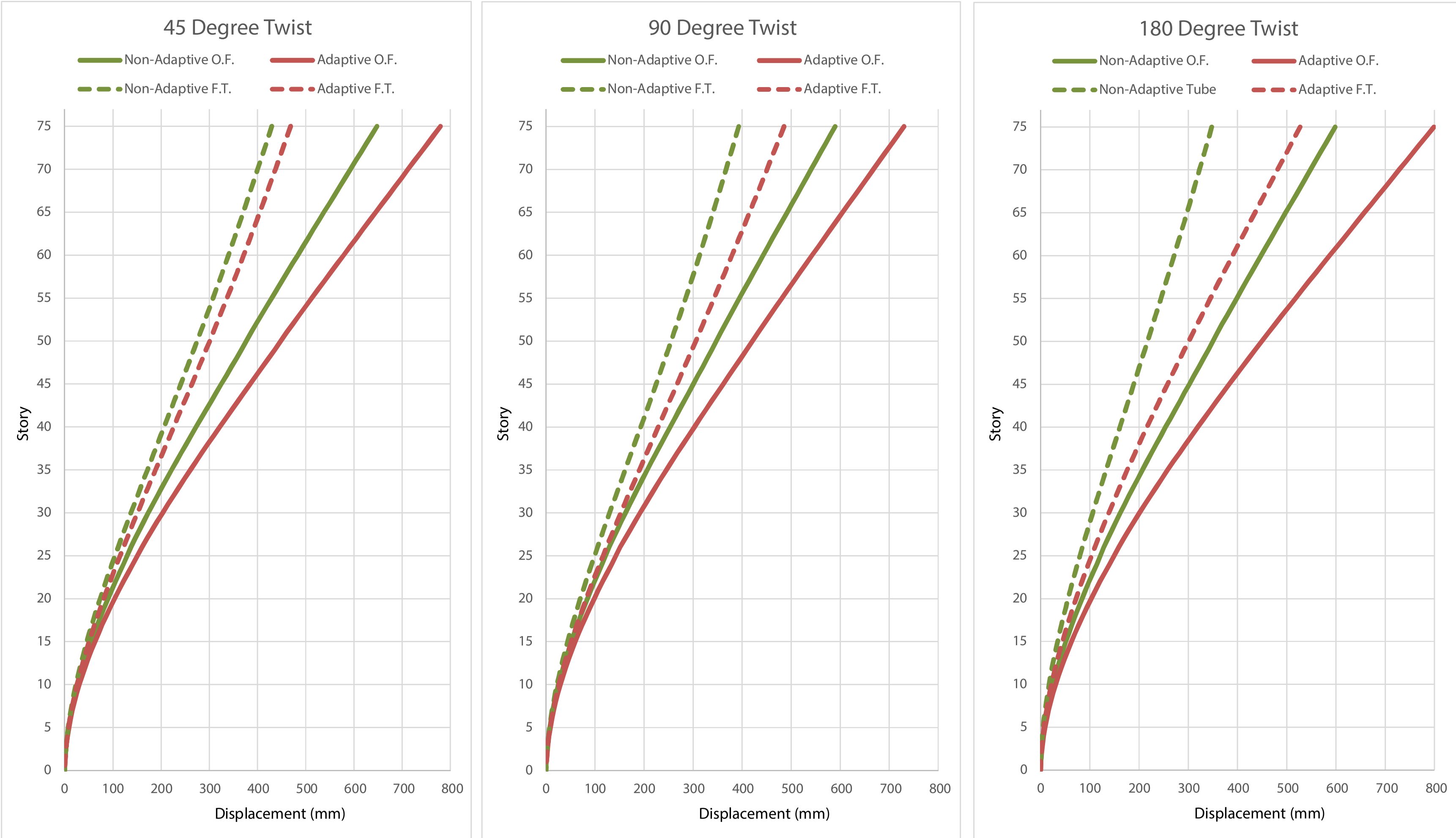


Figure 4.5: Top deflections of 45, 90 and 180 degrees twisted models

Figure 4.5 illustrates that the differences between top displacements of adaptive non-adaptive cases increase as the twist angle increases. Table 4.7 lists top deflection values for adaptive and non-adaptive cases and their differences. The difference between two values are given as the percentage of the adaptive value.

Table 4.7: Top deflection values for adaptive and non-adaptive cases and their differences in terms of percentage of the adaptive value

Structural System	Twist Angle	Adaptive	Non-Adaptive	Δ
Outriggered Frame	45	779.46	647.70	16.90%
	90	728.80	589.73	19.08%
	180	798.99	598.23	25.13%
Tube	45	468.67	429.55	8.35%
	90	485.51	393.14	19.02%
	180	527.16	347.68	34.05%

As the angle increases, top displacement difference between the adaptive and non-adaptive cases increases in both OF and FT systems. In other words, as the twist angle increases, it becomes a critical concern to decide whether the design should be adaptive or non-adaptive. However, preferring adaptive or non-adaptive cases is not only affects structural performance, but also shapes the architectural design process.

4.2.4 Section Cut Results

Section cut forces acting on the core and columns have been obtained for six degree of freedoms. Since the wind is applied on only x direction, moment around y axis is critical. In addition, torsion due to gravity loads is also important for comparisons.

The results show the moment demands and torsion that depend on the structural system (OF or FT), the adaptive and non-adaptive cases and the angle of twist (45, 90 and 180 degrees).

Although the applied wind velocity is the same on all of the models, for different twist angles base reactions are different because of the façade area, as discussed earlier. For this reason, results of the models with the same twist angle are given together.

Figure 4.6 shows the moment forces on the core for 45 degrees twisted models, figure 4.7 shows the moment forces on the core for 90 degrees twisted models and figure 4.8 shows the moment forces on the core for 180 degrees twisted models. Shear force graphs of the same models are given in the appendix C.

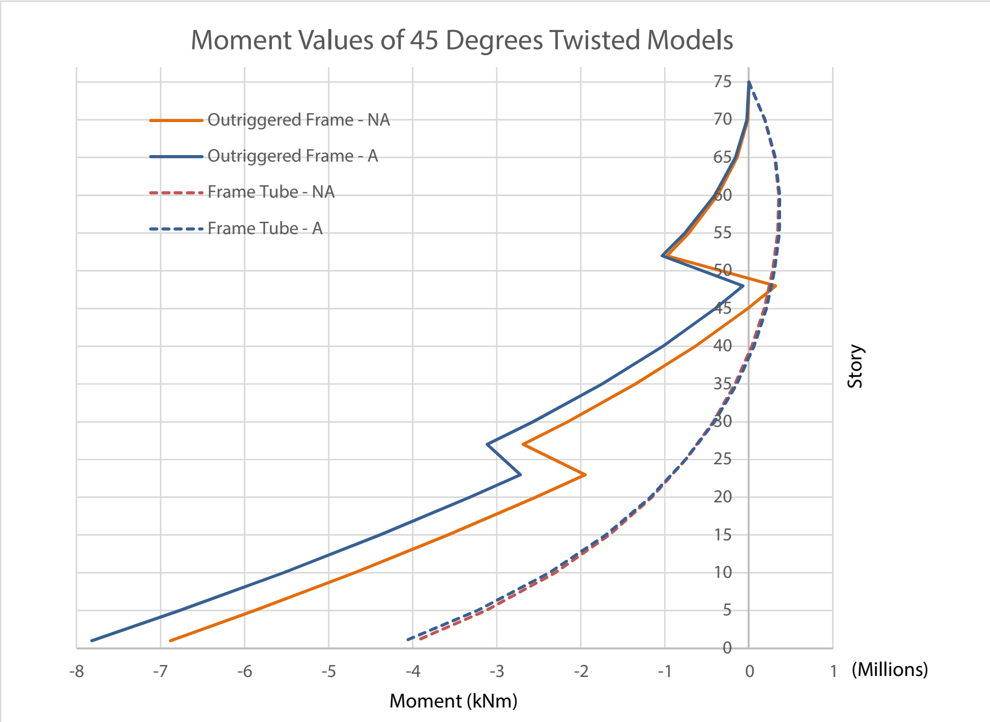


Figure 4.6: Moment values of 45 degrees twisted models

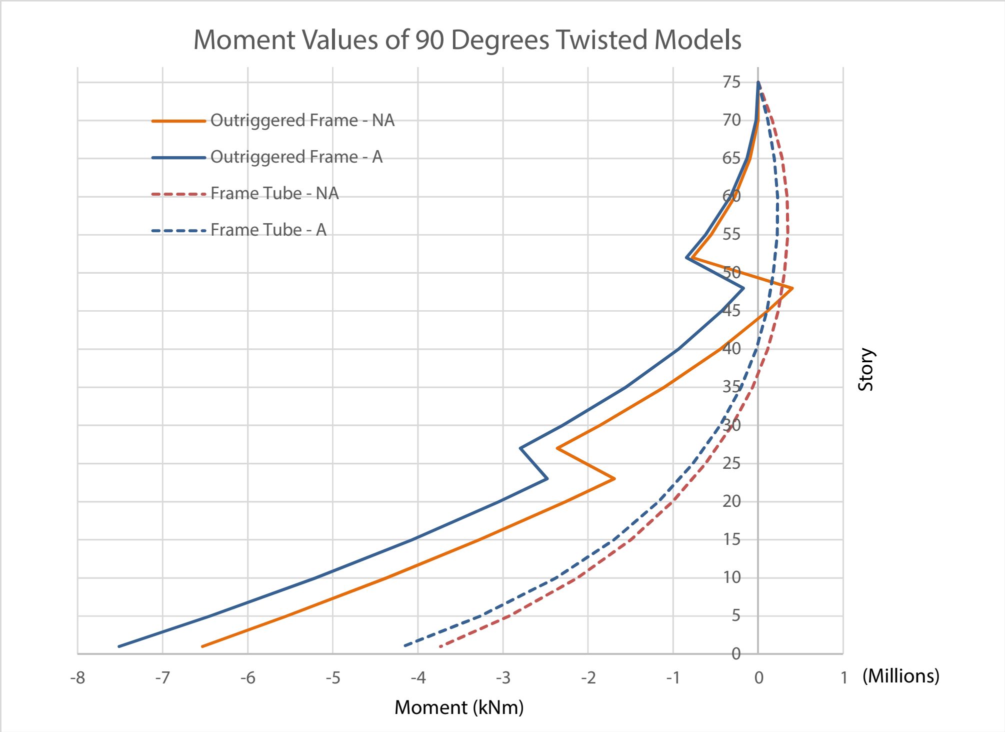


Figure 4.7: Moment values of 90 degrees twisted models

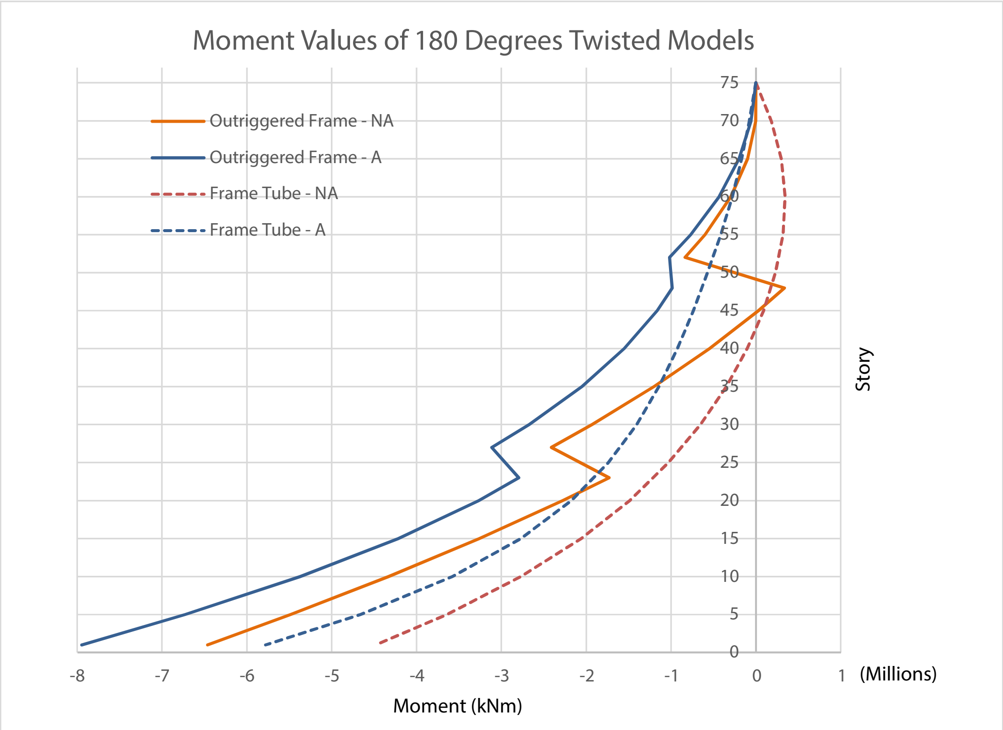


Figure 4.8: Moment values of 180 degrees twisted models

Results show that, in OF adaptive models the core encounters larger moment forces than the core of non-adaptive models. The difference changes with respect to the angle of twist as well. As the angle increases, differences between adaptive and non-adaptive cases increase.

To illustrate the performance of columns in different models, the percentages of the total moments that are carried by the core elements and columns are shown in the table 4.8.

Table 4.8: Percentages of the total moments that are carried by the core elements and columns for 12 models

			Total Moment kNm	% of Core Moment	% of Column Moment
Outriggered Frame System	45 Degree Twist	Adaptive	-10770180	72.59%	27.41%
		Non-adaptive	-10519411	65.42%	34.58%
	90 Degree Twist	Adaptive	-10085683	74.48%	25.52%
		Non-adaptive	-9852883	66.29%	33.71%
	180 Degree Twist	Adaptive	-10272217	77.36%	22.64%
		Non-adaptive	-9794999	65.99%	34.01%
Frame Tube System	45 Degree Twist	Adaptive	-10236556	39.91%	60.09%
		Non-adaptive	-10239275	38.63%	61.37%
	90 Degree Twist	Adaptive	-9438696	44.23%	55.77%
		Non-adaptive	-9423961	39.61%	60.39%
	180 Degree Twist	Adaptive	-9719537	59.46%	40.54%
		Non-adaptive	-9420637	47.58%	52.42%

Because of their leaned geometry, columns in adaptive cases create torsion on the structural system which results from building's own weight. Thus, the torsion on the core under the dead loads is also compared. Figure 4.9 shows torsion on the core of OF system models and Figure 4.10 displays torsion on the core of FT models.

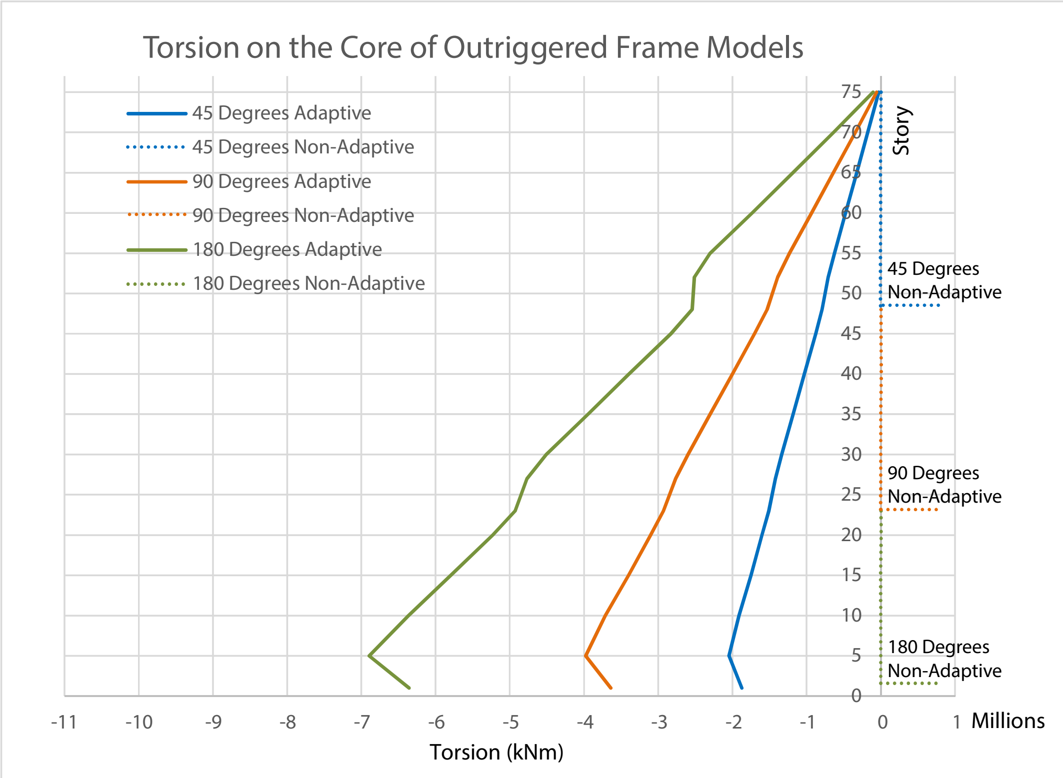


Figure 4.9: Torsion on the core members for outriggered frame system models

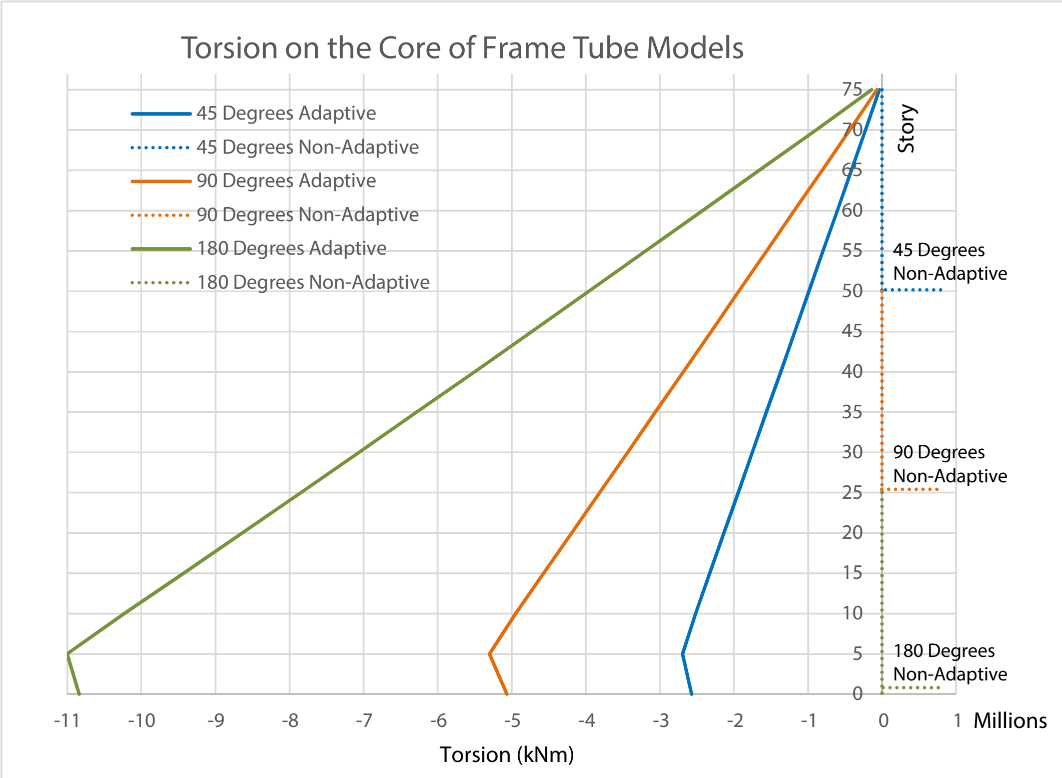


Figure 4.10: Torsion on the core members for tube system models

In adaptive cases, as the twist angle increases torsion under dead load increases where in the non-adaptive cases there is almost no torsion on the core. Wind load also creates torsion effect on the structural system. The results show that, in comparison to the torsional demands originated from dead loads, torsional demands that are originated from wind loads have been found quite small and neglected.

4.3 Result of Models with Different Heights

In addition to four 300 meters 90 degrees twisted models, eight 90 degrees twisted models are created with different heights. Four of them are 200 meters tall and the other four models are 400 meters tall.

4.3.1 Modal analyses results

Modal analyses of these 12 models are carried out for 12 modes and frequencies and modal participating mass ratios are calculated for each model. Detailed results for 300 meters models are already given. Results of the other heights are given in the appendix D. Frequency values of first 5 modes are given in the following tables.

Table 4.9 shows frequency values in second for 200 meters models and indicates translational and rotational modes. Table 4.10 shows the same results for 300 meters models and table 4.11 shows the same results for 400 meters models.

Table 4.9: Frequency values in second for 200 meters models and indication of translational and rotational modes

		200 Meters							
		Outriggered Frame				Frame Tube			
		Adaptive		Non-Adaptive		Adaptive		Non-Adaptive	
		Period (sec)		Period (sec)		Period (sec)		Period (sec)	
Modes	1	6.127	T	5.987	T	6.129	T	5.77	T
	2	6.127	T	5.987	T	6.127	T	5.77	T
	3	1.321	T	1.337	T	1.325	R	1.274	T
	4	1.321	T	1.337	T	1.278	T	1.274	T
	5	1.105	R	1.105	R	1.278	T	1.233	R

T: Translational, R:Rotational

Table 4.10: Frequency values in second for 300 meters models and indication of translational and rotational modes

		300 Meters							
		Outriggered Frame				Frame Tube			
		Adaptive		Non-Adaptive		Adaptive		Non-Adaptive	
		Period (sec)		Period (sec)		Period (sec)		Period (sec)	
Modes	1	9.718	T	9.035	T	8.505	T	7.654	T
	2	9.706	T	9.035	T	8.505	T	7.654	T
	3	1.862	T	1.887	T	2.176	R	1.946	R
	4	1.861	T	1.887	T	1.878	T	1.836	T
	5	1.559	R	1.584	R	1.878	T	1.836	T

T: Translational, R:Rotational

Table 4.11: Frequency values in second for 400 meters models and indication of translational and rotational modes

		400 Meters							
		Outriggered Frame				Frame Tube			
		Adaptive		Non-Adaptive		Adaptive		Non-Adaptive	
		Period (sec)		Period (sec)		Period (sec)		Period (sec)	
Modes	1	12.956	T	12.3	T	10.416	T	9.485	T
	2	12.953	T	12.297	T	10.416	T	9.475	T
	3	2.309	T	2.301	T	2.349	R	2.185	T
	4	2.308	T	2.3	T	2.224	T	2.181	T
	5	1.838	R	1.768	R	2.224	T	2.123	R

T: Translational, R:Rotational

Periods of the models increase as the height increases, as expected. For all different heights, periods of OF system model are higher than FT system models and period of adaptive cases are higher than period of non-adaptive cases.

4.3.2 Top Displacement

Top displacement values of 12 models are compared to scrutinize the effect of building height on adaptive and non-adaptive OF and FT models. Results show that, in terms of top displacement, performance of the FT models is better than the performance of the OF models and the non-adaptive cases perform better than the adaptive cases, for all heights. However, the results revealed the fact that the relative difference on their lateral stiffness changes with height. Figure 4.11 compares top displacement values of 200 meters, 300 meters and 400 meters high models. Table 4.12 lists top displacement values of 12 models as well as the difference between OF and FT top displacement values as the percentage of the OF top displacement value.

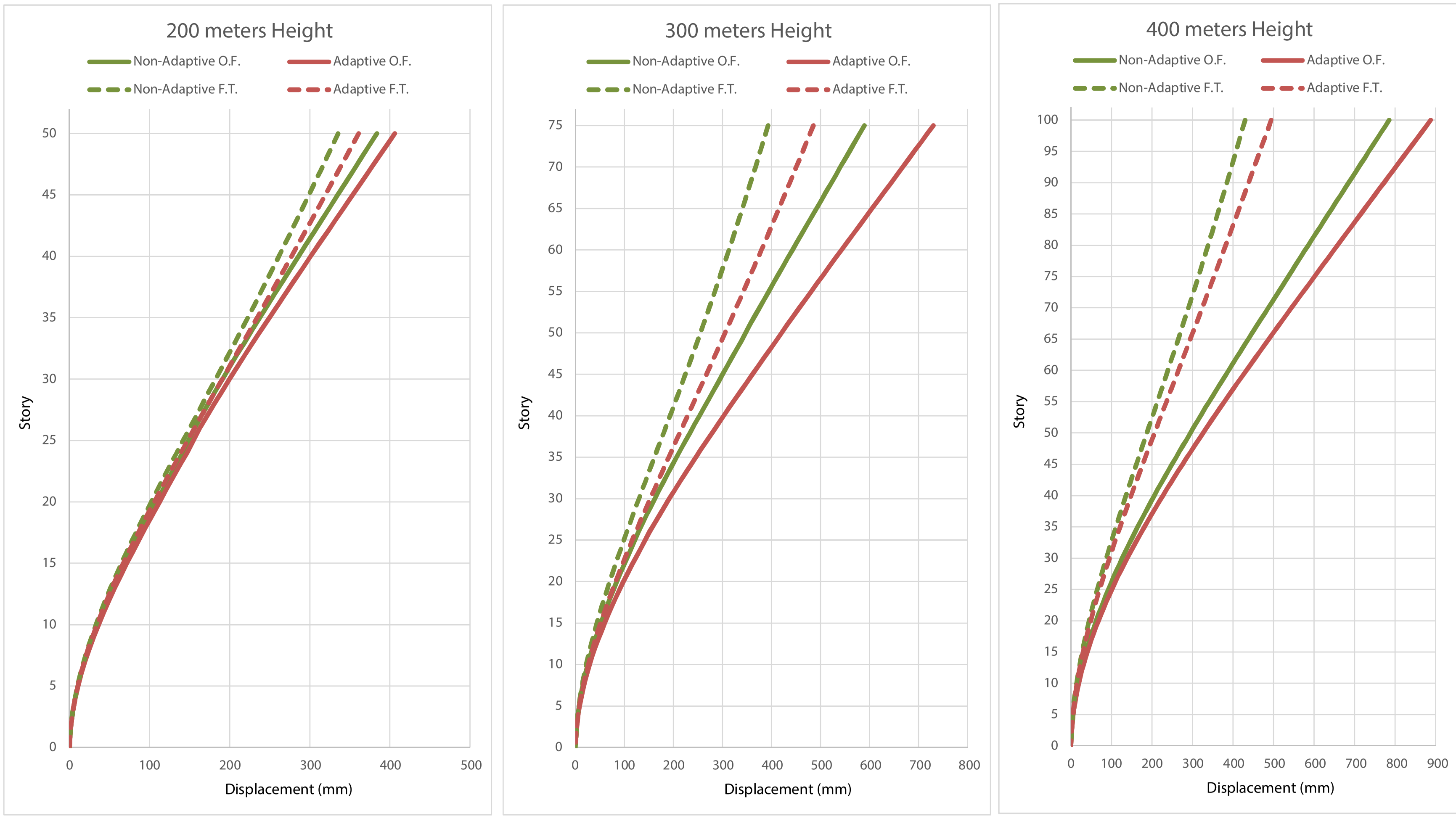


Figure 4.11: Top displacement of 200, 300 and 400 meters models

Table 4.12: Top displacement values of 12 models and the differences between OF and FT models in terms of percentage of the OF model

Height	Case	Outriggered Frame Displacement (mm)	Frame Tube Displacement (mm)	Δ
200	Non-Adaptive	384	335	12.62%
	Adaptive	406	361	11.09%
300	Non-Adaptive	590	393	33.34%
	Adaptive	730	486	33.51%
400	Non-Adaptive	786	430	45.28%
	Adaptive	888	494	44.35%

In the 200 meters high models, the difference between OF and FT systems are 12.62% and 11.09% for non-adaptive and adaptive cases, respectively. The results showed that this difference increases up to 45% for 400 meters high models. In other words, as the height increases, performance difference between OF system and FT system increases.

CHAPTER 5

CONCLUSION

In this chapter, the study is summarized and main outcomes of the research are listed. Limitations of the study are described and recommendation for future studies are stated.

5.1 Summary of the Research

The use of twisted forms introduces challenges to the architectural and structural design of tall buildings.

This study investigates structural system layout of twisted tall buildings. Examining the existing twisted tall buildings reveals the fact that, there are two different ways of designing the structure of a twisted tall building. In this study, these alternative systems are named as “adaptive” in which structural system twists with floor slabs and “non-adaptive” in which structural system is composed of orthogonal members as in the case of conventional structures. Assuming that these two alternative design approaches affect the structural system performance of a twisted tall building differently, this study aims to scrutinize this effect with respect to various building heights, total twist angles and structural systems.

22 hypothetical buildings are defined by using two different design approaches (adaptive and non-adaptive cases), three different angles (45, 90 and 180 degrees), three different heights (200, 300 and 400 meters) and two different structural systems (OF and FT). Computer models of these 22 buildings are created in ETABS and Rhinoceros.

To demonstrate the relative structural performance of the models, linear static and modal analyses are performed by the ETABS software. Results include base reactions, top displacements, modal properties, moments and torsional forces.

Results of 22 models are compared in groups to show the effect of design approach, height, twist angle and structural system separately.

Firstly, adaptive and non-adaptive layouts are compared for a given model with 300 meter height and 90 degrees angle of twist. A special case, adaptive inside is introduced to eliminate the bias resulting from different structural depths of adaptive and non-adaptive cases. The structural performance of these design approaches are compared and in this way, the potentials and problems of twisted tall building design are discussed.

Secondly, the effect of different twist angles on structural performance of 300 meter adaptive and non-adaptive models are evaluated.

Finally, the influence of building height is demonstrated in terms of 90 degrees twisting adaptive and non-adaptive models.

All of the comparisons and evaluations given above are made for outriggered frame and framed tube structures as these are the most common structural systems of tall buildings, particularly supertall buildings.

5.2 Main Outcomes

Main outcomes of the study can be listed as follows;

- Despite its short structural depth compared to adaptive case, non-adaptive case has less top displacement. The comparison of adaptive, adaptive-inside and non-adaptive cases shows that effect of twisted movement is more critical than effect of the structural depth of the system. This is valid for all models with different structural systems, building heights, and twisting angles investigated in this study.
- Non-adaptive case creates difficulties in the architectural design process. Selecting the non-adaptive case means having a more challenging architectural

design process whereas adaptive case creates opportunities in the architectural design by sacrificing from the structural system performance.

- In the scope of this study, it is seen that FT system performs better than OF system in term of top displacement. It is valid for all heights and twist angles that are taken into consideration in this study.
- As the total twist angle increases, the top displacement and demands on members of the twisted tall buildings are affected in a negative way. In FT models, increasing the total twist angle creates a more dramatic performance reduction than the reduction that occurs in the OF models.
- Period values of OF models are higher than period values of FT models. Since the mass of OF and FT models are same, the reason of larger periods is relatively less lateral stiffness of OF models.
- In adaptive models where the columns are leaned, self-weight of the building creates extra torsional forces. This is not observed in the non-adaptive cases because of the conventional positioning of the columns. Torsional demand occurred in adaptive models is a drawback in terms of structural performance.
- As the height of the models increases, the difference in top displacement of adaptive and non-adaptive cases increases.

5.3 Limitations of the Study

Limitation of the study is shaped by the definition of the selected cases, software preferences and methodology of analysis.

In this study, initial models have 300 meters height and 90 degrees total twist. To see the effect of total twist angle on the results, different versions of initial models that have 45 degrees and 180 degrees total twist angle are created. To examine the effect of the building height, 200 meters and 400 meters tall models are used. By comparing the results, it is possible to make predictions about the trends. As the angle or height increases or decreases, results change accordingly. However, all the findings and observations given in this study are limited with the studied cases.

There are several structural systems for tall or super tall building as explained in the literature review. In this study, two of them, outriggered frame system and framed tube system, are selected and studied. Other structural systems are not covered.

To be able to make comparisons between adaptive and non-adaptive or outriggered frame and tube systems, modelling process is conducted with a methodology. Results of this study depends on the decisions of this methodology. Especially deciding to keep the concrete volume same for outriggered and tube models, shapes the relation of these two structural systems. With a different design approach, result may change.

All of the analyses are done with the ETABS software. The analytical results strictly rely on the embedded assumptions and approximations of the ETABS software.

All of the results have been obtained by linear static analyses. Non-linear behavior of the materials or dynamic loading effects are not taken into consideration.

Top displacement and moment results are calculated for wind load whereas torsion force results are obtained for gravity load. Other loads such as earthquake are not taken into consideration which may yield further conclusions on relative performance of adaptive and non-adaptive cases.

5.4 Recommendations for Future Studies

In this study, the comparisons are made for code-based wind load. Instead of code-based wind load, CFD analyses or wind tunnel tests (or both) can be performed to calculate the wind loads in a more accurate way. In addition, structural capacity of twisted tall buildings against lateral loads can be compared by pushover analyses.

Aspect ratio is another important criterion for tall buildings. In this study, aspect ratio is same for all models. Effect of the aspect ratio on the twisted tall buildings can be studied in future researches. Also investigating different twist angles, heights and structural systems may contribute to this study area.

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APPENDICES

Appendix A

DATA OF EXISTING TWISTED TALL BUILDING EXAMPLES

Table A.1: Data of existing twisted tall building examples

	BUILDINGS	LOCATION City	YEAR OF COMPLETION	ARCHITECTURAL HEIGHT (m)	NUMBER OF STORY	AVERAGE FLOOR ROTATION (degree)	TOTAL ROTATION (degree)
1	Shangai Tower	Shanghai	2015	632	128	0.938	120
2	Lakhta Tower	St. Petersburg	2019	462	86	1.047	90
3	Diamond Tower	Jeddah	2020 (Expected)	432	93	3.871	360
4	Oceans Heights	Dubai	2010	310	83	0.482	40
5	Cayan Tower	Dubai	2013	306	73	1.233	90
6	Supernova Spina	Nodia	2020 (Expected)	300	80	1.825	146
7	Evolution Tower	Moscow	2015	246	55	2.836	156
8	F&F Tower	Panama City	2011	233	53	5.943	315
9	AL Majdoul Tower	Riyadh	2019	232	54	2.5	135
10	Al Tijaria Tower	Kuwait City	2009	218	41	1.951	80
11	United Tower	Manama	2016	200	47	3.83	180
12	Al Bidda Tower	Doha	2009	197	44	1.364	60
13	SOCAR Tower	Baku	2015	196	40	0.5	20
14	Turning Torso	Malmo	2005	190	57	1.58	90
15	Trump International Hotel & Tower Vancouver	Vancouver	2016	188	63	0.714	45
16	Generali Tower	Milan	2017	185	44	1.127	49.6
17	Absolute World Building D	Mississauga	2012	176	56	3.732	209
18	Mode Gakuen Spiral Towers	Nagoya	2008	170	38	3	114
19	Absolute World Building E	Mississauga	2012	158	50	4	200
20	Baltimore Tower	London	2017	149	44	2.182	96
21	Avaz Twist Tower	Sarajevo	2008	142	39	1.539	60
22	The Point	Guayaquil	2014	137	36	5.833	210
23	Sichuan Radio & TV Center	Chengdu	2010	136	31	2.903	90
24	PwC Tower	Midrand	2018	106	26	1.154	30
25	Xiamen Suiwa Tower	Xiamen	2020 (Expected)	100	22	4.091	90
26	Grove at Grand Bay North Tower	Miami	2016	94	21	1.843	38.7
27	Grove at Grand Bay South Tower	Miami	2016	94	21	1.843	38.7
28	Tao Zhu Yin Yuan	Taipei	2018	93	21	4.286	90

Appendix B

PERIODS AND MODEL PARTICIPATING MASS RATIO VALUES FOR 45 AND 180 DEGREES TWISTED NON-ADAPTIVE AND ADAPTIVE OF AND FT SYSTEM MODELS

Table B.1: Periods and model participating mass ratio values for 45 degrees twisted non-adaptive and adaptive OF system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	9.04	0.12	0.51	0	0.12	0.51	0	0.30	0.07	0	0.30	0.07	0
Modal	2	9.04	0.51	0.12	0	0.63	0.63	0	0.07	0.30	0	0.37	0.37	0
Modal	3	1.89	0.02	0.16	0	0.64	0.79	0	0.19	0.02	0	0.56	0.39	0
Modal	4	1.89	0.16	0.02	0	0.81	0.81	0	0.02	0.19	0	0.58	0.58	0
Modal	5	1.58	0	0	0	0.81	0.81	0	0	0	0.80	0.58	0.58	0.80
Modal	6	0.74	0	0.07	0	0.81	0.87	0	0.11	0	0	0.69	0.58	0.80
Modal	7	0.74	0.07	0	0	0.87	0.87	0	0	0.11	0	0.69	0.69	0.80
Modal	8	0.54	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.89
Modal	9	0.40	0.03	0	0	0.91	0.88	0	0	0.07	0	0.70	0.76	0.89
Modal	10	0.40	0	0.03	0	0.91	0.91	0	0.07	0	0	0.76	0.76	0.89
Modal	11	0.34	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.26	0.01	0.01	0	0.92	0.92	0	0.02	0.03	0	0.78	0.79	0.93

TABLE: Modal Participating Mass Ratios - Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	9.77	0.21	0.41	0	0.21	0.41	0	0.25	0.12	0	0.25	0.12	0
Modal	2	9.77	0.41	0.21	0	0.62	0.62	0	0.12	0.25	0	0.37	0.37	0
Modal	3	1.93	0	0.18	0	0.62	0.81	0	0.20	0	0	0.58	0.37	0
Modal	4	1.93	0.18	0	0	0.81	0.81	0	0	0.20	0	0.58	0.58	0
Modal	5	1.66	0	0	0	0.81	0.81	0	0	0	0.80	0.58	0.58	0.80
Modal	6	0.74	0	0.07	0	0.81	0.87	0	0.11	0	0	0.69	0.58	0.80
Modal	7	0.74	0.07	0	0	0.87	0.87	0	0	0.11	0	0.69	0.69	0.80
Modal	8	0.56	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.89
Modal	9	0.40	0.03	0	0	0.91	0.87	0	0	0.07	0	0.69	0.76	0.89
Modal	10	0.40	0	0.03	0	0.91	0.91	0	0.07	0	0	0.76	0.76	0.89
Modal	11	0.35	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.26	0	0	0	0.91	0.91	0	0	0	0.01	0.76	0.76	0.94

Table B.2: Periods and model participating mass ratio values for 45 degrees twisted non-adaptive and adaptive FT system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	7.66	0.12	0.54	0	0.12	0.54	0	0.28	0.06	0	0.28	0.06	0
Modal	2	7.65	0.54	0.12	0	0.66	0.66	0	0.06	0.28	0	0.34	0.34	0
Modal	3	1.95	0	0	0	0.66	0.66	0	0	0	0.81	0.34	0.34	0.81
Modal	4	1.84	0.04	0.12	0	0.70	0.78	0	0.19	0.06	0	0.53	0.41	0.81
Modal	5	1.84	0.12	0.04	0	0.82	0.82	0	0.06	0.19	0	0.60	0.60	0.81
Modal	6	0.79	0.01	0.04	0	0.84	0.87	0	0.08	0.02	0	0.68	0.62	0.81
Modal	7	0.79	0.04	0.01	0	0.88	0.88	0	0.02	0.08	0	0.70	0.70	0.81
Modal	8	0.66	0	0	0	0.88	0.88	0	0	0	0.09	0.70	0.70	0.90
Modal	9	0.46	0.01	0.02	0	0.89	0.90	0	0.05	0.02	0	0.75	0.72	0.90
Modal	10	0.46	0.02	0.01	0	0.91	0.91	0	0.02	0.05	0	0.77	0.77	0.90
Modal	11	0.40	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.30	0.01	0.01	0	0.92	0.93	0	0.03	0.01	0	0.80	0.78	0.93

TABLE: Modal Participating Mass Ratios - Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	8.11	0.55	0.11	0	0.55	0.11	0	0.04	0.30	0	0.04	0.30	0
Modal	2	8.11	0.11	0.55	0	0.66	0.66	0	0.30	0.04	0	0.34	0.34	0
Modal	3	2.19	0	0	0	0.66	0.66	0	0	0	0.81	0.34	0.34	0.81
Modal	4	1.93	0.01	0.15	0	0.67	0.81	0	0.25	0	0	0.59	0.34	0.81
Modal	5	1.93	0.15	0.01	0	0.82	0.82	0	0	0.25	0	0.60	0.60	0.81
Modal	6	0.84	0.02	0.04	0	0.84	0.86	0	0.06	0.04	0	0.66	0.64	0.81
Modal	7	0.84	0.04	0.02	0	0.88	0.88	0	0.04	0.06	0	0.70	0.70	0.81
Modal	8	0.74	0	0	0	0.88	0.88	0	0	0	0.09	0.70	0.70	0.90
Modal	9	0.48	0.03	0	0	0.91	0.88	0	0	0.07	0	0.70	0.77	0.90
Modal	10	0.48	0	0.03	0	0.91	0.91	0	0.07	0	0	0.77	0.77	0.90
Modal	11	0.45	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.33	0	0	0	0.91	0.91	0	0	0	0.02	0.77	0.77	0.95

Table B.3: Periods and model participating mass ratio values for 180 degrees twisted non-adaptive and adaptive OF system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	9.04	0.11	0.52	0	0.11	0.52	0	0.30	0.06	0	0.30	0.06	0
Modal	2	9.04	0.52	0.11	0	0.63	0.63	0	0.06	0.30	0	0.37	0.37	0
Modal	3	1.89	0.03	0.15	0	0.65	0.78	0	0.18	0.03	0	0.55	0.40	0
Modal	4	1.89	0.15	0.03	0	0.81	0.81	0	0.03	0.18	0	0.58	0.58	0
Modal	5	1.58	0	0	0	0.81	0.81	0	0	0	0.80	0.58	0.58	0.80
Modal	6	0.74	0	0.06	0	0.81	0.87	0	0.11	0	0	0.69	0.58	0.80
Modal	7	0.74	0.06	0	0	0.87	0.87	0	0	0.11	0	0.69	0.69	0.80
Modal	8	0.54	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.89
Modal	9	0.40	0.01	0.03	0	0.88	0.90	0	0.06	0.01	0	0.75	0.71	0.89
Modal	10	0.40	0.03	0.01	0	0.91	0.91	0	0.01	0.06	0	0.76	0.76	0.89
Modal	11	0.34	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.26	0	0.02	0	0.91	0.93	0	0.05	0	0	0.81	0.76	0.93

TABLE: Modal Participating Mass Ratios - Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	10.19	0	0.62	0	0	0.62	0	0.37	0	0	0.37	0	0
Modal	2	10.19	0.62	0	0	0.62	0.62	0	0	0.37	0	0.38	0.38	0
Modal	3	1.84	0.03	0.16	0	0.65	0.77	0	0.18	0.02	0	0.55	0.40	0
Modal	4	1.84	0.16	0.03	0	0.81	0.81	0	0.02	0.18	0	0.57	0.57	0
Modal	5	1.58	0	0	0	0.81	0.81	0	0	0	0.80	0.57	0.57	0.80
Modal	6	0.73	0	0.06	0	0.81	0.87	0	0.11	0	0	0.69	0.58	0.80
Modal	7	0.73	0.06	0	0	0.87	0.87	0	0	0.11	0	0.69	0.69	0.80
Modal	8	0.55	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.89
Modal	9	0.40	0.03	0	0	0.90	0.88	0	0.01	0.07	0	0.70	0.76	0.89
Modal	10	0.40	0	0.03	0	0.91	0.91	0	0.07	0.01	0	0.76	0.76	0.89
Modal	11	0.35	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.26	0	0.02	0	0.91	0.93	0	0.05	0	0	0.81	0.76	0.93

Table B.4: Periods and model participating mass ratio values for 180 degrees twisted non-adaptive and adaptive FT system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	7.44	0.39	0.26	0	0.39	0.26	0	0.14	0.21	0	0.14	0.21	0
Modal	2	7.44	0.26	0.39	0	0.65	0.65	0	0.21	0.14	0	0.35	0.35	0
Modal	3	1.68	0.16	0.01	0	0.81	0.66	0	0.02	0.23	0	0.37	0.58	0
Modal	4	1.68	0.01	0.16	0	0.82	0.82	0	0.23	0.02	0	0.59	0.59	0
Modal	5	1.62	0	0	0	0.82	0.82	0	0	0	0.81	0.59	0.59	0.81
Modal	6	0.70	0.03	0.03	0	0.85	0.84	0	0.05	0.06	0	0.64	0.65	0.81
Modal	7	0.70	0.03	0.03	0	0.88	0.88	0	0.06	0.05	0	0.70	0.70	0.81
Modal	8	0.55	0	0	0	0.88	0.88	0	0	0	0.09	0.70	0.70	0.90
Modal	9	0.39	0.03	0	0	0.91	0.88	0	0.01	0.06	0	0.71	0.76	0.90
Modal	10	0.39	0	0.03	0	0.91	0.91	0	0.06	0.01	0	0.77	0.77	0.90
Modal	11	0.34	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.26	0.02	0	0	0.93	0.91	0	0	0.05	0	0.77	0.81	0.93

TABLE: Modal Participating Mass Ratios - Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	9.01	0.01	0.62	0	0.01	0.62	0	0.37	0	0	0.37	0	0
Modal	2	9.01	0.62	0.01	0	0.62	0.62	0	0	0.37	0	0.37	0.37	0
Modal	3	1.75	0	0	0	0.62	0.62	0	0	0	0.81	0.37	0.37	0.81
Modal	4	1.63	0.18	0.02	0	0.80	0.64	0	0	0.21	0	0.37	0.58	0.81
Modal	5	1.63	0.02	0.18	0	0.82	0.82	0	0.21	0	0	0.58	0.58	0.81
Modal	6	0.70	0.05	0.01	0	0.87	0.83	0	0.01	0.10	0	0.59	0.68	0.81
Modal	7	0.70	0.01	0.05	0	0.88	0.88	0	0.10	0.01	0	0.70	0.70	0.81
Modal	8	0.60	0	0	0	0.88	0.88	0	0	0	0.09	0.70	0.70	0.90
Modal	9	0.41	0.03	0.01	0	0.91	0.88	0	0.01	0.06	0	0.71	0.76	0.90
Modal	10	0.41	0.01	0.03	0	0.91	0.91	0	0.06	0.01	0	0.77	0.77	0.90
Modal	11	0.38	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.28	0	0	0	0.91	0.91	0	0	0	0.02	0.77	0.77	0.95

Appendix C

SHEAR FORCE GRAPHS OF THE CORE FOR 45 DEGREES, 90 DEGREES AND 180 DEGREES TWISTED MODELS WITH 300 METERS HEIGHT

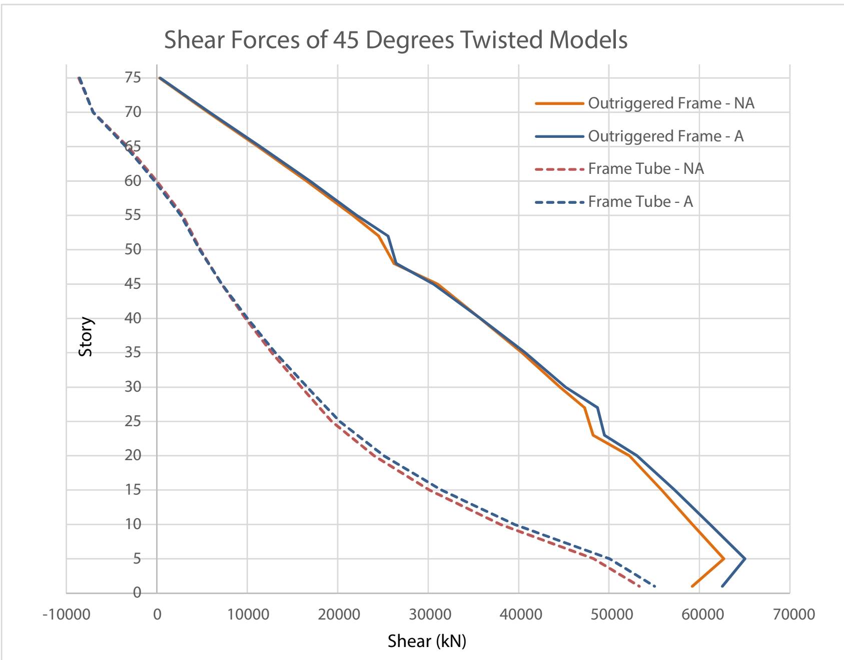

Figure C.1: Shear forces on the core of 45 degrees twisted models

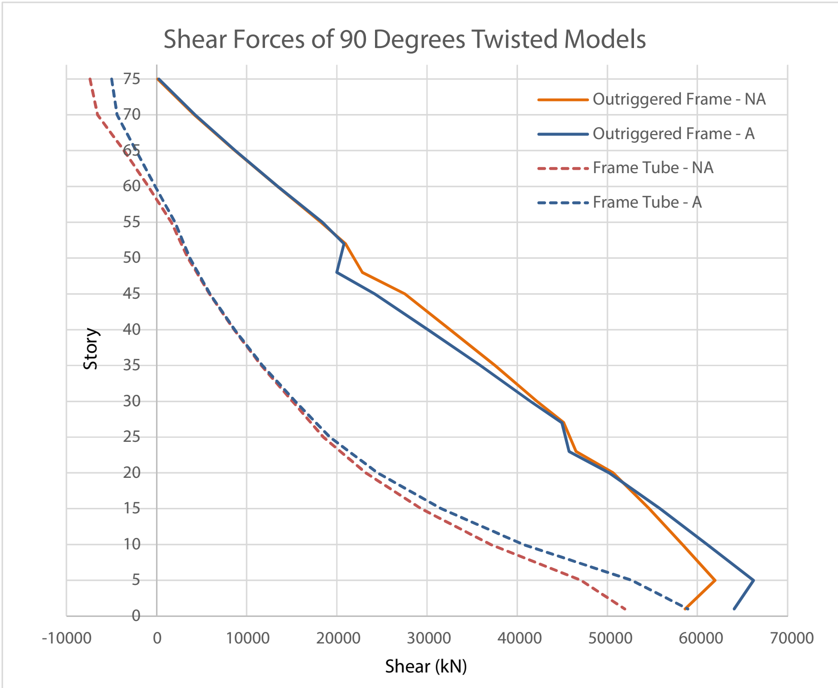

Figure C.2: Shear forces on the core of 90 degrees twisted models

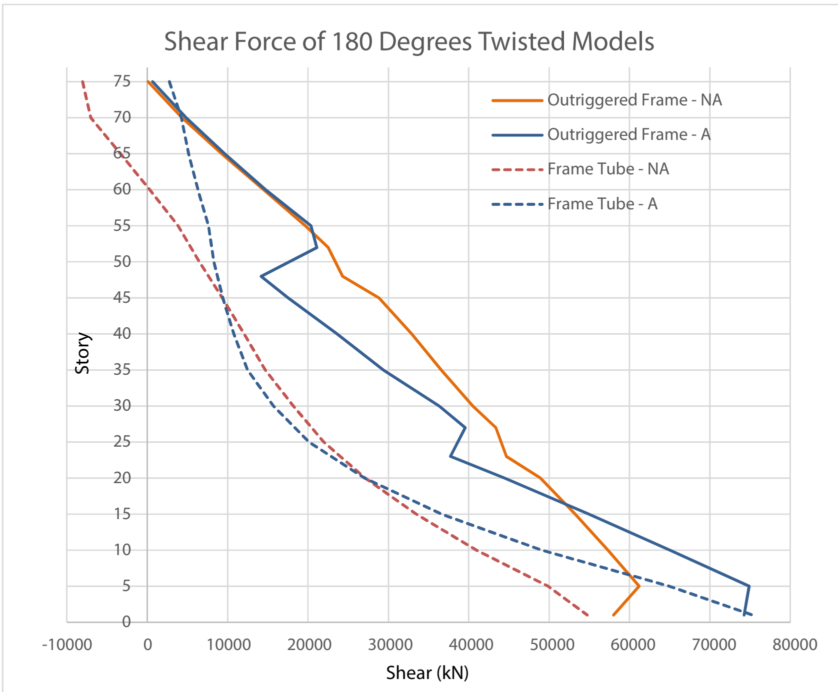

Figure C.3: Shear forces on the core of 180 degrees twisted models

Appendix D

PERIODS AND MODEL PARTICIPATING MASS RATIO VALUES FOR 200 AND 400 METERS NON-ADAPTIVE AND ADAPTIVE OF AND FT SYSTEM MODELS

Table D.1: Periods and model participating mass ratio values for 200 meters, 90 degrees twisted, non-adaptive and adaptive OF system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	5.99	0.59	0.04	0	0.59	0.04	0	0.02	0.35	0	0.02	0.35	0
Modal	2	5.99	0.04	0.59	0	0.63	0.63	0	0.35	0.02	0	0.37	0.37	0
Modal	3	1.34	0.12	0.06	0	0.75	0.69	0	0.07	0.13	0	0.44	0.50	0
Modal	4	1.34	0.06	0.12	0	0.81	0.81	0	0.13	0.07	0	0.57	0.57	0
Modal	5	1.11	0	0	0	0.81	0.81	0	0	0	0.80	0.57	0.57	0.80
Modal	6	0.49	0.03	0.04	0	0.83	0.85	0	0.07	0.05	0	0.65	0.62	0.80
Modal	7	0.49	0.04	0.03	0	0.87	0.87	0	0.05	0.07	0	0.69	0.69	0.80
Modal	8	0.37	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.90
Modal	9	0.28	0.01	0.02	0	0.88	0.90	0	0.05	0.02	0	0.74	0.72	0.90
Modal	10	0.28	0.02	0.01	0	0.91	0.91	0	0.02	0.05	0	0.76	0.76	0.90
Modal	11	0.23	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.18	0.01	0.01	0	0.91	0.92	0	0.03	0.02	0	0.79	0.78	0.93

TABLE: Modal Participating Mass Ratios - Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	6.13	0.14	0.49	0	0.14	0.49	0	0.30	0.07	0	0.30	0.07	0
Modal	2	6.13	0.49	0.14	0	0.62	0.62	0	0.07	0.30	0	0.37	0.37	0
Modal	3	1.32	0.16	0.03	0	0.78	0.65	0	0.04	0.15	0	0.42	0.52	0
Modal	4	1.32	0.03	0.16	0	0.81	0.81	0	0.15	0.04	0	0.57	0.57	0
Modal	5	1.11	0	0	0	0.81	0.81	0	0	0	0.80	0.57	0.57	0.80
Modal	6	0.49	0.04	0.03	0	0.84	0.84	0	0.05	0.07	0	0.62	0.64	0.80
Modal	7	0.49	0.03	0.04	0	0.87	0.87	0	0.07	0.05	0	0.69	0.69	0.80
Modal	8	0.38	0	0	0	0.87	0.87	0	0	0	0.09	0.69	0.69	0.90
Modal	9	0.28	0.01	0.02	0	0.89	0.89	0	0.04	0.03	0	0.73	0.72	0.90
Modal	10	0.28	0.02	0.01	0	0.91	0.91	0	0.03	0.04	0	0.76	0.76	0.90
Modal	11	0.24	0	0	0	0.91	0.91	0	0	0	0.03	0.76	0.76	0.93
Modal	12	0.18	0.01	0.01	0	0.92	0.92	0	0.03	0.02	0	0.79	0.78	0.93

Table D.2: Periods and model participating mass ratio values for 200 meters, 90 degrees twisted, non-adaptive and adaptive FT system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	5.77	0.09	0.55	0	0.09	0.55	0	0.30	0.05	0	0.30	0.05	0
Modal	2	5.77	0.55	0.09	0	0.64	0.64	0	0.05	0.30	0	0.36	0.36	0
Modal	3	1.27	0.01	0.16	0	0.65	0.81	0	0.23	0.01	0	0.58	0.36	0
Modal	4	1.27	0.16	0.01	0	0.81	0.81	0	0.01	0.23	0	0.59	0.59	0
Modal	5	1.23	0	0	0	0.81	0.81	0	0	0	0.81	0.59	0.59	0.81
Modal	6	0.52	0	0.06	0	0.82	0.87	0	0.10	0	0	0.69	0.59	0.81
Modal	7	0.52	0.06	0	0	0.88	0.88	0	0	0.10	0	0.69	0.69	0.81
Modal	8	0.42	0	0	0	0.88	0.88	0	0	0	0.09	0.69	0.69	0.90
Modal	9	0.29	0	0.03	0	0.88	0.91	0	0.07	0	0	0.76	0.70	0.90
Modal	10	0.29	0.03	0	0	0.91	0.91	0	0	0.07	0	0.77	0.77	0.90
Modal	11	0.26	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.19	0	0.02	0	0.91	0.93	0	0.05	0	0	0.81	0.77	0.93

TABLE: Modal Participating Mass Ratios - Adaptive

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	6.13	0.02	0.62	0	0.02	0.62	0	0.34	0.02	0	0.34	0.02	0
Modal	2	6.13	0.62	0.02	0	0.64	0.64	0	0.02	0.34	0	0.36	0.36	0
Modal	3	1.33	0	0	0	0.64	0.64	0	0	0	0.81	0.36	0.36	0.81
Modal	4	1.28	0.07	0.11	0	0.70	0.75	0	0.18	0.05	0	0.53	0.41	0.81
Modal	5	1.28	0.11	0.07	0	0.82	0.82	0	0.05	0.18	0	0.59	0.59	0.81
Modal	6	0.54	0.03	0.03	0	0.84	0.85	0	0.05	0.05	0	0.64	0.64	0.81
Modal	7	0.54	0.03	0.03	0	0.88	0.88	0	0.05	0.05	0	0.69	0.69	0.81
Modal	8	0.45	0	0	0	0.88	0.88	0	0	0	0.09	0.69	0.69	0.90
Modal	9	0.30	0.02	0.02	0	0.89	0.89	0	0.04	0.03	0	0.73	0.73	0.90
Modal	10	0.30	0.02	0.02	0	0.91	0.91	0	0.03	0.04	0	0.77	0.77	0.90
Modal	11	0.28	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.21	0	0	0	0.91	0.91	0	0	0	0.02	0.77	0.77	0.95

Table D.3: Periods and model participating mass ratio values for 400 meters, 90 degrees twisted, non-adaptive and adaptive OF system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	12.30	0.01	0.61	0	0.01	0.61	0	0.36	0.01	0	0.36	0.01	0
Modal	2	12.30	0.61	0.01	0	0.63	0.63	0	0.01	0.36	0	0.37	0.37	0
Modal	3	2.30	0.01	0.17	0	0.64	0.80	0	0.20	0.01	0	0.57	0.38	0
Modal	4	2.30	0.17	0.01	0	0.81	0.81	0	0.01	0.20	0	0.58	0.58	0
Modal	5	1.77	0	0	0	0.81	0.81	0	0	0	0.81	0.58	0.58	0.81
Modal	6	0.87	0.02	0.05	0	0.83	0.86	0	0.08	0.03	0	0.66	0.62	0.81
Modal	7	0.87	0.05	0.02	0	0.88	0.88	0	0.03	0.08	0	0.70	0.70	0.81
Modal	8	0.61	0	0	0	0.88	0.88	0	0	0	0.09	0.70	0.70	0.90
Modal	9	0.47	0.01	0.03	0	0.89	0.91	0	0.06	0.02	0	0.76	0.72	0.90
Modal	10	0.47	0.03	0.01	0	0.91	0.91	0	0.02	0.06	0	0.77	0.77	0.90
Modal	11	0.38	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.31	0	0.02	0	0.92	0.93	0	0.04	0.01	0	0.81	0.78	0.93

TABLE: Modal Participating Mass Ratios - Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	12.96	0.01	0.61	0	0.01	0.61	0	0.37	0.01	0	0.37	0.01	0
Modal	2	12.95	0.61	0.01	0	0.62	0.62	0	0.01	0.37	0	0.37	0.37	0
Modal	3	2.31	0.11	0.08	0	0.74	0.70	0	0.09	0.12	0	0.46	0.49	0
Modal	4	2.31	0.08	0.11	0	0.81	0.81	0	0.12	0.09	0	0.58	0.58	0
Modal	5	1.84	0	0	0	0.81	0.81	0	0	0	0.81	0.58	0.58	0.81
Modal	6	0.87	0.07	0	0	0.88	0.81	0	0	0.12	0	0.58	0.70	0.81
Modal	7	0.87	0	0.07	0	0.88	0.88	0	0.12	0	0	0.70	0.70	0.81
Modal	8	0.63	0	0	0	0.88	0.88	0	0	0	0.09	0.70	0.70	0.90
Modal	9	0.47	0	0.04	0	0.88	0.91	0	0.07	0	0	0.77	0.70	0.90
Modal	10	0.47	0.04	0	0	0.91	0.91	0	0	0.07	0	0.77	0.77	0.90
Modal	11	0.40	0	0	0	0.91	0.91	0	0	0	0.03	0.77	0.77	0.93
Modal	12	0.31	0	0.02	0	0.92	0.93	0	0.04	0.01	0	0.82	0.78	0.93

Table D.4: Periods and model participating mass ratio values for 400 meters, 90 degrees twisted, non-adaptive and adaptive FT system models

TABLE: Modal Participating Mass Ratios - Non-Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	9.49	0.01	0.65	0	0.01	0.65	0	0.34	0	0	0.34	0	0
Modal	2	9.48	0.65	0.01	0	0.66	0.66	0	0	0.34	0	0.34	0.34	0
Modal	3	2.19	0	0.17	0	0.66	0.82	0	0.25	0	0	0.60	0.35	0
Modal	4	2.18	0.17	0	0	0.82	0.82	0	0	0.25	0	0.60	0.60	0
Modal	5	2.12	0	0	0	0.82	0.82	0	0	0	0.81	0.60	0.60	0.81
Modal	6	0.92	0	0.06	0	0.82	0.88	0	0.11	0	0	0.71	0.60	0.81
Modal	7	0.92	0.06	0	0	0.88	0.88	0	0	0.11	0	0.71	0.71	0.81
Modal	8	0.72	0	0	0	0.88	0.88	0	0	0	0.09	0.71	0.71	0.90
Modal	9	0.52	0	0.03	0	0.88	0.92	0	0.07	0	0	0.78	0.71	0.90
Modal	10	0.52	0.03	0	0	0.92	0.92	0	0	0.07	0	0.78	0.78	0.90
Modal	11	0.45	0	0	0	0.92	0.92	0	0	0	0.03	0.78	0.78	0.94
Modal	12	0.34	0	0.02	0	0.92	0.94	0	0.05	0	0	0.83	0.78	0.94

TABLE: Modal Participating Mass Ratios - Adaptive														
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY	Sum UZ	RX	RY	RZ	Sum RX	Sum RY	Sum RZ
		sec												
Modal	1	10.42	0.04	0.61	0	0.04	0.61	0	0.34	0.01	0	0.34	0.01	0
Modal	2	10.42	0.61	0.04	0	0.65	0.65	0	0.01	0.34	0	0.35	0.35	0
Modal	3	2.35	0	0	0	0.65	0.65	0	0	0	0.81	0.35	0.35	0.81
Modal	4	2.22	0.09	0.08	0	0.74	0.73	0	0.16	0.09	0	0.51	0.44	0.81
Modal	5	2.22	0.08	0.09	0	0.82	0.82	0	0.09	0.16	0	0.59	0.59	0.81
Modal	6	0.95	0.05	0.01	0	0.87	0.84	0	0.02	0.09	0	0.62	0.68	0.81
Modal	7	0.95	0.01	0.05	0	0.88	0.88	0	0.09	0.02	0	0.71	0.71	0.81
Modal	8	0.80	0	0	0	0.88	0.88	0	0	0	0.09	0.71	0.71	0.90
Modal	9	0.54	0.02	0.01	0	0.91	0.89	0	0.02	0.05	0	0.73	0.76	0.90
Modal	10	0.54	0.01	0.02	0	0.92	0.92	0	0.05	0.02	0	0.78	0.78	0.90
Modal	11	0.50	0	0	0	0.92	0.92	0	0	0	0.03	0.78	0.78	0.93
Modal	12	0.37	0	0	0	0.92	0.92	0	0	0	0.02	0.78	0.78	0.95