AERODYNAMIC PERFORMANCE OF TALL BUILDINGS: A STUDY ON THE RELATION BETWEEN WIND ESCAPE AND OUTRIGGER FLOORS

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ABSTRACT

AERODYNAMIC PERFORMANCE OF TALL BUILDINGS: A STUDY ON THE RELATION BETWEEN WIND ESCAPE AND OUTRIGGER FLOORS

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Numbers of slender tall buildings, particularly “super-slenders”, are increasing rapidly due to the quest for maximizing the leasable space in plan or being iconic or both. With their relatively short structural depth in plan, limiting the top drift, in other words, satisfying the serviceability limit is usually the governing constraint in their design. Using multi-level outriggers, tuned mass dampers and distinctive aerodynamic modifications such as wind flow openings together is rather mandatory to realization of such designs. However, there is a trade-off between outrigger system and wind escape floor if they are located at the same level. The outriggered-frame structural system gives the building its stiffness whereas openings as wind escape floors are aerodynamic modifications for decreasing the wind load acting on building. This study evaluates the interrelation of outriggers and wind escape floors arranged at the same floor level in terms of several structural response parameters. The relationship between openings as aerodynamic modifications for mitigating the wind loads and outriggers (including virtual outriggers) in slender tall buildings have been investigated with the aim of improving the building performance in the context of top drift limitation and reduced wind loads. The research question is the possibility of having less number of outrigger floors by taking the advantage of wind escapes which have located at the outrigger floors without sacrificing occupant comfort. In other words, if the top drift of a building which has a certain type and number of outriggers organized with wind openings can be kept less than the top drift of a building having more outrigger floors with closed façades, then the architects and engineers may prefer the combined use of outrigger floors with wind escape floors to increase leasable plan area. An existing super-slender building having both outriggers and wind flow openings at mechanical floor levels has been selected and alternative outrigger and wind flow opening configurations have been modelled on this sample building. Then comparisons have been made to scrutinize the optimum use of outriggers with wind openings. Top drift, story shear and moment, particularly core moment, have been used as demand parameters in this study. The results showed that the optimum use of wind openings with certain type of outriggers can yield better structural response to wind loads compared to closed façade building having more number of outriggers. Code based wind loading without vortex shedding effects can be counted as limitations of the study. Thus, wind tunnel testing of promising outrigger wind escape floor arrangements identified in this study can be conducted as future remarks.

Keywords: Super-slender Tall Buildings, Outriggered Frame System, Wind Escape Floors, Optimum Outrigger Configuration, Top Drift

ÖZ

YÜKSEK BİNALARIN AERODİNAMİK PERFORMANSI: RÜZGÂR GEÇİŞ VE YATAY PERDE DUVAR KATLARI ARASINDAKİ İLİŞKİ ÜZERİNE BİR ÇALIŞMA

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Narin yüksek yapıların sayısı kiralanabilir alanları artırmak veya sembolik olmak amacıyla hızlı bir biçimde artmaktadır. Narin yüksek binalarda taşıyıcı sistem derinliğinin nispeten daha az olması, tepe ötelenmesini arttırmaktadır. Dolayısıyla bu tip yapılarda kullanıcı konforunu azaltmadan gerekli tepe ötelenmesi değerlerinin sağlanabilmesi kritik bir tasarım girdisi haline gelmektedir. Yatay perde duvarlar ve ayarlı kütle sönümleyicilerin yanı sıra rüzgâr geçiş katları gibi özel aerodinamik modifikasyonlar narin yüksek yapıların hayata geçirilebilmesi için neredeyse bir zorunluluktur. Yatay perdeli çerçeve taşıyıcı sistem yapıya rijitlik kazandırırken, rüzgâr geçiş katları gibi açıklıklar da yapıya etkiyen rüzgâr yüklerini azaltmak için uygulanan aerodinamik modifikasyonlardır. Bu çalışmada narin yüksek yapılardaki yatay perde duvarlar (sanal yatay perde duvarlar da dâhil) ve rüzgâr geçiş katları arasındaki ilişki, binanın taşıyıcı sistem performansı (tepe ötelenmesi) ve rüzgâr yüklerindeki azalma açısından araştırılmaktadır. Bu çalışmada yatay perde duvarların rüzgâr geçiş katları ile bir arada kullanılması durumunda, tasarım kıstaslarının daha az sayıda yatay perde katı ile sağlanması ihtimali araştırılmıştır. Eğer bu yolla daha az tepe ötelenmesi sağlanabilirse, mimarlar ve mühendisler rüzgâr geçiş katları ve yatay

perde duvarı bir arada kullanarak kiralanabilir kat alanını arttırmayı tercih edebilirler. Mekanik katların aynı zamanda yatay perde duvar ve rüzgâr geçiş katları olarak kullanıldığı çok narin bir yüksek yapı örnek olarak seçilmiştir. Rüzgâr geçiş katları ile beraber kullanılan yatay perde duvarların bina performansındaki iyileştirmesini irdelemek için üretilen çeşitli modellerde taban momentleri ve tepe ötelenmeleriyle ilgili karşılaştırmalar yapılmıştır. Sonuçlar rüzgâr geçiş katlarıyla beraber kullanılan ve buna uygun olarak tasarlanmış yatay perde duvarlar ile binanın tepe ötelenmesini azaltılabileceğini göstermiştir. Bu çalışmada hortum saçıntılarının yarattığı titreşimleri göz ardı eden şartname esaslı rüzgâr yükü kullanılmıştır. Bundan sonraki araştırmalarda bu çalışmada belirlenen başarılı yatay perde katı - rüzgâr geçiş katı kombinasyonlarının rüzgâr tüneli testleri ile doğrulanması faydalı olabilir.

Anahtar Kelimeler: Narin Yüksek Yapılar, Yatay Perdeli Çerçeve Sistem, Rüzgar Geçiş Katları, Yatay Perde Duvar Katlarının Düzenlemesi, Tepe Ötelenmesi

To My Parents, Lovely Husband and Kids…

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For my beloved parents, I would never succeed without them, feeling their existence and love is encouraging me every time in my life.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
BIM	Building Information Modeling
BO-C	Brace Outrigger Model with Closed Façade
BO-O	Brace Outrigger Model with Perforated Façade
CTBUH	Council on Tall Buildings and Urban Habitat
d_{fi}	Storey Displacement Calculated according to F_{fi} in i^{th} floor
f	Building Frequency
F_{fi}	Fictive Loads Acting on i^{th} Floor
G_f	Gust Effect Factor
KPF	Kohn Pedersen Fox Architects
LATBSDC	Los Angeles Tall Buildings Structural Design Council
LERA	Leslie E. Robertson Associates
m_i	Mass of i^{th} Floor
N	Total Storey Number of a Building from Foundation
NO-C	No Outrigger Model with Closed Façade
NO-O	No Outrigger Models with Perforated Façade
RB-O	Reference Building Model with Perforated Façade
RWDI	Rowan Williams Davies and Irwin
SW-C	Shear Wall Outrigger Model with Closed Façade
T	Building Period
T_1	Building Natural Period
TMD	Tuned Mass Damper
VAWT	Vertical Axis Wind Turbines
VO-C	Virtual Outrigger Models with Closed Façade
VO-O	Virtual Outrigger Model with Perforated Façade
1BO-C	One Level of Braced Outrigger with Closed Façade

1BO-O	One Level of Braced Outrigger with Perforated Façade
1NO-O	One Level of Wind Escape Floor without Outrigger
1VO-C	One Level of Virtual Outrigger with Closed Façade
1VO-O	One Level of Virtual Outrigger with Perforated Façade
2BO-C	Two Levels of Braced Outrigger with Closed Façade
2BO-O	Two Levels of Braced Outrigger with Perforated Façade
2NO-O	Two Levels of Wind Escape Floor without Outrigger
2VO-C	Two Levels of Virtual Outrigger with Closed Façade
2VO-O	Two Levels of Virtual Outrigger with Perforated Façade
3BO-C	Three Levels of Braced Outrigger with Closed Façade
3BO-O	Three Levels of Braced Outrigger with Perforated Façade
3NO-O	Three Levels of Wind Escape Floor without Outrigger
3VO-C	Three Levels of Virtual Outrigger with Closed Façade
3VO-O	Three Levels of Virtual Outrigger with Perforated Façade
4BO-C	Four Levels of Braced Outrigger with Closed Façade
4BO-O	Four Levels of Braced Outrigger with Perforated Façade
4NO-O	Four Levels of Wind Escape Floor without Outrigger
4VO-C	Four Levels of Virtual Outrigger with Closed Façade
4VO-O	Four Levels of Virtual Outrigger with Perforated Façade
5BO-C	Five Levels of Braced Outrigger with Closed Façade
5BO-O	Five Levels of Braced Outrigger with Perforated Façade
5NO-O	Five Levels of Wind Escape Floor without Outrigger
5VO-C	Five Levels of Virtual Outrigger with Closed Façade
5VO-O	Five Levels of Virtual Outrigger with Perforated Façade

CHAPTER 1

INTRODUCTION

1.1. Background info

Great temples, pyramids, cathedrals all of which are pointed to sky symbolize the power and the richness. Moreover, these kinds of buildings are very gentle examples of ingenuity of humanity. Growing population and mass migration process, globalization, urban regeneration, agglomeration in business districts, land prices, geographic factors, land preservation for sustainability and human aspirations are constituents behind being tall. Emerging technologies are also motivating for architects and engineers to create innovative designs while reaching the skyline.

Günel and Ilgın (2014) indicate that buildings which lead to sky, described as tall buildings, are symbols of prestige and glory of today. Well-organized teamwork is a must from the scratch till being topped-out. Tall building’s design is a challenging task which necessitates the correlation between numerous different disciplines. There are many systems working in one building as usual, but the problem in tall buildings is its colossal scale compared to other common buildings with average height. Dense population which stacks in tall building brings many problems such as ventilation, transportation between levels and egress during an emergency into the picture. As a result, the collaboration of interdisciplinary professions turns into a crucial burden. Thus, each tall building has numerous structural and architectural design challenges to be faced before realization of the project.

Enhanced construction techniques, improved structural systems, brand new materials and new technological developments make the buildings taller than ever before. Slenderer and structurally efficient tall buildings are ubiquitous, as the designs and techniques used in their constructions let maximizing leasable space which satisfies the architects and engineers, as well as the stakeholders.

Increasing height limits make tall buildings much more sensitive to environmental excitations such as wind which adversely affect the serviceability and occupant comfort since, the lateral movement of the building caused by wind effects the occupants negatively both physiological and psychological. Günel and Ilgın (2007) state that wind induced loads acting on a tall building create excitations and lateral displacement. They cause to discomfort occupants like headaches, dizziness and nausea. They also create serious serviceability problems. In order to control the lateral displacement and wind mitigating excitation, outriggers, tuned mass dampers and distinctive aerodynamic modifications such as wind flow openings are used together inevitably.

After World War II, tall buildings are soared in many countries first in U.S. followed by Pacific Rim Countries, parts of Europe and Middle East. Notwithstanding advanced technology and developments in architectural style, improvement in architectural planning of tall buildings could not reach the decade. However, economic viability and constructional limitations awakes a hesitation in architectural development. However, the situation is changed oppositely the last decade of 20th century with the acquired terms used with tall buildings such as sustainability, iconic architecture, free form massing. Those terms are required for new architectural plan solutions for increasing the ratio of net to gross floor area for the sake of achieving spatial efficiency. (Ali & Al- Kodmany, 2012)

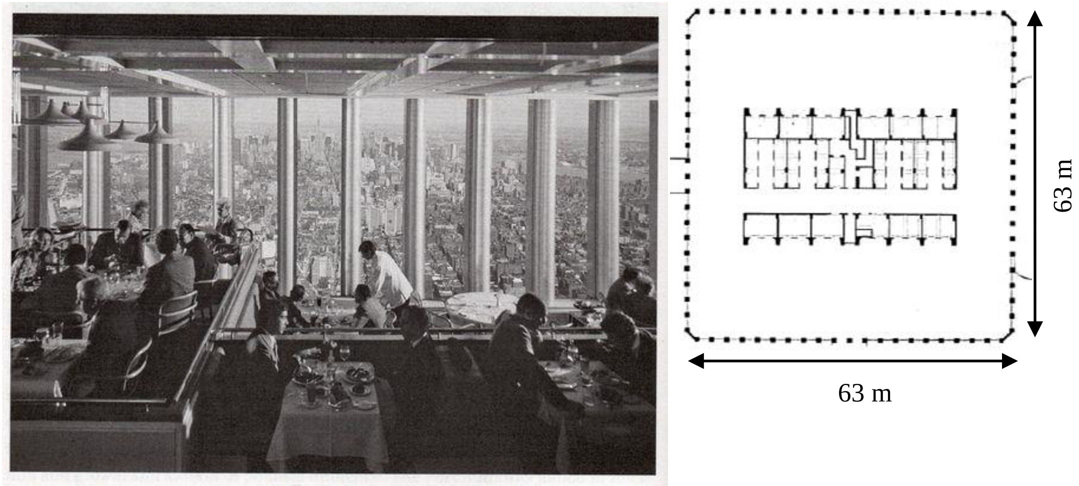
Due to 20th century urbanism in America, tall buildings have a major role for recognizing much defined spaces in official and commercial use. Rapid growth of urban population, demand by business activities after industrial revolution, inadequacy and high cost of land in urban areas, desire to prevent disorganized urban context and influence of cultural significance are reasons of buildings getting higher.

As 2018 ends, Burj Khalifa is the tallest building in the world with its 828 m height. Jeddah Tower also called Kingdom Tower which is under construction planned to be more than 1000 m when it's finished. The title of "being most" has become a serious concern for stakeholders, since being the tallest in Europe, the most iconic building of the year or slenderest in the world draw attention by public a lot. For instance, there were only 30.000 people live in Shenzen, China, that small fishing village in 1970's. Global forces and rapid foreign investments spurred the urbanization process and transfer Shenzen to a modern city of skyscrapers. Today, the city homes over 13 million people and many headquarters of numerous high-tech companies which offices are located at major tall and super tall, (higher than 300m) buildings. Despite the negative effects of tall buildings on the quality of urban life, tall buildings have potential environmental merits such as harnessing wind energy with the turbines on to them or corporate with solar panels and photovoltaic cells. So, enumerated reasons above with emergence technology, the proliferation of high rises are undeniable which is also corroborated by Council on Tall Buildings and Urban Habitat (CTBUH). Statistics given by CTBUH show that the number of tall buildings increased by 402% from year 2000 up to the end of 2018. Additionally, CTBUH year review of 2017 reveals that there are totally 126 super tall building, namely buildings taller than 300 meters, in worldwide. 15 of them were completed in 2017, whereas there were only 76 super tall buildings in 2013. These results indicate that the ambition for constructing tall building for different reasons might remain on the agenda for a while.

The tallest building proposed in Turkey, with its 375 m height Highlife Tower is located in İzmir. Merkez Ankara Office Tower which is under construction and Skyland Office Tower in İstanbul which is completed in 2017 follows it with their 301 m and 284 m heights respectively (Skyscraper Center, 2018). Since, this thesis scope is outlined with super tall buildings, those towers except from proposing tower in İzmir (Highlife Tower) are not tall enough to be studied in this context. However, Highlife Tower is still a proposal.

The loads acting on the building prescribe the structural system characteristics. The literature review reveals that there are several structural systems used in tall building design. Among those, outriggered frame and tube systems are frequently used for super tall buildings . Günel and Ilgın, (2014) state that, compared to outriggered frame system and tube system, shear-frame system (shear trussed/braced frame and shear walled frame system), mega column system (mega frame and space truss), and mega core system can reach relatively lower heights efficiently and economically. On the other hand, tube systems and outriggered frame systems could have architecturally undesirable aspects, *i.e.* they can limit architectural design decisions. Günel and Ilgın (2014) state that outrigger connects the core to perimeter columns and generally used with a belt of same depth around the perimeter columns. This way, outrigger increases the stiffness of the building and decreases core moments. These members' height is generally more than one storey and they can be located at different levels through the height of the building. Günel and Ilgın (2014) also denote that since outrigger floors are usually unoccupied due to the spatial organization of these members, they are located at mechanical floors. Hence, more outrigger floors mean less occupied area or in particular, less leasable area.

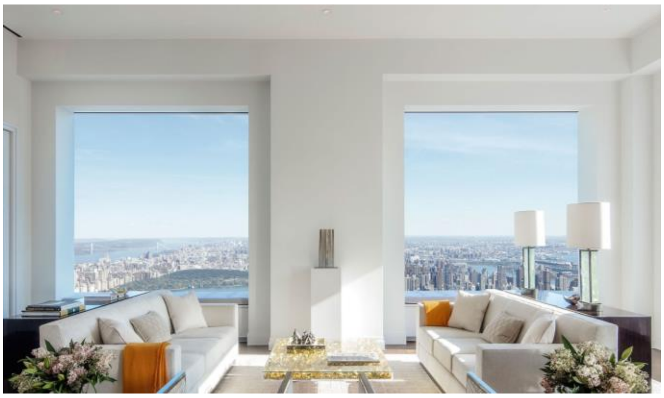
In tube systems, buildings' perimeter behaves as a cantilevered hollow box and resists lateral forces. If it is a framed tube system, also known as vierendeel tube system, closely spaced perimeter columns and deep spandrel beams at floor levels which obstruct the panoramic view (Günel &Ilgın, 2014), constitute the load bearing system. Figure 1.1 shows a photo taken from restaurant interior space, clear span between perimeter columns is approximately 0.66 meters in World Trade Center Twin Towers with 417 m architectural height (Günel and Ilgın, 2014).

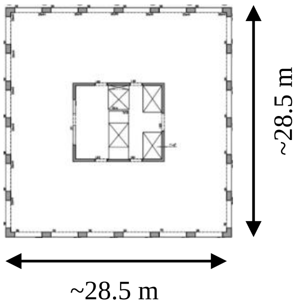


(a) **(b)**

Figure 1.1. (a) World Trade Center Twin Towers interior and (b) its plan scheme (https://en.wikiarquitectura.com/building/twin-towers-new-york/#lg=1&slide=5, September 2018)

As seen in Figure 1.2, span of 3 m between perimeter columns is achieved unhinderedly in 432 Park Avenue building in return for the use of additional outriggers, wind escape floors and a tuned mass damper. However, implementation of outriggers into frame tube system reduces the leasable area. In outriggered frame systems, each additional outrigger level also results in the same problem.





(a) **(b)**

Figure 1.2. (a) 432 Park Avenue Building interior and (b) its plan scheme (https://www.432parkavenue.com, September 2018)

In skyscrapers, usually 70% of the whole floor area is rentable while the rest of the area hosts structural members and circulation spaces whereas more than 80% of floors of low rise buildings is available as architectural space (Ali & Al- Kodmany, 2012). If the amount of leasable areas and their architectural superiority could be increased by reducing the number of outrigger floors or having relatively distant perimeter columns in tube systems, this would provide a significant architectural improvement for tall buildings. Not only the net rentable area but also the use of environmentally friendly materials and reduced carbon foot print of a tall building could be possible by more integrated and innovative solutions. According to Ali & Al-Kodmany (2012) a tall building in urban scale is a sustainable solution for its agglomeration typology. People who live in suburb spend more times on the road to come their works which cause a rise in carbon emission values. Besides more low-rise suburb houses mean more infrastructure, more materials used in construction lead more carbon emission. In addition, tall buildings have a potential on harnessing renewable energy by making use of wind turbines attached on to them (Bahrain World Trade Center, Bahrain, 240m) or photovoltaic façade coverings (Torre Reforma, Mexico City, 246m), or both (Pearl River Tower, Guangzhou, 309.4m). Considering the sustainability of design, using structural members having larger cross sections with the aim of stiffening is not desirable due to the embedded energy into the building. Thus, seeking for an optimization in aerodynamic performance of tall buildings would be helpful for achieving success both in architectural and structural design process.

Günel and Ilgın (2014) stated that since wind speed and thus wind pressure increase with height (wind velocity and pressure profile); aerodynamic responses of tall buildings usually govern the whole design process especially for supertall buildings. There are three design approaches to reduce building sway depend on wind induced loads; architectural, structural and mechanical. The aerodynamic modifications or aerodynamic designs which are architectural design approaches improve building response by reducing the drag coefficient and vortex shedding. The vortices occurred around bluff body objects due to the separation of air flow causes resonant vibrations and reduces the occupant comfort (Amin & Ahuja, 2010). Poon, Shieh, Joseph and Chang (2004) denoted that changing the plan scheme from a absolute rectangular form to a circular form or smoothing the corners of a rectangular plan scheme (corner modification) instead of sharp edges can significantly reduce the wind loads acting on the building. Irwin, Kilpatrick and Frisque (2008) indicated that saw-tooth corner modifications in Taipei 101 reduce the overturning moments up to 25%. Furthermore, tapered, setback and twisted forms are aerodynamic forms which confuse the wind and improve the performance of building against wind loads, too.

The literature review showed that, there are buildings with wind escape floors for mitigating the wind load. Marcus (2015) states that acceleration of the building can be reduced up to 15% by using wind escape floors on a tall building at certain floor levels. Kiktsu and Okada (2000) assert that letting the air flow through wind escape floor in order to reduce drag forces emerged by strong winds on tall buildings, is not an unusual idea. However, the attempts of making taller, more slender, or lighter buildings make those openings come into practice more frequently. There are several buildings which use openings at top levels for reducing the wind loads. This design strategy is utilized in Shanghai World Financial Center as seen in Figure 1.3(a) that is the most significant example, Kingdom Center and Dalian Greenland Center which is on hold status by 2018. (Skyscraper center, September 2018)

(a) **(b)** **(c)**

Figure 1.3. (a) Shanghai World Financial Center, China (b) Kingdom center, Saudi Arabia (c) Dalian Greenland Center, China (Skyscraper center, September 2018)

Wind force (F) is the primary source of the demand for tall buildings whereas structural system and material determine their capacity through stiffness (k) and strength. In particular, stiffness is the amount of force per unit displacement. As the main displacement parameter in tall building design, top drift (Δ_{top}) should be kept within certain limits. The simple yet fundamental relation among these physical quantities ($F=k \times \Delta_{top}$) prescribes the route for creating optimal design of tall buildings. It is clearly seen from the formula that displacement is inversely proportional with stiffness. By changing the structural material and load bearing characteristics of the system, the top drift could be decreased in an intended way. On the other hand, wind force acting on the building which is directly proportional with the top drift can be decreased by building orientation with respect to strong wind direction, building form, geometry as well as other aerodynamic modifications such as open floors. As aforementioned, relationship between structural system and the aerodynamic performance of the building has become a major concern in tall building design. It is, however, a complex issue and there are numerous determinants to be considered.

1.2. Motivation

Over 80% of world population is expected to live in urban areas when the world population reaches to 9 billion (CTBUH, 2017). At that time, accommodation of such dense population in city centers will be a huge problem. In order to address this, high rise development is essential. Ali and Al-Kodmany (2012) state that the fine medieval grain of streets of London could be better maintained with relatively small footprint of tall buildings. Similarly, Marcus (2015) indicates that the land is scarce in centre of New York and glamour and prestige demands of a dense population are met by super slim tall buildings.

However, as slenderness ratio gets higher it would be difficult to provide structural stability and occupant comfort by achieving maximum rentable area, at the same time. In order to make a clear statement, slenderness ratio also termed as aspect ratio is the ratio of building's structural height to the narrowest structural width of the ground floor plan (Günel and Ilgun, 2014). Günel and llgın (2014) denote that buildings which have an aspect ratio of 6 or higher and have unconventional forms should be analyzed in wind tunnels in order to calculate the wind loads on the structure.

In super slender buildings relatively small foot print area limits the available rentable areas. Thicker columns and larger structural elements mean less architectural space. Additionally, floors hosting tuned mass dampers and outriggers make the designer sacrifice more leasable area. However, the wind escape floors organized with outrigger floors can increase building performance by decreasing the wind response on super slim ones instead of reserving more floors to outriggers or tuned mass dampers. This way, leasable areas in super slim tall buildings can be increased in a controlled manner. Occupant comfort can be satisfied by letting the air flow pass through the unoccupied floors of the building.

The number of the existing buildings with wind escape floors is much less than buildings with other aerodynamic modifications. Relatively less information about the performance of wind escape floors could be a reason that discourages clients, architects and engineers from working with these floors during the realization of the project. Another concern could be the need for the optimization process together with numerous wind tunnel tests which are quite time consuming and expensive (Stathopoulos, 1997 and Blocken and Stathopoulos, 2013).

In order to provide more architectural space and leasable area in super slender tall buildings, improving building performance is crucial. It can be achieved by an optimization of structural system and aerodynamic modification. This thesis study outlines a research on super tall buildings with and without outriggers and perforated façades in terms of top drift and overturning moments with the limitation of occupant comfort.

1.3. Aim and objectives

Lateral load resisting system (structural system) gives the building its stiffness, whereas wind escape floors are aerodynamic modifications for decreasing wind effects.

Günel and Ilgın (2014) indicate that building sway has to be limited where maximum lateral top drift of the tall building is expected to be 1/500 of the building structural height (it is also called as drift index). This benchmark is taken into consideration while conducting this study, since improving building performance without sacrificing occupant comfort is an important criteria for architects and engineers.

This study investigates the performance of wind escape floors as an aerodynamic modification in tall buildings, particularly those over 300 meters height. This subject has been studied in three aspects;

i. Performance vs. outrigger typology that compatible with wind escape floors
ii. Performance vs. the number of wind escape floors with outriggers
iii. Performance vs. the location of wind escape floors with outriggers

Using the geometry and structural system features of an existing tall building, 432 Park Avenue building, a generic seed model has been generated and then modified for various cases. Using these models, an optimum outrigger typology and wind escape floor arrangement has been scrutinized with the aim of reducing the number of non-occupancy floors.

This study is expected to enhance the understanding of floor openings as an aerodynamic modification for reducing the wind induced loads, thus the top drift, with respect to alternative outrigger configurations. The information derived by this study would be useful for tall building designers.

1.4. Contribution

The research question of this thesis study is that having less number of outrigger floors is possible if these outrigger floors are used as wind escapes throughout the building height. This research is limited with the top drift requirements for providing occupant comfort and serviceability.

Contributions that this study is exerted for;

- Reducing responding wind forces with the aim of maximizing leasable area in super slim tall buildings,

- Proposing an outrigger typology which is compatible with wind escape floors and having an objective of increasing building performance,
- Setting up a relationship between wind escape floors as aerodynamic modifications and structural system of super slender tall buildings within the limitation of building top drift.

This study provides an integrated approach regarding wind escape floors and advanced structural systems for the topic of tall building performance.

1.5. Procedure and disposition

In this study, wind escape floors coupled with outriggers in different configurations is studied. Although, wind escape floors, also termed as openings was studied before for mitigating the wind forces but independently. This study on the other hand, investigates wind openings as a part of the outrigger floors. The aim of this study is further improving the building performance by using these two approaches in an optimum way.

In order to address optimum solution, two consecutive phases are conducted. In the first phase, outrigger typologies are examined to improve structural system stiffness without sacrificing the wind escape floors spatial organization. In the second phase, two of outrigger typologies are chosen due to the most structural efficient ones among the other typologies. These two types are multiplexed with different combinations of location and numbers in controlled manner. The two phases are composed of modal and static wind load analysis.

With regard to these objectives, first chapter of this thesis is introduction, which includes background info, motivation, aim and objectives, contribution and also procedure and disposition. In this part, “why people need tall buildings?” questioning is pondered over in a clear manner. Overall approach to the introduction is based on understanding the importance of super slim tall buildings and problems of those kinds of buildings.

Second chapter is devoted to the aerodynamic modifications applied to tall buildings in a historical context. Recent studies on tall buildings with openings are also presented. Existing tall buildings with wind escape floors are examined as case studies in terms of correlation between structural systems and wind escape floors. Furthermore, structural system alternatives for super tall buildings are investigated. Considering their historical improvement and classifications according to reached building heights efficiently and economically, this literature survey is emerged for composing of a comprehensive approach to improve structural behavior of the building by finding a correlation between wind escape floors and structural system of slender tall buildings with concern of top drifts and overturning moments.

The third chapter involves material and methodology. Models used in this thesis study are explained carefully and assigned loads are defined in Section 3.1. Procedures used as methodology are given in Section 3.2

Fourth chapter is devoted to the results and discussion on findings. This chapter includes the assessment of tables and graphs. A comparative evaluation is done on the results with discussion of core moments and top drifts.

Lastly, a brief summary of the conducted study, main outcomes, limitation of the study and recommendations for further studies are taken part in conclusion as fifth chapter.

CHAPTER 2

LITERATURE REVIEW

2.1. Aerodynamic modifications applied to tall buildings as architectural design approach

Günel & Ilgın, 2014 state that extremely daring architectural and structural designs of tall buildings with the aid of advanced computer technology push the limits of predecessor's design. Carol Willis, founder and director of skyscraper museum stated (October, 2016) that "super slender" term is a brand new topic and has recently begun to be used in our daily lives. The first examples of slender towers are seen in last decade whereas outrigger frame systems are used for more than 30 years. Marcus (2015) remarks that since 1980's, architects and engineers are familiar with outriggers. However, Marcus (2015) highlights that the conventional structural systems might not be enough for this kind of buildings where the critical challenges are the dynamic movements and motion perception of occupants. Therefore, the correlation between wind escape floors and structural system configuration becomes crucial to improve new strategies without sacrificing the occupant comfort or leasable area.

Tall building response to wind loads is a complex issue determined by combined effects of wind climate, aerodynamic characteristics of building shape and structural system arrangement (Cammelli, Burrgereit, Keliris and Sefton, 2012). In this literature review, recent studies on aerodynamic modifications, especially wind escape floors (openings), are examined. Besides, state-of-the-art researches on structural systems as well as their member arrangements and corresponding effects on architecture of tall buildings are briefly introduced.

Günel & Ilgın (2014) state that in order to mitigate wind induced respond of a tall and slender building with the aim of improving building performance against wind loads, there are three approaches are used;

- ✓ Architectural design approach: aerodynamic-based and structure-based design.
- ✓ Structural design approach: shear-frame, mega-column, mega-core, outriggered-frame and tube systems.
- ✓ Mechanical design approach: auxiliary damping systems.

The relationship between aerodynamic characteristics of a building and resulting wind-induced excitation level has been studied by many researchers (Melbourne & Cheung, 2001; Dutton & Isyumov, 1990; Miyashita, Katagiri, Nakamura, Ohkuma, Tamura, Itoh, Mimach, 1993; Karim & Tamura, 1996; Kikitsu & Okada, 2003; Bekele, 2005; Irwin, Kilpatrick, Frisque, 2008; Holmes, 2011; Tanaka, Tamura, Ohtake, Nakai, Kim, 2012; Li, Q.S., Chen, Li Y.G., 2013). Aerodynamic modifications on a tall building could significantly reduce the wind induced dynamic response both along wind and across wind directions (Poon *et al.*, 2004). Besides, improved building performance can reduce the cost, and carbon footprint of the structure, too as well (Menicovich, Vollen, Amitay, Letchford, DeMauro, Rao, Dyson, 2012).

Melbourne & Cheung (2001) state that a tall building responses differently against across-wind and along-wind motions. Figure 2.1 represents wind response directions of a building where along-wind direction is parallel with wind flow. Contrary to that, cross-wind direction is perpendicular to the air flow. Both of motions have resonant response, yet across-wind motion resonant response usually dominates the design process due to the torsion created on the structure which's response is shear forces on structural members.

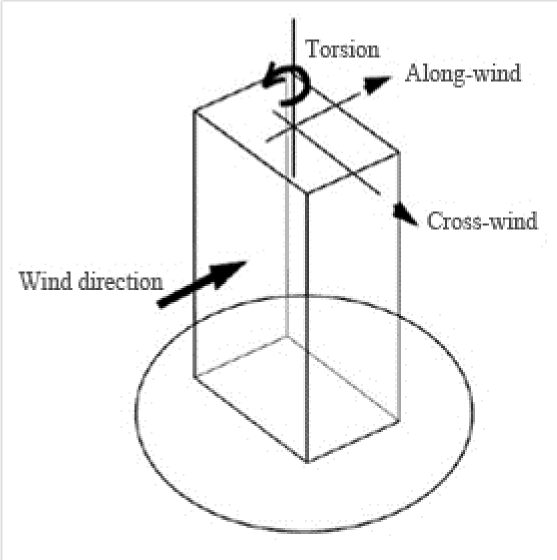


Figure 2.1. Wind response directions of a building (Melbourne & Cheung, 2001)

Reduction of across wind force spectrum could be provided by changes in building shape. For instance, circular plan schemes or square and rectangular shaped buildings with rounded corners could be designed. Tapered forms or doing setbacks up through the height of a building and also openings on the façade could be introduced to reduce shear forces formed on the structural members.

Figure 2.2 displays the cross wind response of tall buildings with respect to changing wind velocities. Irwin *et al*. (2008) underlined that the height of peak due to vortex shedding is sensitive to the building shape and with some aerodynamic modifications, that peak can be reduced, even be eliminated. Usual approach for limiting the building response is increasing the stiffness or damping properties which can be extremely expensive, yet inadequate.

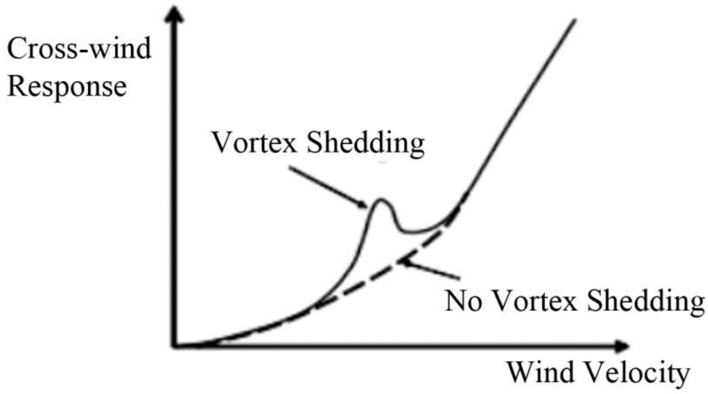


Figure 2.2. Effect of vortex shedding on response (Irwin et al., 2008)

2.1.1. Building form and corner modifications

In order to understand form effects on aerodynamic forces, flow around the body must be explained briefly. A bluff -body can be described as a body which creates separation in the flow at the leading-edge corners in contrast to streamlined bodies such as air craft wings and yacht sails. A rectangular sectional box (a typical bluff body) as shown in Figure 2.3 (b) creates a separated flow around the body and vortices are occurred at the points of reattachment which is called free shear layer. Contrary to that, flow patterns around a streamlined body (an airfoil) represented in Figure 2.3 (a), closely follows the conturs of the body and the separation from the airfoil surface occurs only in a thin boundary layer similar to free shear layer in bluff bodies, but not attached to the surface. (Holmes, 2015)

Holmes, (2015) indicates that concentrated vortices are formed in the wake. As represented in Figure 2.3 (b) reattaching separated shear layers on to surface of a bluff body is failed with vortices which are not stabilized and end up with rolling down to wake region.

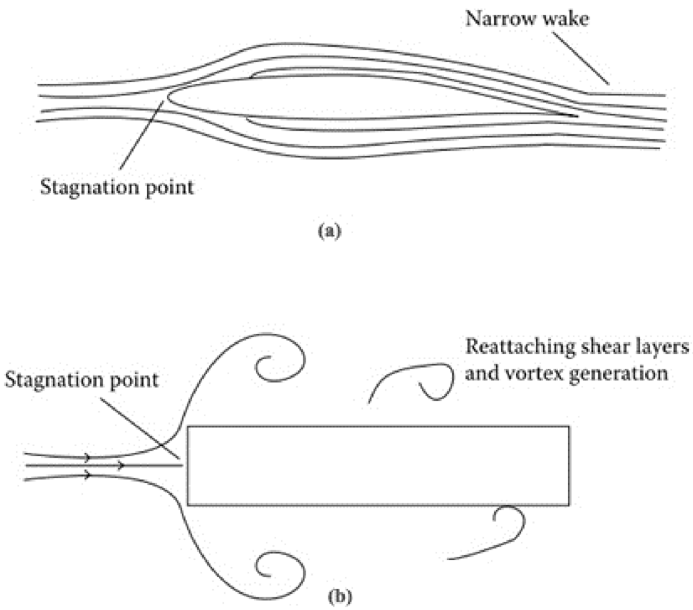


Figure 2.3. (a) Flow around streamlined and (b) bluff bodies (Holmes, 2015)

Günel & Ilgın (2014) states that cylindrical, elliptical, conical and twisted forms are aerodynamically superior since they are significantly effective in responding wind induced loads. Günel & Ilgın (2014) referred to Davenport's study (1971) where they showed that maximum lateral drift value of a building with square shaped plan is nearly two times bigger than the building with a circular plan given that both of these model buildings have about 70 stories. Similarly, a building with a rectangular plan has 20% more wind load according to a building with circular plan. (Taranath, 2005) Calatrava's Chicago Spire (never completed) and Burj Khalifa in Dubai are examples of tall buildings using aerodynamic form in plan schemes.

Reducing plan area toward the top of the building is another strategy for mitigating wind forces. In order to provide this reduction, using setbacks (Willis Tower) or tapering (John Hancock Center) is two ways (Gunel & Ilgın, 2014). Studies on this topic showed that 10 to 50% improvement in lateral drifts could be achieved in this way (Schueller, 1977; Irwin et al.,2008). Figure 2.4 depicts 6 super tall (+300) buildings and mega tall (+600m) Burj Khalifa as examples of buildings with aerodynamic modifications such as tapering and setbacks.

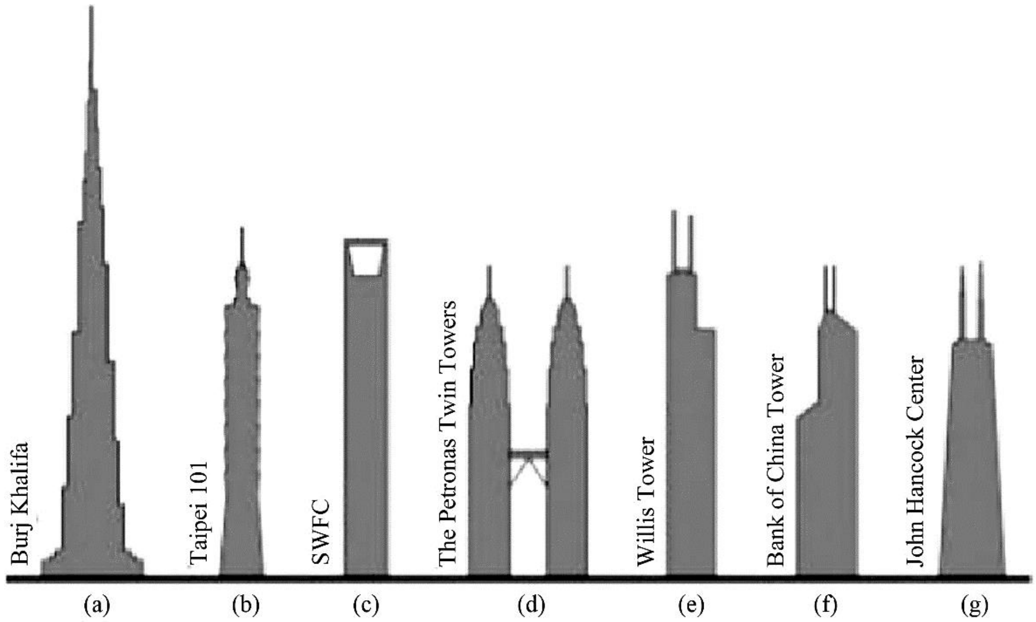


Figure 2.4. Some examples of buildings with aerodynamic modifications such as tapering and setbacks (CTBUH, 2016)

2.1.2. Wind escape floors

Using wind openings is another approach for reducing the wind loads by allowing the wind flow through the building. By this way, the formation of vortex shedding gets disrupted and become weakened in a desired way (Irwin, 2009).

Dutton and Isyumov (1990) investigated different vertical gap widths on cross wind response of square cross section tall building. The results showed that openings near the top reduce the vortex shedding effectively. The effectiveness of vortex shedding disruption varies with the width. Large reductions are observed for openings as small as 4% of building width. Miyashita *et al.* (1993) studied on the effects of openings with 25% breadth on square prisms in wind tunnel. Results showed that fluctuating wind force coefficients along across wind are reduced quite compared to square plan. Okada and Kong (1999) observed that even very small openings of 1.5% on each side of four walls significantly reduce the across wind dynamic deflection by about 20-25%. Kiktsu & Okada (2003) examined the openings for open passage configurations in vertical positions and section configurations. Figure 2.5 demonstrates the elevations of three models used in the study with belonged plan dimensions, where “B” represents the width; “D” is used for “depth” in the right. The section variations are given in the below part. Kiktsu & Okada (2003) denote that the building’s reference height (H) is 300 m in full scale, where the openings are located at 0.6H, 0.7H, 0.8H and 0.9H height throughout the building respectively. Authors concluded that sections which have along wind open passages as section A and C, presented in the Figure 2.5 improve the aerodynamic damping effects contrary to section B in Figure 2.5 which opening is in across wind direction. Furthermore, 0.8H-0.9H is the most effective for reducing the wind forces; whereas, 0.6 reference height tend to have adverse effects in case of open passages.

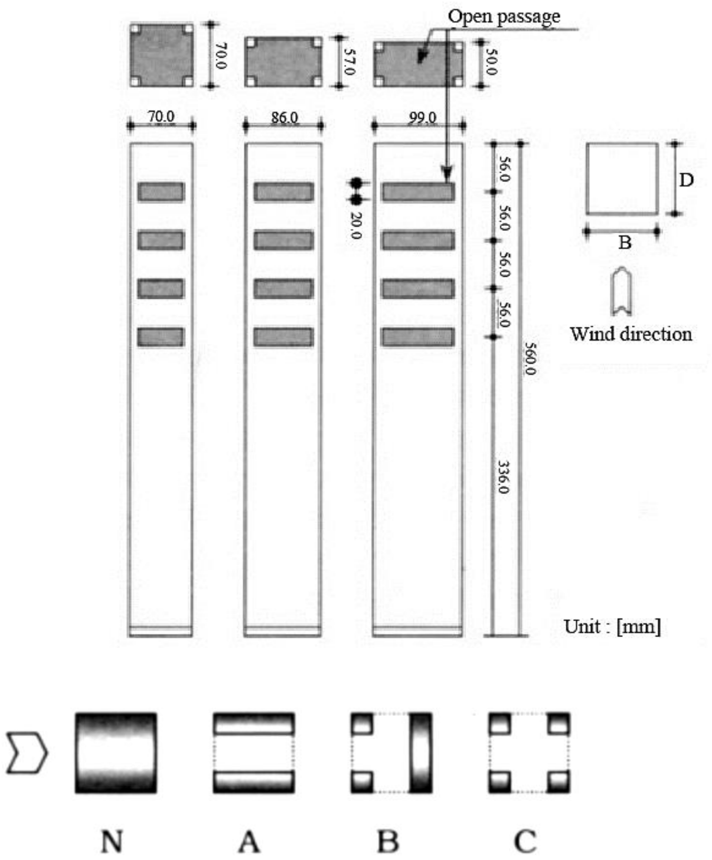


Figure 2.5. Open passage configurations vertically and section configurations (Kiktsu & Okada, 2003)

Bekele (2005) made a research on base opening geometry effects on tall buildings. The author investigated three opening sizes (20, 25 and 30 square meters) and three opening geometries through the base of a 200 meter height tall building modeled with a scale of 1:400 for determining torsion and overturning moments. According to the results, the model having a base and top opening (see Figure 2.6) showed 25% less deflection whereas 10-20% improvement has been achieved by other models with openings at the base.

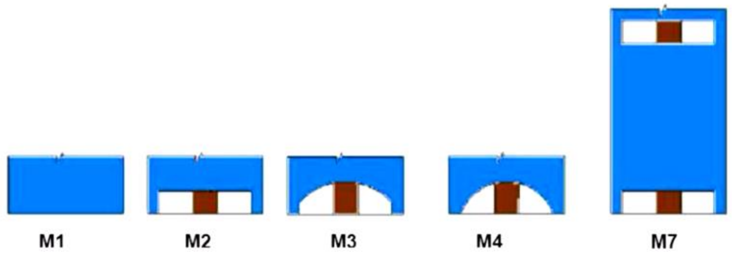


Figure 2.6. Test models with different opening size and shapes (Bekele, 2005)

Recent trends in tall building design differ from traditional designs that mainly rely on orthogonal forms. Since free style, unconventional and irregular forms with complex designs are quite popular, wind pressures and forces acting on these forms attract more attention lately. As an initial attempt of this, Tamura, Tanaka, Ohtake, Nakai, Kim (2012) have done a series of wind tunnel tests of building models with various configurations; setbacks, tapered, tilted, twisted, *etc*. Following this study, Tamura *et al*., (2012) investigated building models with openings in different sizes including oblique opening case as well (see Figure 2.7). The results showed that the opening with the h/H=11/24 ratio, where “h” represents the opening height, whereas H is total height of the building, have better aerodynamic behaviors compared to others investigated in the same study.

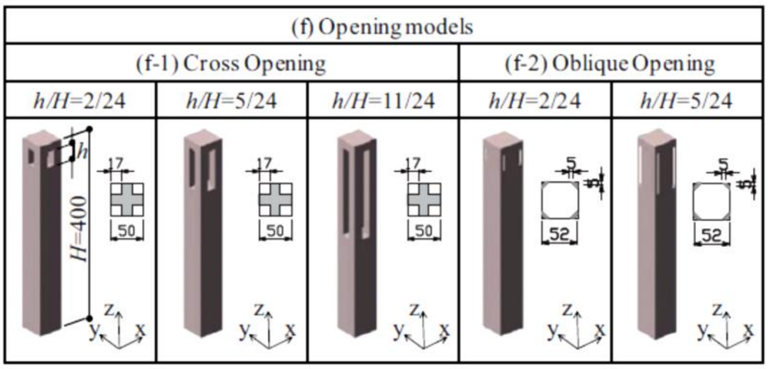


Figure 2.7. Opening models with different heights (Tamura et al., 2012)

To *et al.* (2012) showed that many of the through openings are at middle levels of the elevation of building for several reasons such as sky gardens, refugee floors etc. where the air can flow without blockage. Thus, they examined wind openings having two pattern configurations; one open in core, other open in perimeter, at the mid-height of a building (see Figure 2.8). The results in terms of *r.m.s.* loading coefficients and load in the across wind direction show that the opening along the perimeter of the floor is more effective in reducing across wind excitation.

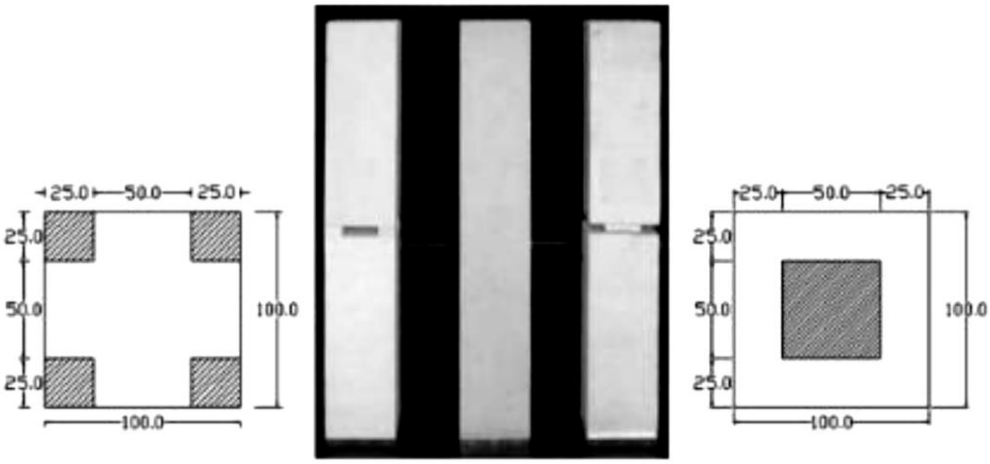


Figure 2.8. Building models with opening configurations (To et al., 2012)

2.1.3. Existing tall buildings with wind escape floors

There are four tall buildings, Wuhan Greenland Center in China, 111 West 57th Street building in New York, Pearl River Tower in Guangzhou and 432 Park Avenue Building in New York, having wind openings on certain floors. For super-slender tall buildings, since the size of structural elements inversely correlated with rentable areas, wind escape floor arrangements become a necessity rather than a design decision (Marcus, 2015).

Among super-tall buildings having wind openings, Wuhan Greenland Center used alteration of wind slots in several floors. It has 636 m height in designed project.

However, after the construction of the building started, the building height is decreased to 472 m and structurally topped out, by 2018 (Skyscraper center, September, 2018). The mentioned studies about Wuhan Greenland Centre are performed according to 636 meter height.

Fu, Betancur, Poon and Dannattel (2012) reported that, according to wind tunnel test data, building performance get increased in both principle directions by the use of wind slots. Besides, opening between dome and crown added to slotted floors shown in Figure 2.9(a) yield better results in design (Fu *et al.*, 2012). The further discussion on the building is given in Section 2.1.4

111 West 57thStreet (435.3m, under construction) building in New York has 1:24 slenderness ratio which makes it the slenderest tower in the world. Marcus (2015) states that, in order to provide improved acceleration response by as much as 12%, three wind escape floors are added to this super-slender tower (see Figure 2.9(b)). In this building, stories locating wind escape floors are different than the mechanical floor levels (See 2.1.4 for detailed information).

Pearl River Tower (309.4m) in Guangzhou has been completed in 2013. The designers of this building have an aim of achieving net zero energy building. Thus, the building has several features, including wind turbines, to produce its own energy. Wind turbines are integrated to the building in two levels of wind escape floors which also host outriggers. The aerodynamic shape of the Pearl River Tower shown in Figure 2.9(c) directs the wind into the turbine holes. Since the major aim is to increase the wind flow, i.e. the power generation, rather than to decrease the wind loads, the building is oriented toward strong wind direction, in contrary to the usual approach. Although this building does not use wind escapes for improving the aerodynamic performance, it still represents a good example for buildings having outriggers and openings (Frechette and Gilchrist, 2008) at the same floor level. This building differs from others with openings, thus it will be examined in part “2.3 Wind turbine integrated tall buildings.”

Similar to Pearl River Tower, 432 Park Avenue (425.5m) in New York has wind flow openings at outrigger floors which also partially used for mechanical equipment. The structural system of this super-slender can be named as framed-tube system. In this building, outriggers were used at certain levels to increase the performance of framed-tube system for wind loads. This super-slender building shown in Figure 2.9(d) has 1:15 slenderness ratio and similar to 111 West 57th Street the major aim of having wind escape floors is to reduce the wind demands. There isn’t any aerodynamic modification in the form of the building, as this is the design decision of the architect, Rafael Vinoly. Marcus (2015) claimed that this super-slender tall building necessitates a comprehensive design approach containing both wind escape floor optimization at outrigger levels as well as tuned mass dampers. As this building is chosen for sample building of this thesis study the detailed explanation will be given in Section 2.1.4.

(a) **(b)** **(c)** **(d)**

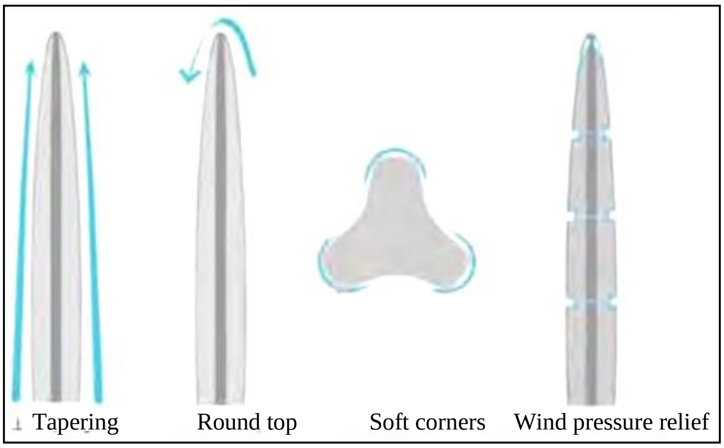
Figure 2.9. (a) Wuhan Greenland Center, (b) 111 West 57th Street, (c) Pearl River Tower, (d) 432 Park Avenue (courtesy of The Skyscraper Center /CTBUH)

2.1.4. Aerodynamics and structural systems of tall buildings with wind escape floors

As mentioned before, there are few examples built with wind escape floors. In this part, those buildings will be scrutinized for enhancing relationship between openings and structural systems and discussing this study on to that understanding. Hence, this thesis examines the interaction between that components and optimization process.

I. Wuhan Greenland Center, China

Figure 2.10(a) depicts Wuhan Greenland Center. This tall building is located in Wuhan, China. It is estimated finish date is 2019 with its 636 meter architectural height. However, the project height is updated after the construction starts and structurally topped out by the year of 2018. Its structural system is outrigger frame system with composite structural elements. It is mixed used building and has 125 storeys. Aerodynamic design of the building with soft corners tapered building shape, triangular plan and round top reduces wind induced top drift of the building (Wimer, Baker, Nagis and Mazeika, 2012). It is denoted that four massing concept (tapered form, round top, triangular floor plans with soft corners and vent slots) applied to building design have an impact on reducing structural elements material quantity with minimizing negative wind effects and decrease the cost significantly. (Fu *et al.*, 2012)



(a) **(b)**

Figure 2.10. (a)Wuhan Greenland Center, (b) Architectural building massing concept (Fu et al., 2012)

Three massing options are tried for better results in wind load response. The building is in tapered form for all three options. In option 1 the solid surface, in other words, without openings model was tested. In option 2, the vent slots and top opening between crown and dome was applied. Option 3 is featured wing walls and vertical slots (Fu *et al.*, 2012).

Table 2.1. *Wind load response for different massing options (Fu et al., 2012)*

Option	Wind Load: X Direction			Wind Load: Y Direction		
	Force	Overturning Moment (KN-M)	Relative Value	Force	Overturning Moment (KN-M)	Relative Value
Option 1	8.24E+04	2.62E+07	100.00%	6.95E+04	2.32E+07	100.00%
Option 2	7.01E+04	2.32E+07	85.10%	6.49E+04	2.17E+07	93.40%
Option 3	7.58E+04	2.52E+07	92.00%	7.06E+04	2.37E+07	101.60%

Table 2.1 presents the results, and it shows that Option 2 reduces the overall wind load 15% and 6.6% along “X” and “Y” direction, respectively. On the other hand, Option 3 do not significantly change the results. Fu *et al.* (2012) highlights that opening created the top between dome and crown helps decreasing wind loads acting on the building. Additionally, these openings serve as building maintenance unit with window cleaning machine for the envelope. Thus, the non-occupancy floor as the wind escape floor is brought in practical use.

On the other hand, the structural system of Wuhan Greenland Center comprises of four composite columns, and secondary steel columns at the perimeter of the building. Three storey height two steel outrigger trusses and two storey height one outrigger truss are located throughout the building height. Additional to the belt trusses at outrigger levels, there are 7 more at certain levels. Taghizadeh and Seyedinnoor (2013) state that belt trusses and outriggers through floors are used for increasing structural efficiency. However, the outrigger and belt truss floors are located either at refuge floors or mechanical floors specifically not to lose leasable areas. Building’s slabs have a tendency of buckling in xy plane due to Y shaped plan scheme under lateral loads. In order to prevent this, braces presented in Figure 2.11 are added to slabs horizontally at the below and above stories of belt truss floors.

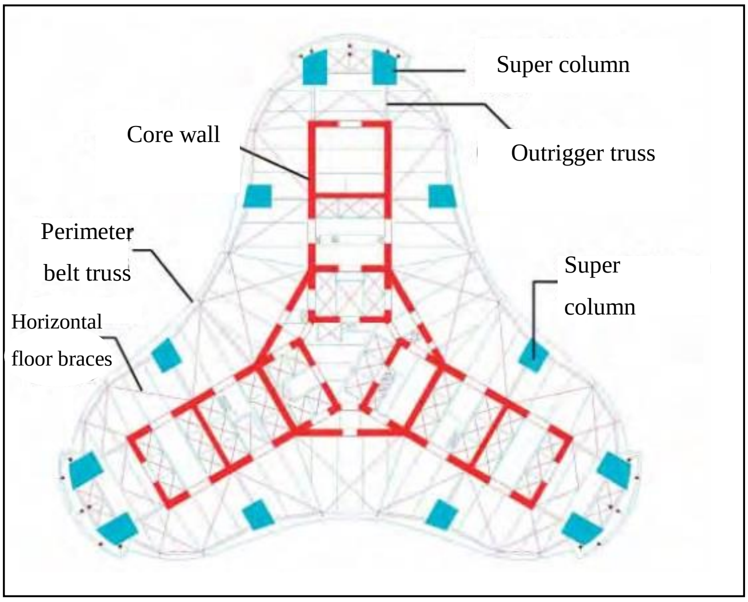
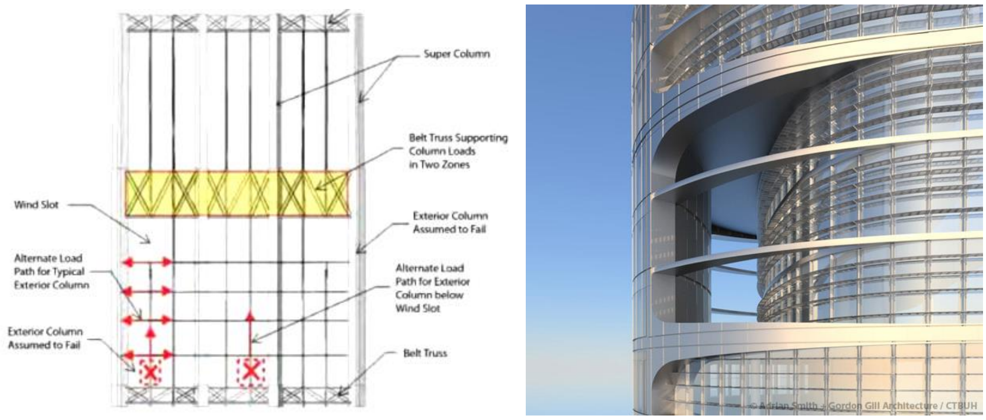


Figure 2.11. Structural system of Wuhan Greenland (Fu et Al., 2012)

The locations of vent slots are optimized in wind tunnel testing process in order not to impact structural system continuity. The engineers of the building designed a secondary load path for improving structural safety. If the exterior super column fails, the floor beams can transfer it to steel secondary columns due to vierendeel frames located in front of the vent slots. It is also asserted that belt trusses are located above vent slot floors for the same reason. (Fu *et al.*, 2012)

The vent slots have vierendeel frames as shown in Figure 2.12 (b) which have relatively less structural efficiency compared to belt trusses. However, these vierendeel frames have an important role to transfer loads to perimeter columns and adjacent belt trusses in failure progress (see Figure 2.12(a)). Note that, conventional trusses with diagonal elements as used in belt truss stories obstruct the wind flow inside the slot. However, if belt trusses or vierendeel frames were not used in these floors, structure's strength would be reduced and building is impacted negatively in terms of top drifts. (Fu *et al.*, 2012)

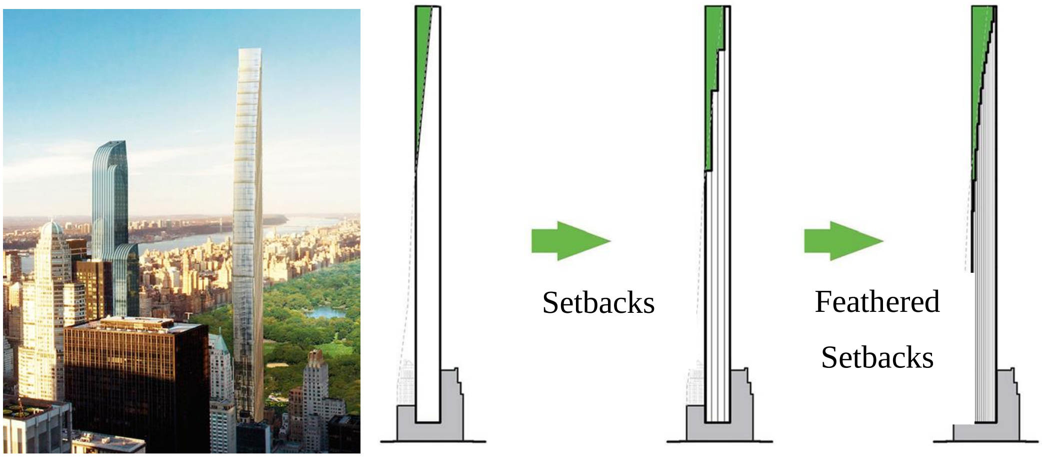


(a) **(b)**

Figure 2.12. (a) Progressive collapse analysis of perimeter frame (Fu et al., 2012), (b)Vierendeel frame located in front of vent slots (www.skyscrapercenter.com)

II. 111 West 57th Street Building, New York

111 West 57th Street Building in New York by Shop Architects is the slenderest tower in the world with its 1/24 slenderness ratio. The construction began in 2015 and estimated finish date is in 2019. The condominium is located nearby the Central Park and contains 58 dwelling units. It is the second tallest residential building with residential building use and has 438.3 m architectural height with 80 floors above ground. The basement area is 29.357 m^2 (Skyscraper Center, September, 2018).



(a) **(b)**

Figure 2.13. (a) 111 West 57th Street Building, (courtesy of CTBUH)
(b) Design Concept (Massing strategy)
(http://www.skyscraper.org/EXHIBITIONS/SKY_HIGH/111Shop.php -November 2016)

This super tall building is on adjacent site of Steinway Hall Building which was designed in 1955 by Warren and Wetmore. The architect of 111 West 57th Street Building states that this original landmark building has to be preserved carefully. Thus, the entrance of the tower is designed with glass panels and setbacks. Therefore the initial form generation process originates in “setbacks”. In order to emphasize the massing concept, later stages of its design, it is become feathered, eliminated approach of setbacks. As a result, 111 West 57Th Street Building so much gently tapers up into sky with feathered setbacks on the north façade. Figure 2.13(b) present the massing strategy of the building.

In 2017, Silvian Marcus, the structural engineer of the project states that structural system of the building is designed to resist lateral movements of the building. Also, he denotes that slenderness ratio (the ratio of the height to the narrowest width of a building) higher than 7 is called super slender and this building slenderness ratio is 1:24. Thus, in this slenderness ratio, the building gets more flexible and have higher period than normal values. Building generalized mass and shape have an important role while resisting lateral loads such as wind. Acceleration is inversely proportional to mass. If the force is pegged, increasing mass leads a decline on acceleration. Therefore, dynamic movement of the building is minimized and occupant comfort is improved by this way.

Besides, wind load response of building changes with the form of building, as mentioned in section 2.1. Wind induced dynamic movement is less in the tall buildings with aerodynamic modifications or having aerodynamic forms than buildings which do not have aerodynamic designs. In order to provide serviceability and occupant comfort with maximum space utilization and efficient construction criteria, structural system of the tower is organized by punched shear walls in east and west side whereas, columns are used in north and south sides, not to obstruct central park and city center panoramas. Figure 2.14 presents plan of the structural system of the 111 West 57th street building.

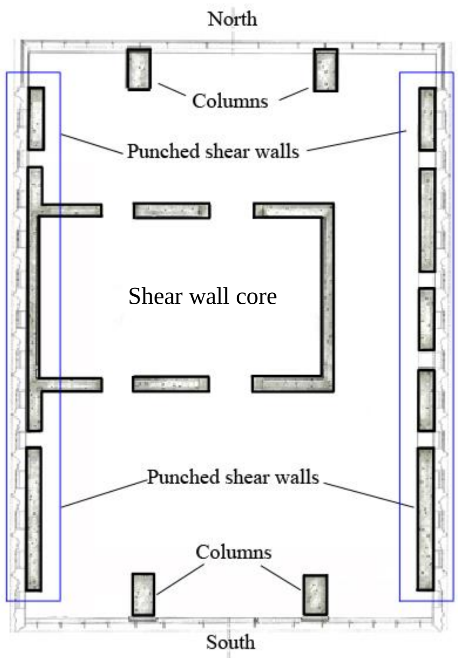
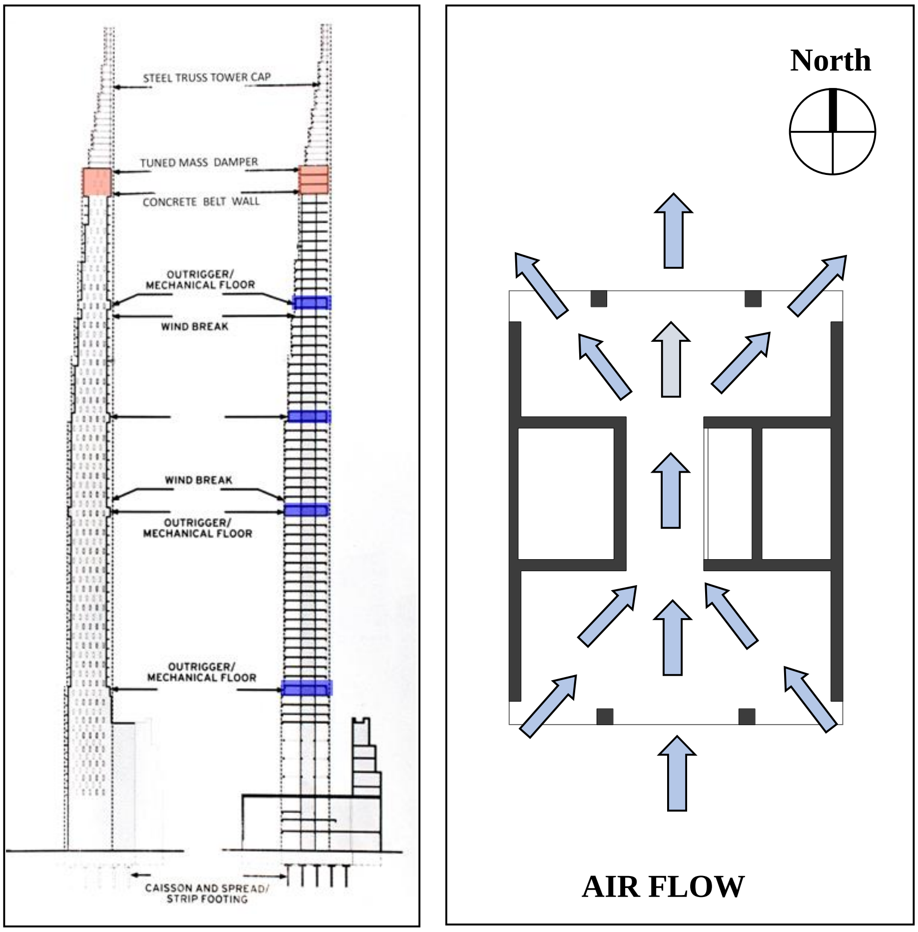


Figure 2.14. Structural plan from middle floors (https://www.6sqft.com/revealed-new-rendering-for-111-west-57th-street-shows-ethereal-views/ - November 2016)

Marcus (2017) indicates that those kind of slender building's design process is dominated with 4 main topics; Rigidity which means stiffness, generalized mass (weight), natural damping as well as auxiliary systems and lastly porosity or confusing the wind. As enumerated reasons above, the structural system is stiffened with outriggers located in mechanical floors. There are 4 mechanical floors arranged with outriggers in Figure 2.15(a). Also, there is one tuned mass damper (TMD) near the top of the building to decrease lateral movement.



(a) **(b)**

Figure 2.15. (a) Location of outrigger/mechanical floors and TMD on west section of the building in first proposal (Architectural Record, April 2014, p.141) (b) Wind escape floors scheme on upper floor plan (111 W. 57th St: Architects' on the and Engineer's Presentations at https://www.youtube.com/watch?v=lIy2HPTCz3g&t=2997s – March 11, 2014)

In order to let air flow through the building, 4 wind escape floors are composed. Those floors help minimizing the building acceleration. Air flow scheme is shown in Figure 2.15(b) and locations of the wind escape floors highlighted with blue lines are seen in Figure 2.15(a). The architect of 111 West 57th Street Building indicates that location of the wind breaks is specially organized with outrigger/ mechanical floors or refugee floors in order to maximize leasable space. Silvian Marcus (2017) denotes that the spire, steel truss tower cap is also having a significant role to reduce acceleration due to lateral movement. Rowan Williams Davies and Irwin (RWDI) Consultant Company perform the wind tunnel tests of the building and wind consultant corroborates the explanation done by Silvian Marcus (2017), structural engineer of the project.

III. Pearl River Tower, Guangzhou

Pearl River Tower (as shown in Figure 2.16(a)) is located in China, Pearl River New Town, Guangzhou. This tower has 71 stories with a height of 310 meters and it is designed by Skidmore, Owings and Merrill LLP. The construction of this office building finished in 2013. RWDI is wind consulting firm of the Pearl River Tower.

The tower is designed for being the most sustainable tall building in the world. In order to achieve this aim, integrated photo voltaic panels, daylight responsive controls, daylight reflectors, high efficiency lighting, radiant cooling coupled with under floor air ventilation, high efficiency chiller system and so on. Beyond other sustainable design decisions, it hosts four vertical axis wind turbines (VAWT) in two different levels which are mechanical floors. The tower is first with harnessing wind turbines onto a single tower in different levels. (Li *et al.*, 2013) Further discussion on wind turbines integrated buildings will be held in section 2.3

(a) **(b)**

Figure 2.16. (a) Pearl River Tower, (b) Construction photo of the tower (https://vula.uct.ac.za/wiki/site/d0b9b4ca-4293-46c0-bae9-c01cdb19e88b/construction%20gallery.html)

Lateral load resisting system of the tower is designed to resist both seismic and wind loads. Tomlinson, Baker, Leung, Chien and Zhu (2014) state that dual structural system is applied to the building; the primary system is reinforced concrete shear wall core is connected to perimeter columns with outriggers and belt trusses in certain floors. Composite mega columns at the corners are linked by end bracings (see Figure 2.16(b)). Tomlinson *et al.* (2014) note that closed form of core with varied shear wall thickness from 700 to 1.500 millimeters throughout the height give extra stiffness to building and increase resistance to torsion forces.

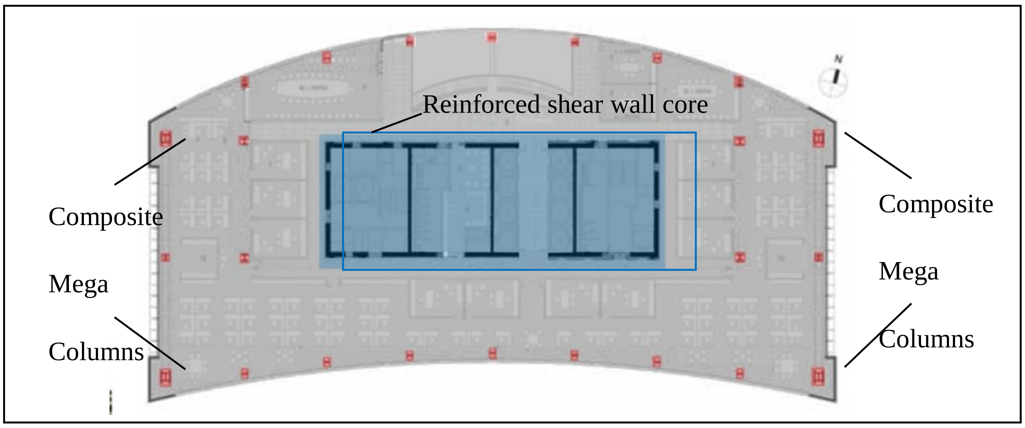
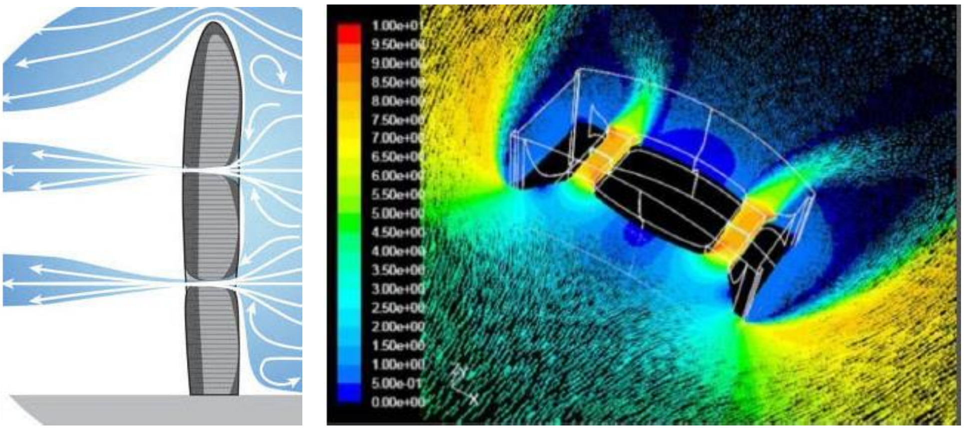


Figure 2.17. Structural layout of typical floor plan (Tomlinson et al. 2014)



(a) **(b)**

Figure 2.18. (a) Concave shape of wind holes in section diagram (b) Wind velocity vectors at mechanical floor (Frechette et al., 2008)

The openings are designed as bell-mounted shape holes for increasing air flow through opening and thereby the power generation efficiency. The vertical axis wind turbines are worked effectively even in prevailing winds. Frechette & Gilchrist (2008) remark that these openings are pressure relief valves of the building. Reducing surface area is inversely proportional to pressure, too.

Figure 2.18(b) presents air flow around the Pearl River Tower at mechanical floor with colored wind velocity vectors. Wind velocity within the openings as indicated with orange vectors in Figure 2.18(b) is increased, whereas the leading edges at the corners in the windward direction (direction where the wind is coming to the object) of the building have relatively less wind velocity, presented with turquase and green vectors in the same figure due to the bell-mouth shaped openings and form of the mechanical floor plan. Frechette & Gilchrist (2008) indicate that building façade is designed for optimizing wind velocity passing through openings and reducing drag forces by capitalizing pressure difference at windward and leeward sides (other part of the object which is on the opposite side).

IV. 432 Park Avenue Building, New York

432 Park Avenue Building which is located in New York, nearby the Central Park is designed by Rafael Vinoly Architects and structural engineering works done by WSP Cantour Seinuk (Skyscraper Center, September, 2018). It has 85 floors above ground and 425. 7 m height. The building is the second slenderest building in the World with a slenderness ratio of 1/15 (Willis, 2016). This residential tower is finished in 2015 (Skyscraper Center, September, 2018).

Rafael Vinoly (2014) indicates that in his lecture speech that the architectural idea behind 432 Park Avenue is a simplified Hoffmann Box which is designed by Josef Hoffmann, an Austrian architect and designer, lived in 19th century. Hoffmann studied on formulating the aesthetics and theory of modernist design (Johnson, 2016). Many of designed objects are based on the square and industrial metal square grid was used in his designs to manufacture many different objects as fruit baskets, garden planters under the effect of modernism (Education resource of Vienna Art and Design Exhibition, 2011). Figure 2.19 (b) demonstrates a trash bin which is manufactured with industrial metal grid as an example of Hoffmann objects.

Hence, the square grid is created by using structural members such as columns, beams and non-structural member as glass and openings in 432 Park Avenue Building to make a pattern on façades so as to emphasize the effect of Hoffmann's object as seen in the Figure 2.19.

(a) **(b)**

Figure 2.19. (a) 432 Park Avenue Building (www.skyscraper.com), (b)A trash can designed by Josef Hoffman (https://cdn.archpaper.com/wp-content/uploads/2015/06/432-park-avenue-and-josef-hoffmann-trash-can.jpg)

Due to high slenderness ratio, the core is relatively small to that height and there are no columns in used space except perimeter ones. Framed-tube system with high strength reinforced concrete and outriggers in certain floors with wind openings can be outlined as structural system of the building. Beams and columns constitute the outer tube, while 2 foot (60.96 cm) thickness core creates the inner tube. (Nasvik, 2015)

According to Seward (2014) the plan layout is 28.40 to 28.40 meters square from begin until end (including columns). The corresponding dimension of all columns at façade is 111.8 cm, whereas their depths varies from 162.6 cm at the bottom to 50.8 cm at the top (Nasvik, 2015). Floor to floor height is 4.72 meter with a slab thickness of 25.4 cm. Exceptionally, near to top floors slabs are 45.72 in order to increase building mass. Leslie E. Robertson Associates (LERA) peer review (2011) for structural and wind engineering topics, corroborates that building stability is increased due to the mass increase.

Figure 2.20 presents the structural plan scheme of an upper floor. Note that corner columns are different shaped from rectangular ones. The depth of the columns is increased throughout the building height. In order to keep façade pattern same, the corner columns get deeper diagonally different then columns located in x and y axis. The same principle is used in perimeter column dimensions. For instance, the column dimensions are 163 x 112 cm for the perimeter columns located in east and west sides, whereas 112 x 163 cm dimensions are used in the columns at north and south sides.

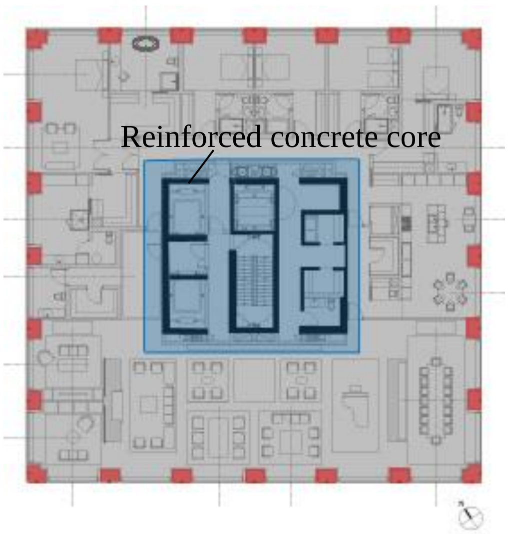
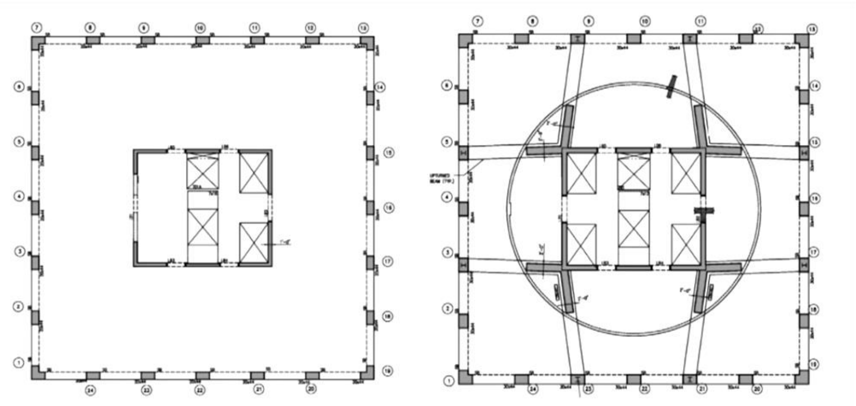


Figure 2.20. Structural plan of 432 Park Avenue Building (Image is retrieved from http://www.ctbuh.org/TallBuildings/FeaturedTallBuildings/FeaturedTallBuildingArFeatu2016/432ParkAvenueNewYorkCity/tabid/7394/language/en-US/Default.aspx)

Nasvik (2015) states that in 432 Park Avenue Building, Grade 97 rebar is used for reinforcement instead of grade 60 to reduce congestion. Additionally, high compressive strength is provided by using 14.000 psi (96.52 MPa) concrete with 7.7

megapounds/square inch (msi) (53080 MPa) modulus of elasticity. It is denoted that concrete strength varies with building height. Concrete strength is 14.000 psi (96.52 MPa) from ground level up to 40th floor, 12.000 psi (82.73 MPa) from 41th to 51th floors and 10.000 psi (68.94 MPa) from 52th floor until the highest floor.

There are 5 sets of outrigger floors which host also mechanical equipment in drums. Those outriggers are double story height and reinforced shear walls are rise up till the drum and the rest is go through as a relatively deep beam at the top and floor plane. Marcus (2015) states that these outriggers are designed for letting the air flow inside, otherwise, outrigger members can block the flow. Figure 2.21 (b) illustrates mechanical floor plan of the building. The lines which are approximately perpendicular to the perimeter columns demonstrated in Figure 2.21 (b) are beam outriggers on the ground. Similarly, sheet metal usage called as drum around mechanical equipment is for creating streamlined bodies on the wind escape floors and also it protects the mechanical equipment located at those floors. A circle around the core describes drum and specifies the connection of beam outriggers with extended outrigger walls as seen in Figure 2.21(b) and Figure 2.22.



(a) **(b)**

Figure 2.21. (a) Typical Tower plan (b) Mechanical Floor plan (Silvian Marcus speech in Skyscraper museum, 2015)

(a) **(b)**

Figure 2.22. (a) Construction photo of outrigger/mechanical floor, (b) Outrigger floor with drum (images are retrieved from http://2015.ctbuh.org/tours/technical-tours/432-park-avenue/)

Besides, Silvian Marcus (2015) speech of CTBUH Conference states that 5 levels of double height outrigger stories have no windows. In other words, those wind escape floors, helps minimizing acceleration of the tower by preventing sail effect which is mentioned before. Marcus (2015) notes that the building has problem with 1 month return period acceleration and in order to address it, 5 opening were added to building. It reduces the acceleration 50%. According to LERA peer review (2011), slots located at two story height mechanical floors let the air flow inside and disrupt and weaken the vortices. By this way, it helps to reduce wind acceleration.

Additionally, LERA Peer Review (2011) compares the results of building period the in aeroelastic report which is final report of aeroelastic wind tunnel study, dated August 30, 2011 from RWDI and ETABS analysis in WSP (See Table 2.2).

Table 2.2. *Building Periods comparison (LERA Peer Review, 2011)*

Mode	Used in Aeroelastic Study	ETABS Analysis (from WSP Model)
1	13.55 s	14.01 s
2	13.11 s	13.42 s
3	3.42 s	4.17 s

Table 2.2 shows that the results are close each other except from mode 3 which gives period of torsional mode. There is approximately 20% discrepancy between two results. However, LERA (2011) reported that this discrepancy have no significantly change the conclusions made on structural system.

V. Visionary Towers with openings

Number of towers which are designed with wind escape floors is limited. Openings in certain floors of a slender and super tall building are applied in several towers. In this thesis, previous section is devoted to the constructed tall buildings with openings whereas there are other buildings that have been designed but never completed. These unconstructed towers can be also well organized and structurally and architecturally designed primarily. Thus, this part investigates visionary tall buildings with openings.

Sky Mile tower is an example which is proposed for Tokyo Bay in the concept of "Next Tokyo". Kohn Pedersen Fox Architects (KPF) collaborates with Leslie E. Robertson Associates (LERA) for designing the project components. "Next Tokyo" asserts a megacity which can deal with climate changes in 2045.

The coastal zone of Tokyo has low-elevation buildings which is vulnerable to seismic actions, rising sea levels and threat of typhoons. The project is for drawing attention to these vulnerabilities and proposes a new city scale. A water filled infrastructure network throughout the shore line is envisioned with island clusters. A mile high tower, in other words Sky Mile Tower is one of the facilities on the island to meet dense population accommodation and office needs in a small footprint area. (Malott, Hiei, Werner, 2015)

According to Skyscraper Center (2018) it is proposed with 1700 meter height which means if it has been constructed, it would have pushed the limits up for being tallest in the world after Burj Khalifa and Jeddah Tower which is planned for finishing in 2021. 55,000 tenants are envisioned to use the tower. Thus, a vertical network of segmented residential communities is necessitated. Those segments are linked together by sky lobbies in overlapping zones (See Figure 2.23(a)). Also, public amenities such as restaurants, hotels, shopping are offered in those segments. (Malott *et al.*, 2015)

(a) **(b)**

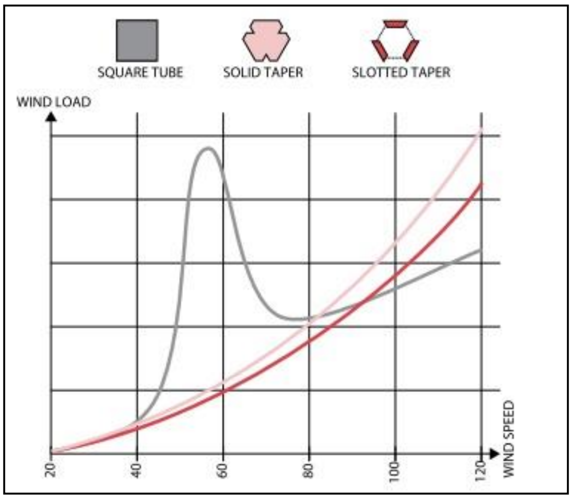
Figure 2.23. (a) Render of Sky Mile Tower, (b) Structural system of the tower with section (Images are retrieved from Courtesy of KPF)

Structural system of the tower is designed to minimize acceleration values and stresses occurred on the system imposed by the wind. Lateral load resisting system involves mega bracings on each leg’s inner parts and reinforced concrete shear walls placed onto sides. In the overlapping floors, large scale steel trusses which are plenary, connect the two sets and make the building movement unify. Relatively small perimeter columns carry the load of concrete slabs. Belt trusses placed within 30-40 story intervals support that perimeter block. (Malott *et al.*, 2015)

Malott *et al.* (2015) draw attention that wind is the most dominant criterion while designing a mega tall building. Even the code used in countries which is in active seismic regions, the design requirements for wind exceeds those for earthquakes.

The Sky Mile Tower is extremely tall, so its period is relatively long. In order to address it, exploratory wind tunnel process is applied to tower design. Tests are carried out on three models which are extruded square tube, a solid stepped and tapered form and a similarly stepped and tapered form with varied placed slots to allow the wind to pass through.

RWDI corroborates that square shape mass have 10 times bigger results in across wind dynamic response than slotted tapered form. The overall base loading of stepped and tapered forms with and without openings shows the same results. However, solid tapered form has 20% higher dynamic response and vibration compared to the model with openings (See Figure 2.24).



(a) **(b)**

Figure 2.24. (a) The primary tower models for wind tunnel testing, (b) Wind response of models (Malott et al., 2015)

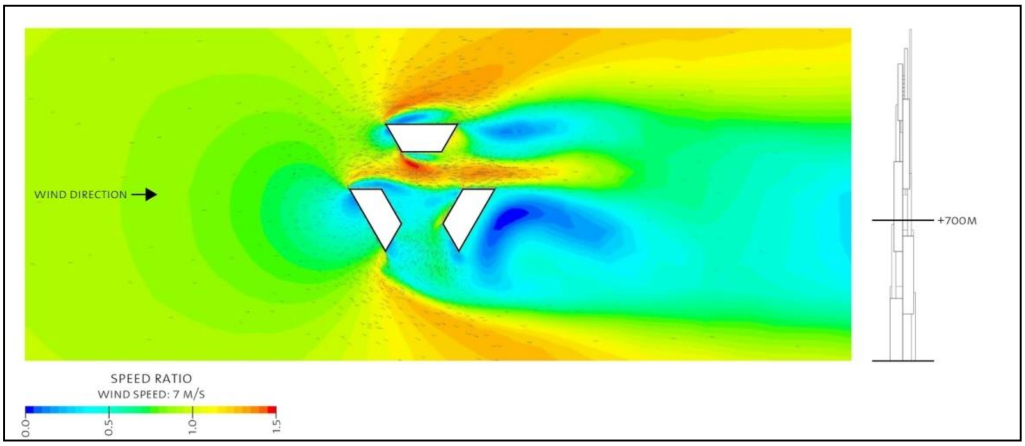


Figure 2.25. CFD analysis of Sky Mile Tower, RWDI (Image is retrieved from https://www.archdaily.com/780457/kohn-pedersen-fox-associates-plus-leslie-e-robertson-associates-next-tokyo-2045-masterplan-features-a-mile-high-skyscraper/569a931ee58eceddc6000077-kohn-pedersen-fox-associates-plus-leslie-e-robertson-associates-next-tokyo-2045-masterplan-features-a-mile-high-skyscraper-)

Computational Fluid Dynamics (CFD) analysis of the primary models was done by RWDI. Figure 2.25 demonstrates wind speed ratios at reference height of 700 m wind speed ratio have to be defined to estimate that amplifications. Wind speed ratio is the ratio of wind speed in a tunnel over at a reference height for 7m/sn wind speed with shown direction for the model with wind slots. As presented with orange areas in the Figure 2.25, the wind speed increases the windward side of leading edges, especially in the upper part. The right below part on lee ward side of the building, represented with blue colored area in Figure 2.25, have minimum wind speed ratio due to the angle of the mass and openings, too.

It is also denoted that vortices, occurred along-wind direction causes higher dynamic response which can be perceived by the occupants on higher stories. The model with vertical slots confuses the wind with allowing air flow through the hole and the results are more efficiently worked than models without wind slots in terms of wind disruption. (Malott *et al.*, 2015)

2.2. Wind turbine integrated tall buildings

Bahrein World Trade Center is the first example of integrating wind turbines on to tall building for harvesting energy. Those turbines generate the 11-15% of the energy needs of the building (Killa & Smith, 2008).

When completed in 2011, Pearl River Tower is expected to be the most energy efficient high-rise in the world since “net zero energy” concept led the design process of the tower. Integrating four vertical axis wind turbines on the openings of the building not only accommodates better aerodynamic performance due to the openings but also generates energy with accelerated wind loads through funnel formed openings (Frechette & Gilchrist, 2008)

Although Li *et al.* (2013) claimed that the most feasible way of power generation is on open sites compared to those on to or integrated with a building. Pearl River Tower, which is the first attempt of mounting wind turbines into wind openings, could be inspiring for further benefits of floor with openings.

A study about wind loads and wind speed amplifications are done by Li, *et al.* (2013). A rigid 1:150 model representing the Pearl River Tower has been used in wind tunnel tests. They have examined four cases as without wind turbines and surroundings, *w*ith surroundings but without wind turbines, *w*ith wind turbines and surroundings and with wind turbines but without surroundings. Among the cases, those with and without wind turbines has been shown in Figure 2.26.

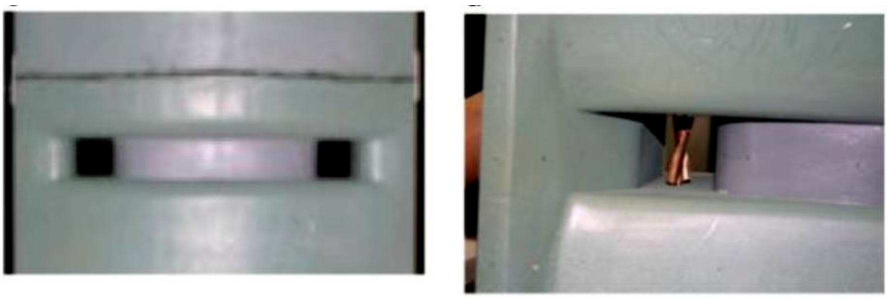


Figure 2.26. Local views of tunnels without/ with wind turbines (Li, et al., 2013)

Li *et al.* (2013) state that wind power is proportional to cube of wind speed and in order to know wind power, wind speed amplifications inside the tunnels are required to be investigated. For these models, the reference height is taken 10 m above ground.

The largest wind speed ratio of 3.5 was measured in tunnel 2 for the second case whereas the minimum wind speed amplification was observed in case 3 in all four tunnels since the openings has been obstructed by the turbines to some extent (Li, *et al.*, 2013).

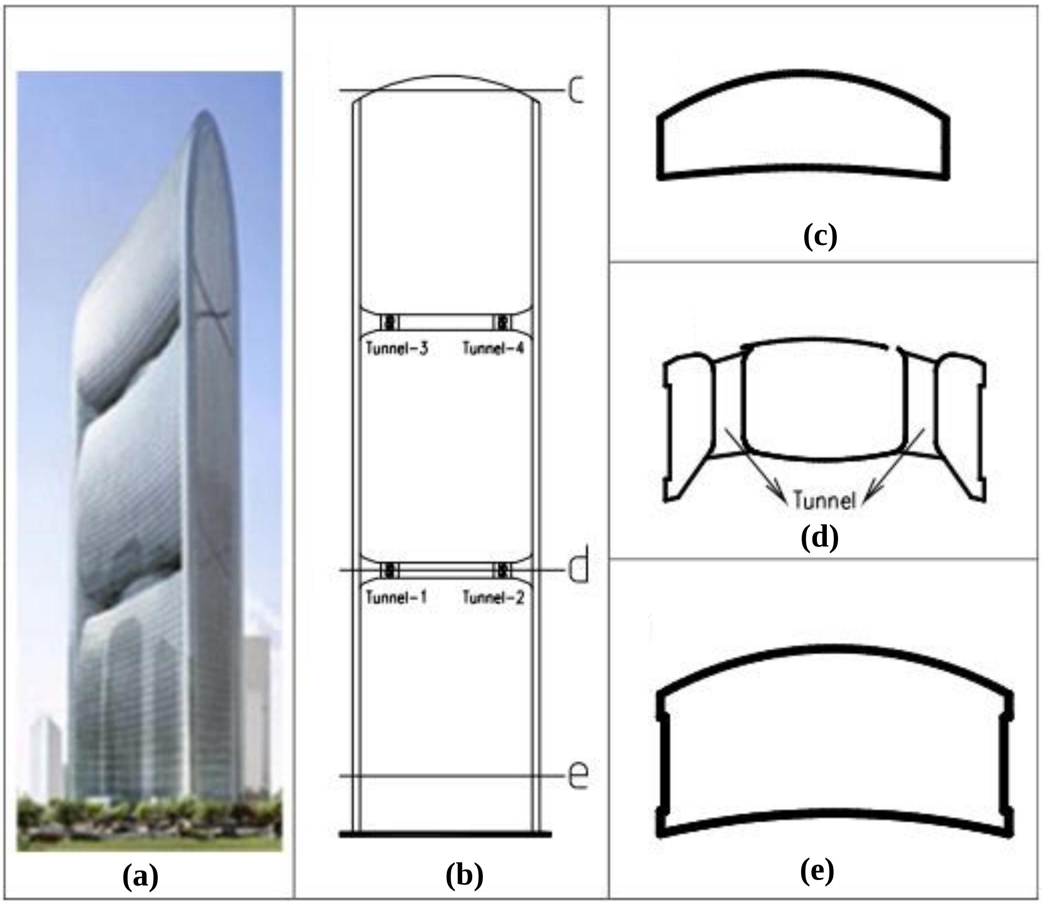


Figure 2.27. (a) Pearl River Tower, (b) Location of tunnels, (c) Plan form at height of 295m, (d) Plan form at height of 108m and 209.4 m with wind tunnels (e) Plan form at 51.3 m height (Li et al., 2013)

2.3. Structural design approaches used in tall buildings

Previous section is devoted to architectural approaches applied to tall and slender buildings to control wind induced building sway and fulfill the comfort requirements. In this section, structural design approaches such as outriggered frame and tube systems will be scrutinized.

Structural design approaches applied to tall and slender buildings can be listed as shear-frame, mega-column, mega core, outriggered frame and tube systems (Günel & Ilgın, 2014). However, the systems except from outriggered frame and tube do not response effectively to lateral loads in terms of rising height. In order to form an opinion on the topic the classification and development of structural systems will be explained in following section.

2.3.1. Classification of structural systems

Gunel & Ilgın (2014) mentioned that “the control of dynamic response of a tall and flexible building can be achieved by increasing the stiffness by the use of shear walled frame systems, mega column - mega core systems, outriggered frame systems or tube systems.”

In 1969, Fazlur Rahman Khan classified structural systems of tall buildings with respect to their heights considering the efficiency in the form of “heights for structural systems with concrete and steel” diagrams (Khan, 1969)(See Figure 2.28 and 2.29).

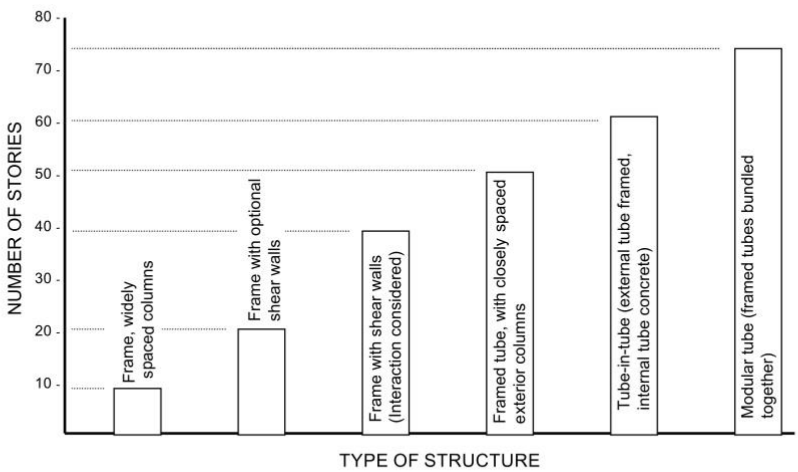


Figure 2.28. F. Rahman Khan’s structural classification of concrete (Mufti & Bakth, 2002)

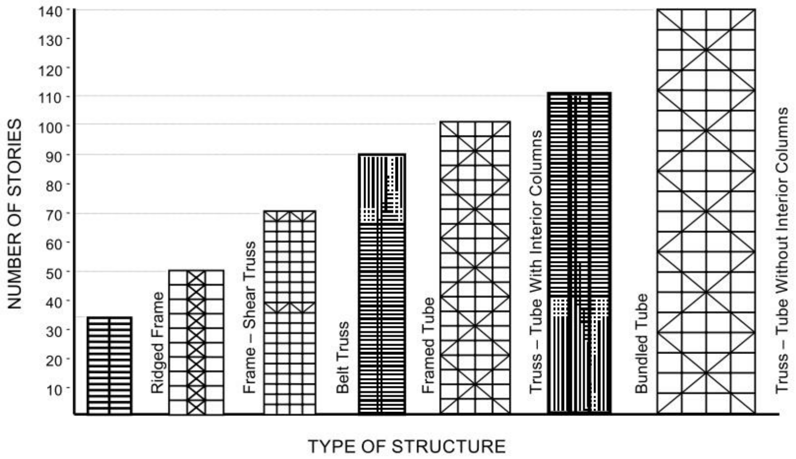


Figure 2.29. F. Rahman Khan's structural classification of steel (Mufti & Bakth, 2002)

These diagrams then developed by Khan, himself and several other researchers in different ways (Ali, 2001; Ali & Armstrong, 1995). Ali and Moon (2007) states that classification of structural systems related with height can be categorized into two; interior and exterior as a matter of lateral load resisting systems. The component's location which is used in the lateral load resisting system determines whether it is interior or exterior. Tube and super frame as exterior structure and outrigger frame system as an interior structure have maximum floor numbers in the sake of efficiency. (Ali & Moon, 2007)

Figure 2.30 and Figure 2.31 demonstrate the structural efficiency related to increased building height, which is classified for interior structures and exterior structures, respectively. Figure 2.30 represents the interior structures' structural systems with elevations and plans are showed below the belonged elevation. Outrigger structure works efficiently up to 150 floors above ground, whereas concrete shear wall and concrete frame work efficiently up to 70 floors. The interior structure capitalizes use of outriggers and over turning moment of tall building decrease. Therefore, improvement in building height, more than double times in floor numbers reached by concrete shear wall and concrete frame is succeeded due to outriggers. Space truss and steel braced tube with interior columns can reach 150 stories as exterior structures.

Super frame is exceeded that number with reaching 160 stories as shown in Figure 2.31.

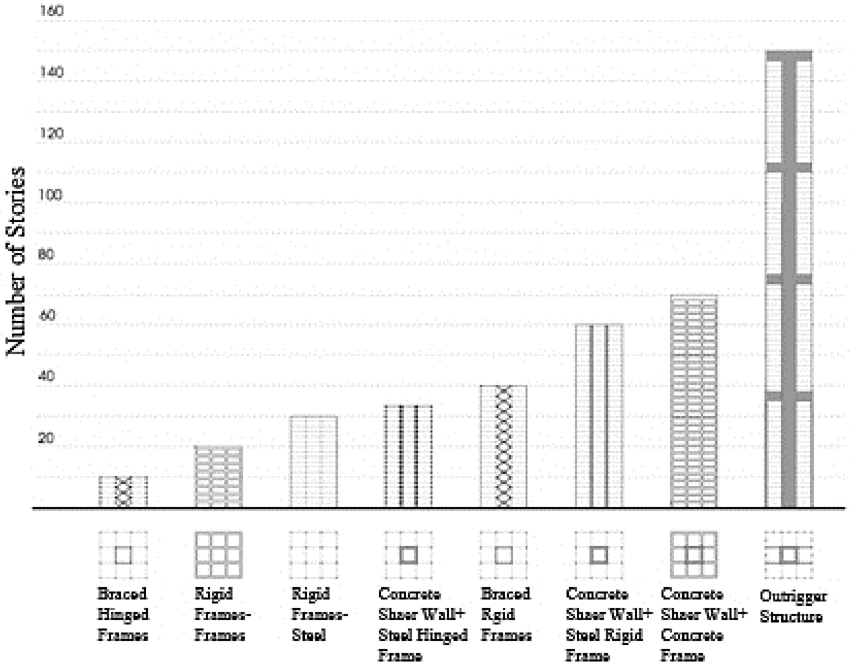


Figure 2.30. Interior structures (Ali & Moon, 2007)

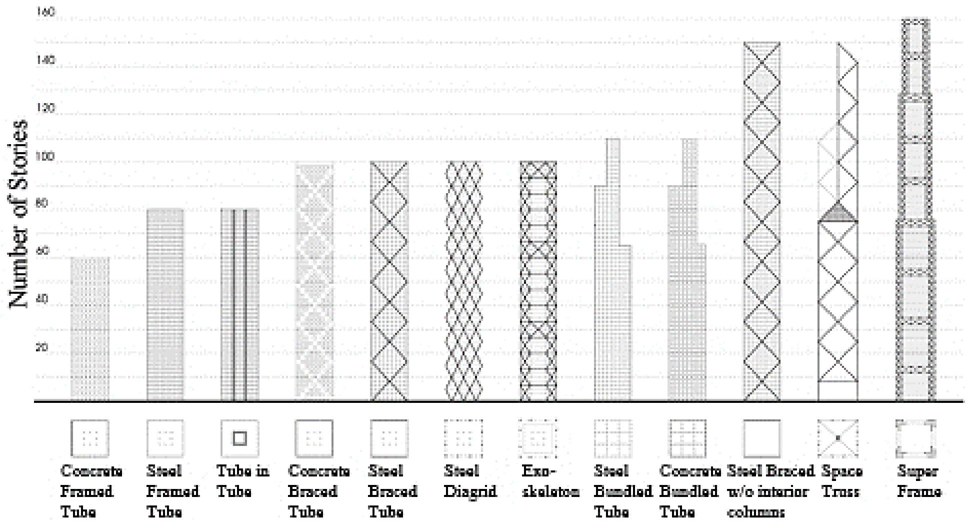


Figure 2.31. Exterior structures (Ali &Moon, 2007)

Another system classification is done by Günel and Ilgın (2014) about tall buildings structural systems and the number of floors they can reach efficiently and economically. Different than other studies, in this classification, authors define on one hand, “tall buildings” which have 40 storeys and below. On the other hand, “supertall buildings” and “skyscrapers” which have over 40 storeys. The structural systems defined by Günel & Ilgın (2014) are classified according to this division. Structures of shear frame systems, mega column systems, mega core systems, outriggered frame systems and tube systems are used for super tall buildings and skyscrapers for satisfying structural safety and serviceability (occupant comfort) with the constraints of maximum lateral drift limitation which is 1/500 of the building height. Rigid frame systems, flat plate/slab systems, core systems and shear wall systems are reached up to 40 floors, in terms of efficiency and economy. Table 2.3 demonstrates the systems with floor numbers they can reach.

Table 2.3. *Tall building structural systems and number of floors they can reach (Günel & Ilgın, 2014)*

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

2.3.2. Outriggered frame system and tube systems

As mentioned in section 2.3.1, outriggerred frame systems and tube systems are the most efficiently and economically worked system for limiting lateral drift of tall building and providing occupant comfort. Thus, these systems will be explained briefly in this section. Tube system is much conventional 3 dimensional façade structure which shows tubular behavior with building exterior members as a hollow box column cantilevered from ground. The whole building's perimeter resists lateral loads and this system is evolved from rigid frame systems (Günel & Ilgın, 2014). Super frame is composing of mega columns with braced frames at the corners linked with mega trusses. Outrigger frame system, which is defined as an interior structure in Ali & Moon (2007) study, is developed from shear-frame systems composed with core (core-frame systems), by an addition of outriggers to configure a couple with core and the perimeter (exterior) columns (Günel & Ilgın, 2014). Figure 2.32(a) presents core supported outrigger structure behavior under lateral loading. Those outriggers transfer lateral load from core to perimeter columns and resist bending moment with creating extra stiffness for the tall building. Axial tension and compression forces are corresponded by columns on two façades perpendicular to bending direction. Therefore, leeward side columns are under compression with a contraction as shown in Figure 2.32 (a) and columns at windward side are elongated due to tension, contrary to the other side (Günel & Ilgın, 2014). Generally, the outrigger stories have belt trusses around perimeter columns in order to prevent deformation on to structural members and to compose a stiff box in those floors. Nanduri, Suresh and Hussain (2013) indicates that storey drift does not significantly reduce with or without belt trusses of outriggers as cap trusses (located at the top of the building).

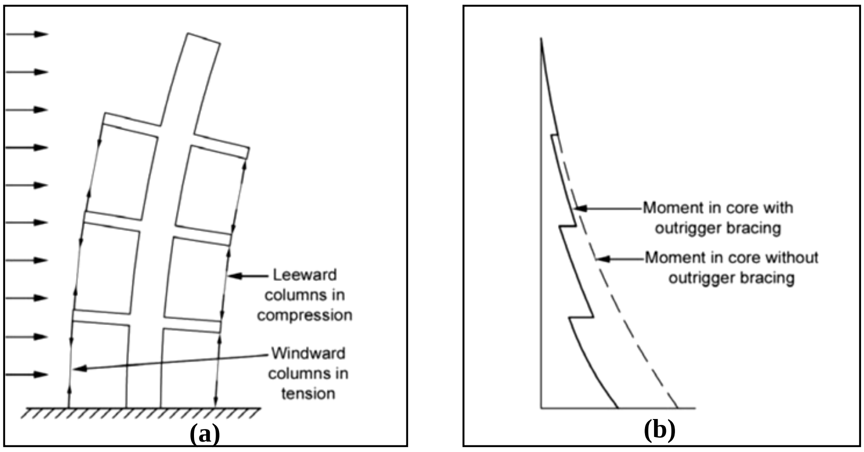
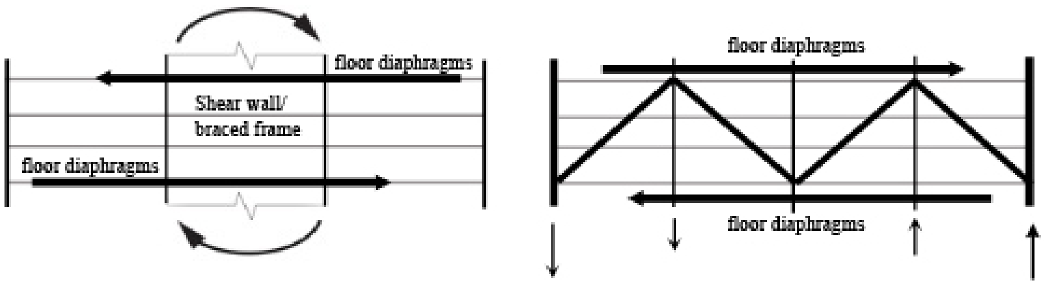


Figure 2.32. (a) Core supported outrigger structure behavior under lateral load (b) Moment diagram of outrigger frame system (Ali & Moon, 2001)

On the other hand, Nanduri *et al*. (2013) claim that, use of outriggers even in mechanical floors can create problems of using space efficiently, since the structural members (especially the diagonals) interrupt the space unity. Authors believe that those members which come out from core may create constrains for architects and engineers too.

Choi and Joseph (2012) indicate that virtual outriggers are also an option used in tall buildings. In this system, a stiff, strong floor diaphragm is used for transferring bending moment from core to belt trusses or walls located at perimeter as seen in Figure 2.33. In order to achieve this, diaphragms at the top and bottom chord of each belt truss/wall are significantly thicker than other floors (Choi, Ho, Joseph and Mathias, 2012). However, these floors are not still used as architectural floors, since they are framed with belts which obstruct the view, as shown in Figure 2.34.



(a) (b)

Figure 2.33. (a) Transfer of forces from core to floor diaphragms, (b) transfer of forces from floor diaphragms to columns through belt truss (Choi, Ho, Joseph and Mathias, 2012)

Figure 2.34. U.S. Bank Center, Milwaukee, 1973 (https://structurae.net/structures/us-bank-center/photos, September, 2018)

Günel and Ilgın (2014) also state that there are different types of outriggers used in tall buildings such as shear walled and braced outriggers in different configurations. The outrigger typology depends on the tall buildings structural system (Choi, Ho Joseph and Mathias, 2012).

Besides, Ho (2016) studies on the topologies of outriggers which have same space constraints. It is demonstrated in the Table 2.4 that the strength of the outrigger does not directly affect the structural efficiency of the building. Ho (2016) point out that the stiffest outrigger may not work efficiently in the specified building. Thus, appropriate system has to be designed for selected tall buildings.

Table 2.4. *Summary of outrigger typologies studied by Ho (2016)*

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

2.4. Critical review on challenges and potential of tall buildings with wind escape floors

Several studies have been mentioned in previous parts for making a historic overview to the topic. Recent studies on wind escape floors showed reduction of wind effects achieved by different arrangements (height, shape, location as well) to some extent. However, their combined use with advanced structural systems (i.e. outriggered frame or tube systems9 which are mainly used for increasing the stiffness of high-risers should also be evaluated to provide a broader view on the optimum use of wind escape floors to designers.

Tall buildings with wind escape floors have much potential with harnessing energy on to them, linking buildings as egress floors or correlation between structural system of the building and building performance as in this research. Changing building design approaches with an aerodynamic modification improves the building performance and by improving building performance, occupant comfort is increased too which is very important for designers, engineers and stakeholders. The leaseable areas in plan is extremely important in super-slender tall buildings and increasing these areas by improving building performance is an advantage for architects by providing more space in design.

CHAPTER 3

MATERIAL AND METHOD

3.1. Material

This chapter is composed of three sub sections. First, the sample building is introduced and the reason of selecting this building is discussed. Then, the structural analysis platform, ETABS Software, is presented briefly. Finally, the detailed model properties as well as the assumptions used in modeling phase are expressed.

3.1.1. Selection of sample building

Among existing tall buildings with openings (see Chapter 2 for detailed information) 432 Park Avenue Building is chosen for scrutinizing the relationship between the use of wind escape floors and the corresponding effects on aerodynamic performance of super slender tall buildings.

The main reason of selecting 432 Park Avenue is its form, a perfect prism with a square cross section which is free from any aerodynamic modification. In Wuhan Greenland Center on the other hand, the openings are only slots in mechanical floors rather than wind escape floors. As Fu *et al.* (2012) reported, the impact of the vent slots in Wuhan Greenland Center is minor when compared to massing design decisions. In 111 West 57th Street Building, the role of wind escape floors is relatively major but with some issues decreasing its efficiency. For instance, the configuration of the core in wind escape floors, shown in Figure 2.15 (b) in Chapter 2, makes the air pass into a single narrow passage without any modification applied to core, which is not the case in 432 Park Avenue Building's drum. Major aerodynamic modifications of 111 West 57th Street Building is its stepped tapered form which continuously changes the plan of wind escape floors as getting higher. So, wind escape floors organized with outrigger/mechanical floors work relatively less effective than other aerodynamic modifications applied to building in terms of dynamic response. Finally, investigating the number of wind escape floors on building aerodynamic response would be biased with such a tapered form. Another building with wind escape floors, Pearl River Tower, has wind turbines harnessed on to the openings. Thus, in this building the primary goal is to obtain wind energy rather than rehabilitating the building wind response. As a matter of fact, Frechette *et al.* (2008) stated that air flow through the openings is reduced because of these turbines which constitute a resistance force to the flow indeed.

Kiktsu & Okada (2003) state opening floors typical plan scheme (see "section A" Figure 2.5 in section 2.1.2) lets wind pass through the building only south-north direction which minimize wind induced loads for only along-wind directions. Building's wind load response decreases in south-north direction where the openings located directions due to those openings.

432 Park Avenue building has five wind escape floors organized with outriggers and also mechanical equipment. The structural system of the building is framed tube according to the structural system classification proposed by Günel and Ilgın (2014). Relatively closely spaced perimeter columns with deep spandrel beams, a core and flat slabs, are the structural elements of this reinforced concrete building. The outriggers located at wind escape floors are designed such that, they create an unobstructed volume for letting the wind easily flow. Besides, there is a thin sheet of metal, called as "drum", surrounding the core cylindrically (as shown in Figure 2.21 (b) in Chapter 2) which not only sheltering the mechanical equipment but also changes the core from a bluff body with square cross section into a streamlined body with a circular cross section. Finally, the square plan of the building as well as symmetrically distributed structural members in both principal directions makes 432 Park Avenue a perfect candidate to scrutinize the wind escape floors and their optimum use in tall

buildings. Although all the alternatives of wind escape floors and outrigger applications are applied on the same plan based on 432 Park Avenue building, the findings of this study can be generalized for other super tall slender buildings having similar opening width to along wind width ratio.

3.1.2. Selection of software used in the study

ETABS (ver 16.1) software is used for analyzing the three dimensional models of the building. ETABS is a structural analysis program developed by Computers and Structures engineering company based on the finite element method. The program can perform both nonlinear and linear analysis by comprehensive design capabilities. The interface of the software is specialized for engineers and architects. Buildings can be modeled by using simple features on the menu. CAD drawings can be converted into ETABS models or used as templates. The program can also be involved into Building Information Modeling (BIM) practices.

In ETABS, shell elements containing 3 or 4 nodes area are used to model reinforced concrete walls (shear walls), cladding elements and slabs. On the other hand, frame elements which are straight objects connecting two nodes linearly are used to model beams, columns and braces.

The program is devoted to building structures, especially tall ones. The program has embedded wind and seismic loading models based on several codes and specifications such as Eurocode 8, ASCE 7-10 (www.wiki.csiamerica.com, 2018/05). Thus, the relative ease on applying code-based wind loading on models as well as its user-friendly interface for graphic displays and reports are the reasons of using ETABS in this study.

3.1.3. Analytical model samples

34 generic models are modeled and analyzed on ETABS software to obtain their base shear, core moment and top drift due to ASCE7-10 based wind loading. 8 models are created and compared in the first phase of the study whereas 26 variants are included in second phase. These models are examined in a detailed manner in this part.

Plan dimension of the models is same for each model and similar to 432 Park Avenue Building. It is 28.54 x 28.54 meters (93.63 x 93.63 feet, Nasvik, 2015). Figure 3.1 demonstrates typical floor plans between 1th -7th (left panel) and 8th – 90th floors (right panel). 7 axes are in both x and y direction with an equal axis-to-axis distance of 4.57 m. Maximum span on a slab is 7.46 m. The storey height is taken as 4.75 m for all 90 floors which yield a 427.5 m total height of building (the same with 432 Park Avenue) which makes models' aspect ratio of 1:15.

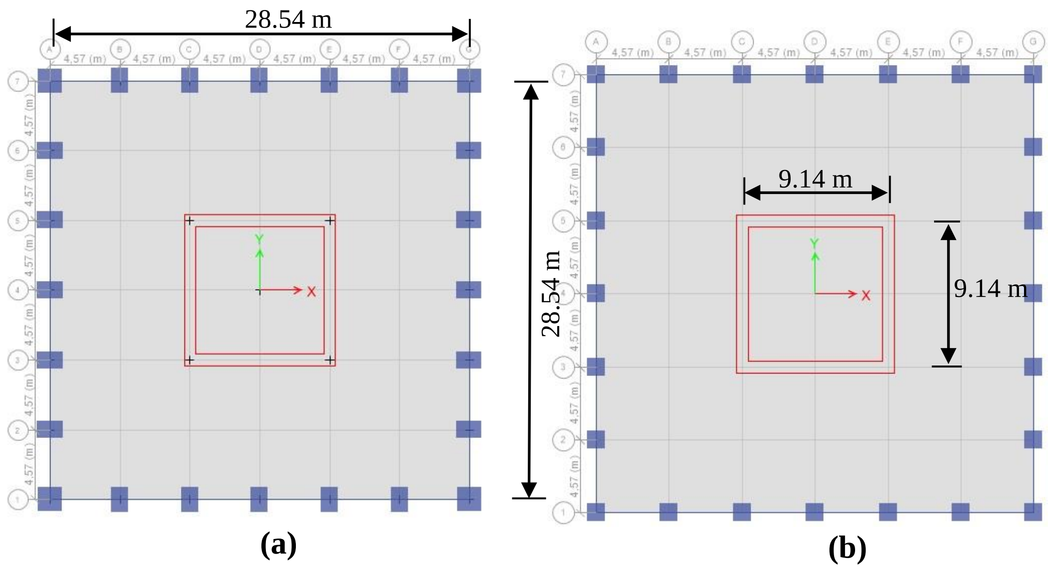


Figure 3.1. (a) Floor plan of stories between ground and 7th floor (b) Typical Floor Plan for stories between 8th and 90th floor

Stiffness modifiers have been used as suggested by several codes for tall buildings (eg., PEER Report 2017/06 (2011), LATBSDC Alternative Analysis and Design

Procedure (2015), etc). Modifiers given in ACI318-14 (American Concrete Institute, 2014) are applied into the relevant members of the structural system. The flexural and shear modifiers used in all models are listed in Table 3.1.

Table 3.1. *Stiffness modifiers/ properties stated in code for tall buildings*

	Flexural	**Shear**
Structural Wall	0.75 Ig	1.0 Ag
Diaphragms	0.50 Ig	0.8 Ag
Beam	0.70 Ig	1.0 Ag
Column	0.90 Ig	1.0 Ag

- Columns:

Twenty-four perimeter columns (seven columns at each side) are located with 4.57m spacing based on 432 Park Avenue Building, named as reference building in this thesis study. Although, the reference building column dimensions are decreased gradually in five levels, the models used in this study have only two different cross-sections to eliminate the possible bias among alternative number of wind openings. Corner column dimensions are 158 centimeter (cm) x 158 cm from ground up to 8^{th} floor throughout the building. Other columns are 167 x 112 cm, where short dimension (112cm) is always oriented parallel to the building façade. From 8^{th} to 90^{th} floors columns dimension became 112 cm x 112 cm. These dimensions are taken from reference building, except the corner columns which are shaped differently in the real case (see Figure 3.2). Note that, the area of corner columns are similar to those of reference building but square in cross section. C90/105 class concrete is used in models based on indicating that C90/105 concrete used in 432 Park Avenue building. The modulus of elasticity of concrete is taken as 53080 Mpa (Nasvik, 2015).

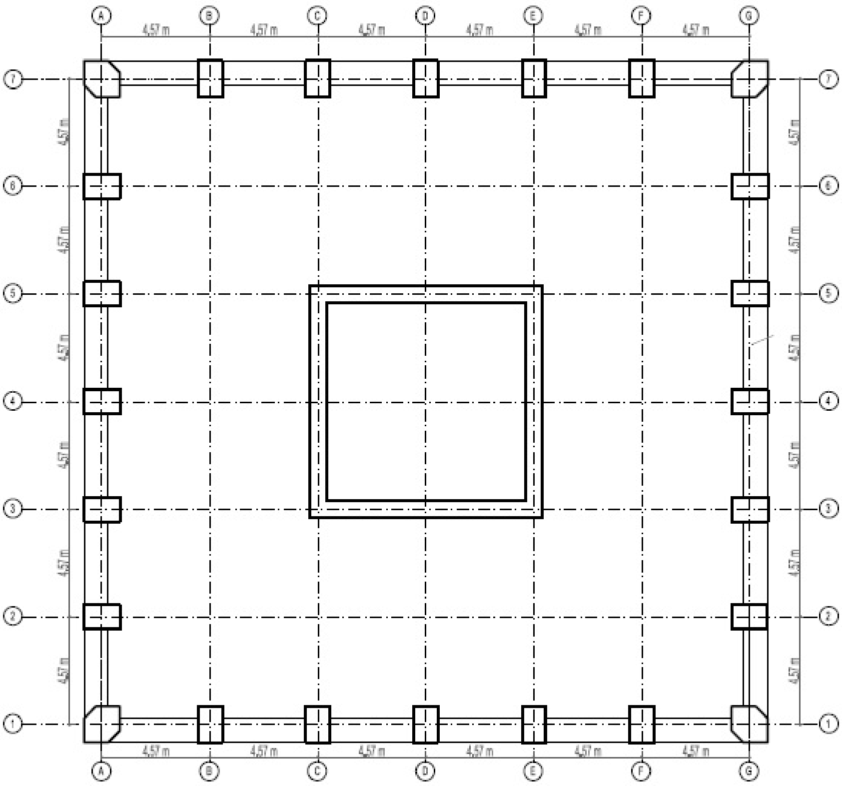


Figure 3.2. Typical Floor plans of 432 Park Avenue Building which stories are between ground and 7th floors (Rafael Vinoly lecture: 432 Park Avenue and other towers, January 2018)

- Beams :

The dimensions of spandrel beams for all stories are 112 cm x112 cm with class of C90/105.

- Core :

The building has 9.14m x 9.14m square core with a wall thickness of 76cm. C90/105 concrete is used also for core. The core is located at the center of the building.

- Slabs :

The slabs used in the models are flat plate, similar to 432 Park Avenue building. Slab thickness has taken as 25 cm. C30/37 class concrete with a modulus of elasticity of 27000 MPa has been used for slabs (Nasvik, 2015). The slabs in all floors are modeled as semi-rigid diaphragms. Since rigid diaphragms stimulate infinite in-plane stiffness, they cannot interpret the actual plane deformation and report associated forces.

Therefore, semi-rigid diaphragms are preferred while modeling this tall building. The slabs between 2-storey-high outrigger floors, named as wind escape floors, have been excluded as in the case of 432 Park Avenue Building.

Besides, two types of diaphragms are defined as D1 and D2 which are semi-rigid and rigid, respectively and those are assigned to slabs. All of the slabs are assigned as D1 (semi-rigid). Virtual outrigger models' wind escape floor slabs are the only exception since they are assigned to D2.

- Outriggers :

Four different types of outriggers are modeled which are all double-storey-high. Detailed information on outrigger typologies and properties will be explained in Section 3.1.3.1.

- Cladding :

ETABS Auto draw cladding tool is used for model claddings. They are implemented around the outer perimeter of the structure. Note that, these are weightless special members without stiffness. They are composed by ETABS for wind load analysis.

3.1.3.1. Models having alternative outrigger typologies with or without façade perforation

Figure 3.3 and 3.4 demonstrate the façades and core sections as well as outrigger floor plans of 8 alternative designs which are compared in this study. Models with closed façade are demonstrated in Figure 3.3 whereas models with perforated façade are presented in Figure 3.4. Three dimensional views of perforated and closed façades can be seen in Figure 3.3. Five levels of double-storey-high outriggers (located at wind escape floors) are located in these models throughout the height of the building. Four alternative outrigger applications and models without outrigger members which are listed below are compared in this study to investigate their relative performance;

I. Shear wall outrigger model with closed façade (SW-C)

II. Reference building model with perforated façade (RB-O)

III. Brace outrigger models with perforated and closed façades (BO-O & BO-C)

IV. Virtual outrigger models with perforated and closed façades (VO-O& VO-C)

V. No outrigger models with perforated and closed façades (NO-C & NO-O)

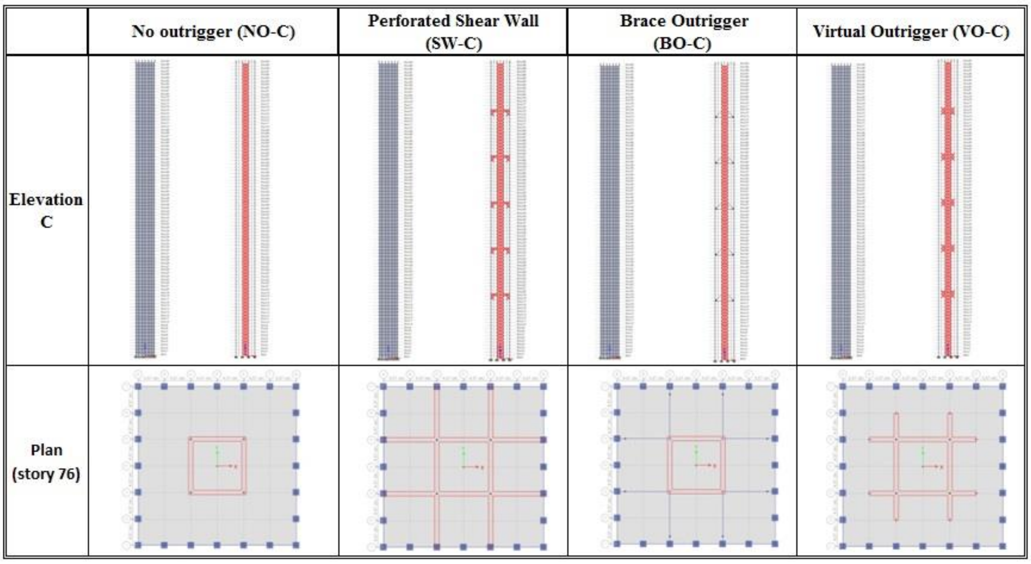


Figure 3.3. Elevations (top row) and plans (second row) of models with closed façade

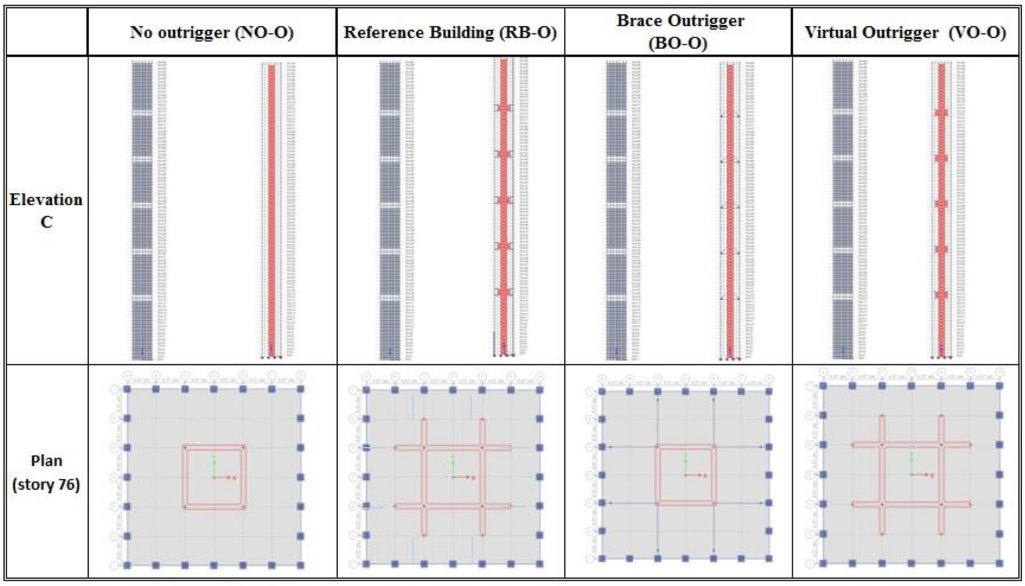
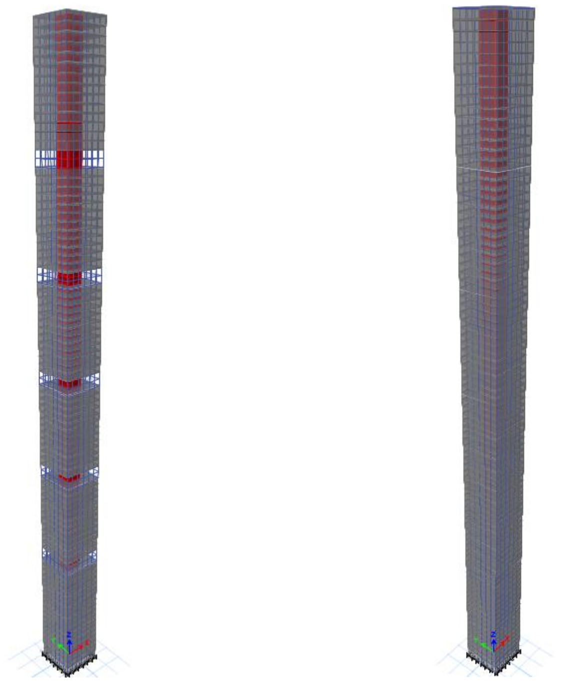


Figure 3.4. Elevations (top row) and plans (second row) of models with perforated façade

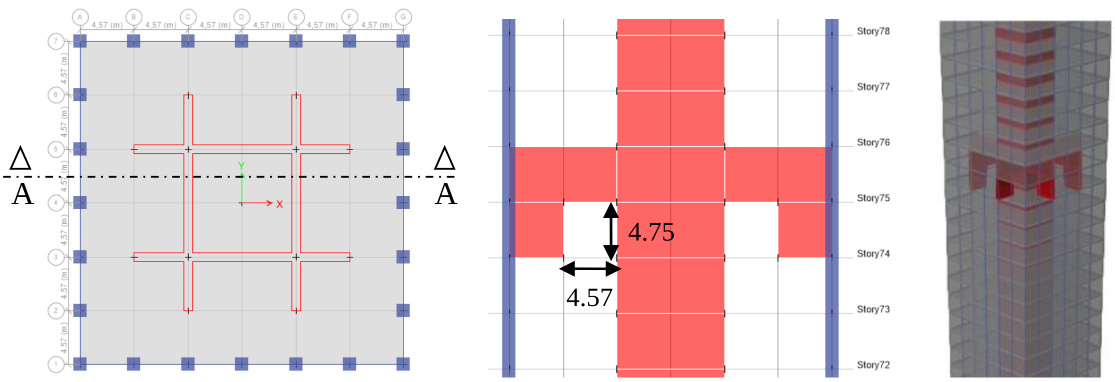


(a) **(b)**

Figure 3.5. Three- dimensional views of (a) Models with perforated façade and (b) Models with close façade

I. Shear wall outrigger model with closed façade:

Reinforced concrete walls with class of C90/105 concrete are used to study shear wall (SW) outrigger model with closed façade (C) as seen in Figure 3.6. Outrigger walls have 76 cm thickness, similar to core. Shear walls with passages shown in Figure 3.6(b) represent the conventional outrigger applications in most of the tall buildings with outriggered frame system. Red lines represent outriggers on plan view in Figure 3.6(a). Three dimensional view of this outrigger typology is provided in the third column of the same figure. 5 levels of double storey high outriggers are located through the height of the building. Passages of 4.57m x 4.75m as seen on Figure 3.6(b) are introduced to outriggers with architectural concerns. Since, these floors host also mechanical equipment, the passages are essential for spatial organization without sacrificing the outrigger effectiveness. It is important to note that SW-C model was compared to another model with closed shear walls (without passages) and their identical performance was verified. In order to reflect real case, SW-C Model with passages is used in this thesis study.

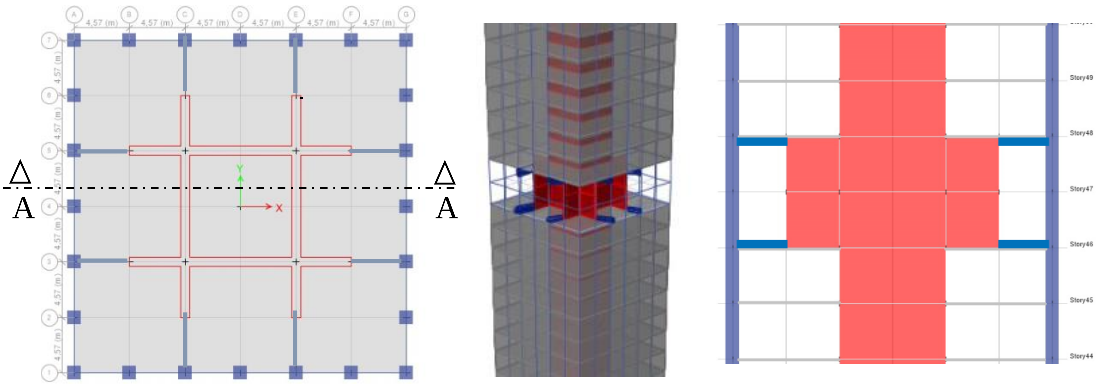


(a) **(b)** **(c)**

Figure 3.6. (a) Outrigger floor plan (74th storey) (b) Section A-A and (c) 3 dimensional view of shear wall outrigger model (SW-C)

II. Reference Building model with perforated façade:

Reference Building (RB) with openings (O) model is abbreviated with RB-O. This outrigger typology is composed of reinforced concrete walls and relatively deep beams between reinforced concrete walls as an extension of core and the perimeter columns. C90/105 concrete is assigned to these reinforced concrete members which are 4.57 m in length and 9.5 m in height. Relatively deep link beams (112 cm x 112 cm) are used at slab levels of wind escape floors,. Figure 3.7(a) demonstrates the configuration of the outrigger of reference building where the red lines represent the extended shell elements, and blue lines represent the link beams. RB-O has been used to reflect the case of reference building in comparisons.

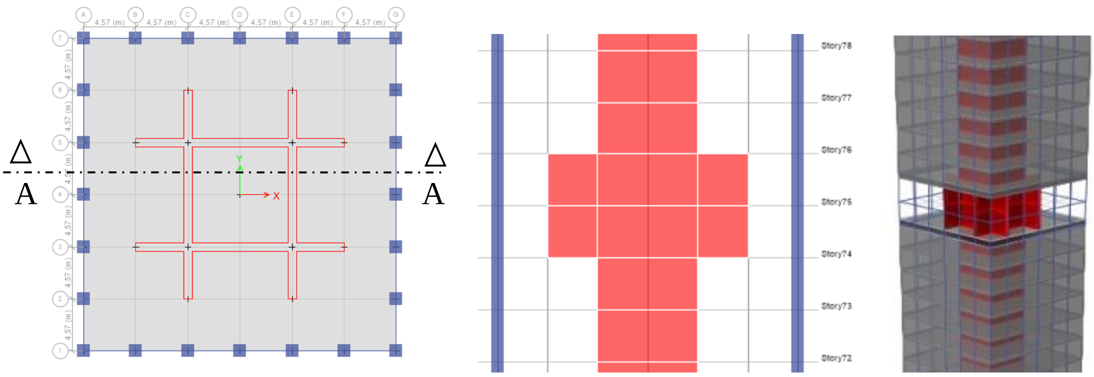


(a) **(b)** **(c)**

Figure 3.7. (a) Outrigger floor plan (74th storey) (b) Section A-A and (c) three-dimensional view of reference building (RB-O)

III. Virtual outrigger models with perforated and close façades:

Virtual outriggers (VO) are used both with perforated (O) and closed (C) façade alternatives, named as VO-O and VO-C, respectively. Such an outrigger application capitalizes on floor diaphragms by increasing their thickness to eliminate vertical members (outriggers) to couple of core and perimeter columns. The floor’s located above and below levels of the wind escape floors thicknesses are increased from 25 cm to 112 cm which is equal to depth of the spandrel beam. Günel and Ilgın (2014) stated that the efficiency of virtual outriggers depend on the rigidity of floor slabs and belt. Belts consist of a horizontal shear truss or a shear wall with a depth equal to the outrigger around the perimeter. However, use of belts is contradictory to the design idea of 432 Park Avenue explained in Chapter 2, section 2.1.2.2.4. Besides, belts might reduce the air flow through the open floors. So, the closely spaced reinforced concrete columns and spandrel beams having large cross-sections are assumed to behave like a box section. Moreover, in order to increase the efficiency of a virtual outrigger without belts, the reinforced concrete wall as an extension of core towards perimeter columns are used, which is already within the drum hosting the mechanical equipment. Figure 3.8 shows the plan of virtual outriggers and RC extension walls indicated with red lines A model without reinforced concrete extensions is also performed for comparative purposes but virtual outriggers without belts and core extensions did not yield sufficient results in terms of top drift and core moments.



(a) **(b)** **(c)**

Figure 3.8. (a) Outrigger floor plan (74th storey) (b) Section A-A and (c) three-dimensional view of virtual outrigger (VO-O)

IV. Brace outrigger model with perforated and closed façades:

Braces (B) as outrigger (O) members are used in both closed (C) and perforated (O) façade models abbreviated as BO-C and BO-O which can be seen in the third column of Table 3.2 & 3.3. These members are modeled as composite frame elements with class A99Fy50 steel tube sections of 112 cm x 112 cm with 40 mm thickness and they are filled with concrete class of 90/105. The diagonally placed members as well as horizontal elements are marked with blue bold lines as seen in Figure 3.9 (b). End releases are introduced to brace outriggers which are shown with black spots on the Figure 3.9 (a) and (b).

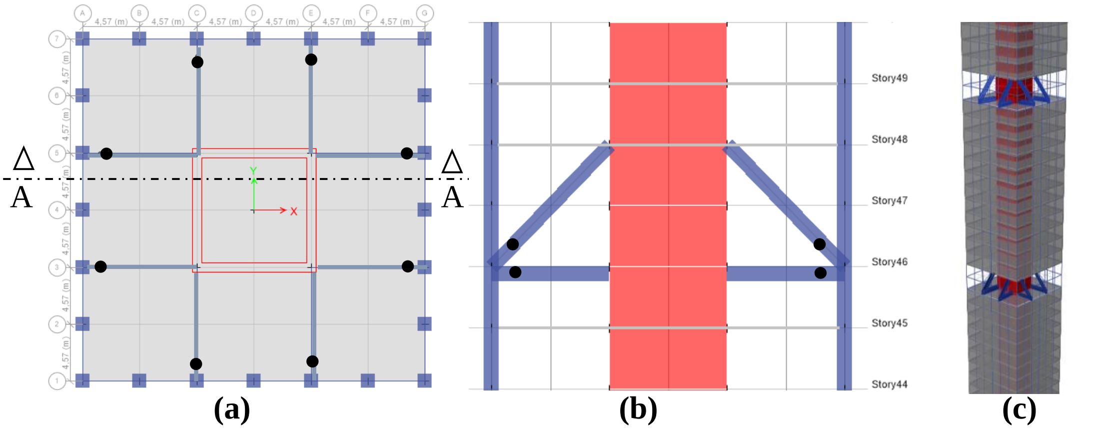
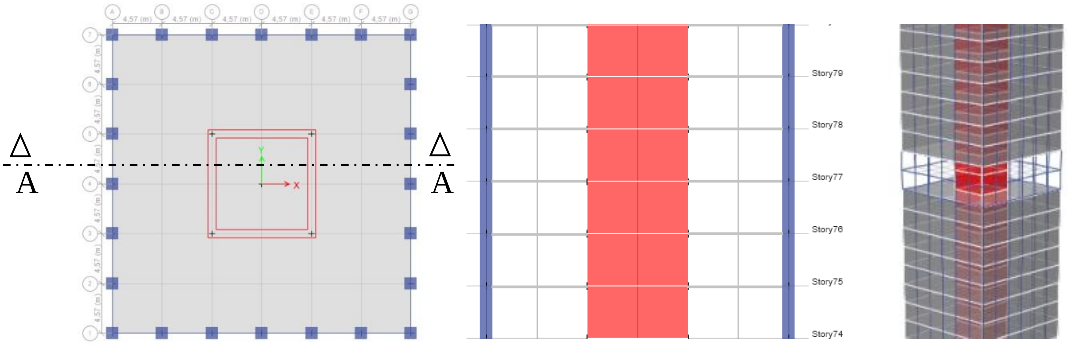


Figure 3.9. (a) Outrigger floor plan (74th storey) (b) Section A-A and (c) three-dimensional view of brace outrigger (BO-O)

V. No outrigger models with perforated and close façades:

In the first column of Figure 3.3 and 3.4 no (N) outrigger (O) models with openings (O) and with closed (C) façades (NO-O& NO-C) are demonstrated with plan schemes and elevations. There are no outriggers in these models. The floor plan scheme of no outrigger models is shown in Figure 3.10. NO-O model has five wind escape floors in 18^{th}-20^{th}, 32^{th} -34^{th}, 46^{th}-48^{th}, 60^{th}-62^{th} and 74th – 76^{th} storeys. Figure 3.10 represents the plan, partial elevation and three dimensional view of NO-O.



(a) **(b)** **(c)**

Figure 3.10. (a) Outrigger floor plan (74th storey) (b) Section A-A and (c) 3D view of no outrigger model (NO-O)

3.1.3.2. Models having alternative number of wind floor openings

Twenty-six models are prepared for studying on wind floor opening variations with respect to outrigger applications in terms of number and location throughout the height of the building. The aim of the comparisons among prepared models is to exert an optimum solution for wind floor openings in outrigger levels. Two certain types of outriggers are taken from the previous studied models; brace and virtual outrigger, as they are the most efficient systems among those used with wind floor openings. These are chosen according to their efficient performance results in terms of top drift and core moments. Basically, brace and virtual outriggers are modeled into certain floor levels indicated in Table 3.4. Model names are abbreviated in accordance with their number of outrigger levels placed in front of the outrigger type and façade condition (i.e., perforated or close). For instance; 1BO-C denotes there is only one brace outrigger located between 46th and 48th floors (as seen in the Table 3.4) within a closed façade building. The same logic is valid for the rest of models with stated levels of outriggers in Table 3.4. 1BO-O, 2BO-O, 3BO-O, 4BO-O, 5BO-O are used for defining brace outrigger models with 1, 2, 3, 4, 5 levels of outriggers within wind escape floors, respectively. 1BO-C, 2BO-C, 3BO-C, 4BO-C, 5BO-C are used for brace outriggers with close façade. In virtual outrigger models (VO) same principle explained above is valid. All model's abbreviations studied in the second phase are shown in Table 3.5.

Table 3.2. *Outrigger numbers with assigned floor levels*

Number of outriggers	**Outrigger levels floor to floor (f.)**				
5	18^{th} - 20^{th} f.	32^{th}-34^{th} f.	46^{th}-48^{th} f.	60^{th}-62^{th} f.	74^{th}-76^{th} f.
4	18^{th} - 20^{th} f.	36^{th}-38^{th} f.	54^{th}-56^{th} f.	72^{th}-74^{th} f.	
3	22^{th}-24^{th} f.	46^{th}-48^{th} f.	70^{th}-72^{th} f.		
2	30^{th}-32^{th} f.	60^{th}-62^{th} f.			
1	46^{th}-48^{th} f.				

The five levels of outriggers are arranged for every 12 floors, based on 432 Park Avenue building's wind escape floors. On the other hand, the other four options are organized by dividing the building height into equal pieces. Therefore, there are 16, 22 and 28 floors in between wind escape floors for 4, 3 and 2 levels of outriggers, respectively.

Besides the sets briefed above, there is another set composed of five models without outriggers but with perforated façades in certain floors which is defined in Table 3.4. Finally, one more model which is a closed façade model without any outrigger is analyzed. These last set of models are used for composing a control group within the limits of the study.

Table 3.3. *Abbreviations of second phase models*

Outrigger level	Outrigger type					
	Brace outrigger		Virtual outrigger		No outrigger	
	Perforated	**Close**	**Perforated**	**Close**	**Perforated**	**Close**
1	1BO-O	1BO-C	1VO-O	1VO-C	1NO-O	NO-C
2	2BO-O	2BO-C	2VO-O	2VO-C	2NO-O	
3	3BO-O	3BO-C	3VO-O	3VO-C	3NO-O	
4	4BO-O	4BO-C	4VO-O	4VO-C	4NO-O	
5	5BO-O	5BO-C	5VO-O	5VO-C	5NO-O	

Table 3.4. *1NO-O, 2NO-O, 3NO-O, 4NO-O and 5NO-O models 3D views with wind escape floor levels*

3D views of 5 models with perforated façade					
Perforation levels	46^{th}-48^{th} floors	30^{th}-32^{th} floors 60^{th}-62^{th} floors	22^{th}-24^{th} floors 46^{th}-48^{th} floors 70^{th}-72^{th} floors	18^{th}-20^{th} floors 36^{th}-38^{th} floors 54^{th}-56^{th} floors 72^{th}-74^{th} floors	18^{th}-20^{th} floors 32^{th}-34^{th} floors 46^{th}-48^{th} floors 60^{th}-62^{th} floors 74^{th}-76^{th} floors

3.2. Methodology of modelling process

This section outlines the method of this thesis including modeling process and analysis. “Assigned loads” section explaining the loads applied to models are followed by the Modal analysis section discussing the calculation of the gust factor. Finally, structural analysis section introduced the assumptions and features of the analysis of sample models.

As an initial step of the research, a comprehensive literature survey is done on buildings with wind escape floors, aerodynamic modifications applied to tall buildings, classification of structural systems and features of outriggered frame systems to understand what was studied in past years about the research question of this thesis.

As mentioned in Section 3.1, conducted study is divided into two stages. First phase of the study is devoted to comparisons among alternative outrigger types used in buildings with wind escape floors. Ho (2016) indicates that the most structurally efficient outrigger system does not mean the outrigger with highest stiffness. So, outrigger typologies are examined deliberately to find out which is working properly within wind escape floors.

In the first step, twelve models are studied with five levels of openings and outriggers located at the same floors. Outrigger types are the only difference between models. There are 5 types of outriggers which are brace outrigger, virtual outrigger with extended reinforced walls, virtual outrigger without extended reinforced walls, reference building outrigger, and shear wall outrigger. Brace outriggers with alternative configurations are modeled considering the reference of Ho (2016) outrigger typologies. The defined brace outrigger model in Section 3.1 is the most efficiently worked outrigger type among Ho (2016) typologies. Therefore, it is preferred to study with. Hence, 4 types of outrigger that are introduced in section 3.1 are chosen to continue of the analysis process.

Following the first phase, the most efficient two types of outriggers are chosen to investigate the optimum number and location of the wind escape floors within the scope of thesis. The second phase is composed of three sub-groups for two certain types of outriggers which have five variations regarding the number of wind escape floors (illustrated in Table 3.5). Results are examined within the top drift limitation of 1/500 building height and the base shear forces.

All in all, more than 30 models are scrutinized to understand the optimum use of outrigger configuration with respect to wind escape floor arrangement.

3.2.1. Assigned loads

Primarily the gravity loads as dead load, live load and super-dead load is defined to all models. Mass source is defined as the sum of dead, super-dead and live loads, with multipliers of “1”, “1”, and “0.3”, respectively. (ASCE7-10, 2010)

In addition to the buildings self-weight, gravity loads are assigned to shell objects as uniformly distributed live load of 2 kN/m^2 (residential and office use) similar to the values given in ASCE 7-10 (2010) and as super-dead loads of 3.5 kN/m^2 in accordance with the common engineering practice.

Wind is defined according to the ASCE 7-10 (ASCE, 2010) code. Exposure from frame and shell objects is chosen from the wind load pattern table. Main wind force resisting system (MWFRS) directional procedure given in Chapter 27 of ASCE 7-10 (ASCE, 2010) is used to calculate wind loads on the building. According to ASCE 7-10, MWFRS can be applied to tall building designs to determine minimum design loads of enclosed, partially enclosed and open buildings of all heights. Wind speed is taken as 38 m/sn (85milesperhour (mph)). This value is retrieved from ASCE 7-10

(ASCE, 2010) wind speed map according to location of 432 Park Avenue building. Topographical factor (K_{zt}) is taken 1 from the code. Directionality factor (K_d) is taken 0.85 since the structure type is building. According to MWFRS the ratio of solid/gross area is calculated and taken as 0.27 for all perforated models. Exposure B is applied to defined wind load. Since gust effect factor depends on the building period, it is determined for all models separately.

Gust effect factor is defined as a ratio of peak wind gust to mean wind speed over a period of time (ASCE 7-10). According to Section 26.2 of ASCE 7-10 (ASCE, 2010), slender buildings or other structures of which natural frequency is less than 1 Hz are accounted as flexible structures. Code requirements indicate that gust effect factor for a rigid building can be taken as 0.85, whereas the gust factor of flexible or dynamically sensitive buildings should be calculated as given in Section 26.9.5 of ASCE 7-10. Therefore, modal analyses are performed at first in order to find the natural frequency of the building. Building natural period is then applied into gust effect factor calculation as defined in ASCE 7-10 (ASCE, 2010) (Section 26.9.5). Calculated gust factor is become a proper input for wind loads applied to the building.

Wind pressure coefficients are assigned to cladding and shell objects as core wall located at the wind escape floors. 0.8 is used for windward, whereas 0.5 is used for leeward side.

Wind loads can be assigned to frame and shell objects separately. Frame elements except from wind escape floors are not assigned by and wind loading to prevent double counting. Since, the building façade is modeled with cladding and it is loaded by using wind pressure coefficients.

3.2.2. Analysis Process

There are two types of analysis used in conducted study; modal and static. As mentioned before, modal analyses are performed for determining natural period of the building which is necessary for gust factor calculations. Since, ETABS software applies wind load on to buildings as a constant value, determination of wind load response is performed via static analysis method. To note that, static analysis method involves constant parameters, not varied in time. Classification of analysis is according to type of applied forces. Since the loads are well within the elastic range of deformation and superimposition principle is applicable according to material behavior, the performed analyses are also linear. (Laurenço, P.B., 2018)

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is composed of three sub sections. Section 4.1 presents modal and static analysis results of models with different outrigger typologies (as indicated in Section 3.1.3.1). These results are scrutinized within a comparative framework in terms of top drift and core moments. Modal and static results of models having alternative number of wind escape floors are presented in Section 4.2. Thereafter, Section 4.3 presents results of alternative outrigger type - number of wind opening configurations and corresponding discussions to understand the optimum number and location of a certain type of outrigger used with wind escape floors.

4.1. Results of models having alternative outrigger typologies with or without façade perforation

An analytical research has been conducted to make comparisons on core moment distributions and top drifts. Modal analysis is performed for each model to find out models' fundamental (natural) period (T_1). An undamped structure would undergo simple harmonic motion without change in a given characteristic deflected shape, provided that this deflected shape is initiated by appropriate distribution of loads. Each one of these deflected shapes is a *natural mode of vibration* of that structure and the fundamental period of vibration T_1 of this structure is the longest time passes during one complete cycle of any natural mode of this structure (Chopra, 2012).

$$T_1 = 2\pi \left(\frac{\sum_{\mathrm{i=1}}^{\mathrm{N}} m_{\mathrm{i}} d_{\mathrm{fi}}^2}{\sum_{\mathrm{i=1}}^{\mathrm{N}} F_{\mathrm{fi}} d_{\mathrm{fi}}} \right)^{1/2}$$

Where;

T_1= Building natural period

m_i= Mass of i^{th} floor

d_{fi}= Storey displacement calculated according to F_{fi} in i^{th} floor

F_{fi}= Fictive loads acting on ith floor for calculation of building natural period
N= Total storey number of a building from foundation (the number of stories will be count from ground floor where basement floor of the building is constructed with rigid framed with shear walls)

Building period and frequency are inversely proportional values as seen in formula given below.

$$T = \frac{1}{f}$$

Where;
T= Building period (sec)
f= Building frequency (Hz)

As shown in the formula above, building period is related to building mass and stiffness. Thus, fundamental period of the building depends on the buildings structural system and also construction materials. Relatively flexible (less stiff) buildings have longer fundamental periods. The gust effect factor (G_f) representing the dynamic response of the structure to wind loads is a function of the buildings fundamental natural frequency as given in Section 3.2.1. Thus, fundamental period and frequency as well as corresponding gust effect factor of studied building models are given in Table 4.1.

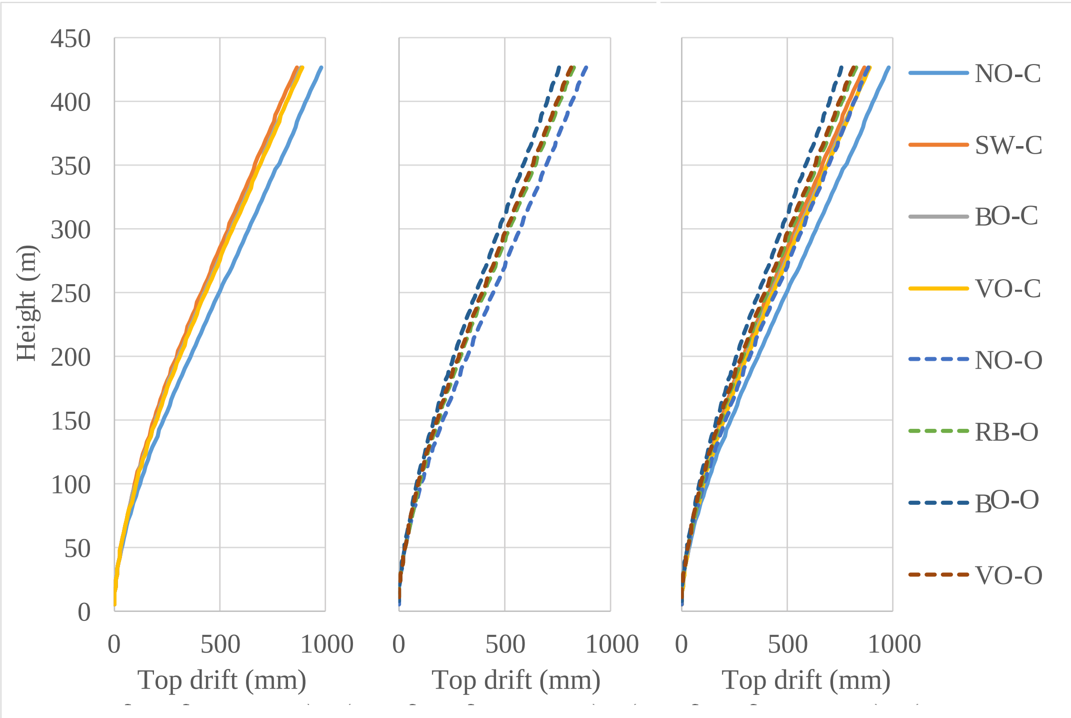
According to ASCE 7-10 (ASCE, 2010), in Section 26.2, buildings having a fundamental natural frequency (f) more than 1 Hz are called as rigid buildings. Since the energy in turbulence spectrum is small for rigid buildings, gust effect factor can be taken as 0.85. (ASCE, 2010) However, buildings with a fundamental natural frequency less than 1 Hz are flexible buildings and these are likely to be dynamically excited by the wind. Hence, their gust factors are calculated according to ASCE 7-10 (ASCE, 2010), Equation 26.9-10 given in Section 26.9.5. Since, the loading parameters and structural systems of virtual outrigger models with closed and perforated) façades (VO-O and VO-C, respectively) are identical; these models' natural periods (T_1) are similar as well as their gust effect factors as seen in Table 4.1. The same condition is also valid for Braced Outrigger models with closed and perforated façades (BO-O and BO-C, respectively).

Shear wall outrigger model with closed façade (SW-C) have the shortest natural period, indicating that shear walled outrigger typology increases the building stiffness much more than other alternative outrigger types.

Table 4.1. *Modal analysis and determined gust factors of first phase models*

Models	**T_1** (sn)	**f_1** (Hz)	**G_f**
NO-C	14.384	0.069	1.223
SW-C	13.436	0.074	1.196
BO-C	13.54	0.073	1.198
VO-C	14.362	0.069	1.223
BO-O	13.54	0.073	1.198
VO-O	14.362	0.069	1.223
RB-O	13.986	0.071	1.212
NO-O	14.384	0.069	1.223

The static wind load analyses are performed to understand the building's structural behavior under along wind loading. Figure 4.1 presents the top drift values of models with closed façade (a), perforated façade (b) and their combination (c) in millimeters according to building height graphically. Results shown in Figure 4.1 confirms that no outrigger model with closed façade (NO-C) have highest top displacement value as expected. Since, this model has no outrigger; its structural system is less rigid than other models. Braced outrigger model with closed façade (BO-C) and virtual outrigger model with closed façade (VO-C) results are almost identical and slightly better than top drift of NO-C model. Although shear wall outrigger is the most effective outrigger type among alternatives investigated in this study, its use with closed façade (SW-C) results in larger top drift value compared to reference building model with perforated façade (RB-O) since openness in façade yields relatively smaller wind loads as it lets the wind flow through the building. Among outrigger typologies capable of wind flow openings, braced outrigger model with open façade (BO-O) have better performance compared to other three open façade models (VO-O, RB-O and NO-O) as shown in Figure 4.1(b). Finally, Figure 4.1 (c) shows that the best performed configuration is the braced outrigger with perforated façade (BO-O) in terms of top drift with a value of 757 mm. Following brace outrigger model having perforated façade (BO-O), virtual outrigger model and reference building model with perforated façades (VO-O and RB-O, respectively) have almost the same results as 809 and 810 mm, respectively . Brace outrigger (BO) and shear wall (SW) models with closed façade (C) perform slightly worse than these models. The results confirmed that perforated façade can improve building performance as much as an outrigger in some configurations. Although BO-C and BO-O models have identical building periods (as given in Table 4.1) which are directly proportional to models' stiffness, the model with perforated façade takes the advantage of wind escape floors. Therefore, BO-O has 1.25% relatively less top drift compared to BO-C model. Figure 4.1 (c) also represents that VO-C and NO-O models fairly similar to each other in terms of top drift and their results are more than SW-C and BO-C models. Notwithstanding, VO-C model is stiffer than NO-O as seen in Table 4.1. Similar to BO-O and VO-O models, NO-O model takes advantage of wind escape floors, and thus its top drift is lesser than NO-C as shown in Figure 4.1(c).



(a) **(b)** **(c)**

Figure 4.1. Top drift values of models (a) with closed façade (b) with perforated façade (c) and all configurations

Wind induced forces are resisted by core and perimeter columns in outrigger frame systems. Thus, understanding the moment distribution between core and perimeter columns is a way of understanding the structural response too. In Table 4.2, the results are given in numerical values to compare top drift values in milimeters (mm) with overturning and core moments in kilonewton meter (kNm) and the ratio of overturning moment (OM) carried by core to the total overturning moment. Analysis results show that no outrigger models with and without perforated façade have the highest core moment ratios. Those models have no outriggers and cannot reduce core moment through outrigger behavior. Even though, no outrigger (NO) and reference building (RB) models with wind escape floors (O) have close results in terms of OM carried by core, but reference building with perforated façade (RB-O) model has still better top drift results. Among alternatives, brace outrigger model with perforated façade (BO-O) have the minimum OM carried by core. Virtual outrigger model with perforated façade (VO-O) follows the brace outrigger (BO-O) model results where VO-O model performed better than other models both in OM carried by core and top drift value.

Table 4.2. *Top driftt, overturning and core moment comparisons of models*

Model Code	**Top Drift (mm)**	**Overturning Moment (OM) (kNm)**	**OM Carried by Core (kNm)**	**Ratio (%)**
NO-C	979	4.08E+06	0.71E+06	17.4
VO-C	887	4.06E+06	0.66E+06	16.3
BO-C	884	4.15E+06	0.67E+06	16.1
NO-O	880	3.65E+06	0.63E+06	17.4
SW-C	860	4.14E+06	0.66E+06	15.9
RB-O	823	3.66E+06	0.61E+06	16.7
VO-O	810	3.69E+06	0.60E+06	16.3
BO-O	758	3.53E+06	0.57E+06	16.1

Figure 4.2 points out that core moments and total moment of open models. Core moments are approximately close to each other. Although, outrigger typology affects the stiffness of the building, moment reduction in core are almost identical. In outrigger frame systems, bending moment which is carried by core is reduced up to %40, mostly (Choi, Ho, Joseph, Mathias, 2012). However, the core moment results showed in Table 4.2 are nearly up to 20%. The sample building is framed-tube system; outriggers are not as effective as they are in outriggered frame buildings.

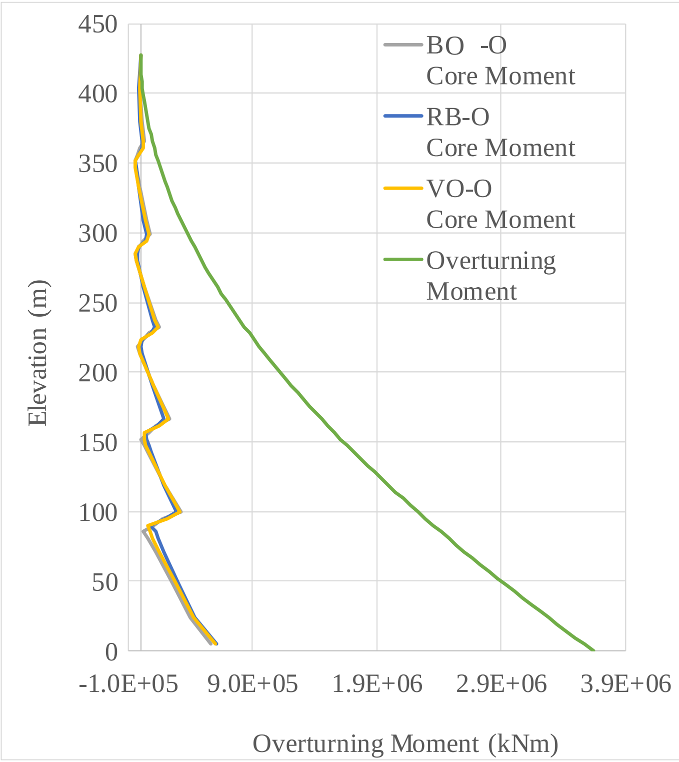


Figure 4.2. Overturning Moments of models with perforated façade

4.2. Results of models having alternative number of wind floor openings

There are 26 models investigated in the second phase of the study. These models are generated from certain type of outriggers (brace and virtual) which is selected according to the observations at the first phase of this study. Braced and virtual outrigger models are the most compatible with the all models tested in this study and the top drift values are the least ones among alternative outrigger types. In this part, alternative number of wind floor openings used with certain type of outriggers is scrutinized with the aim of achieving an optimum design in terms of top drift and core moment.

Figure 4.3 presents top drift values of virtual outrigger (VO) models with closed (C) and perforated (O) façades throughout the height of the building. The model having 3 levels of outriggers used with perforated façade (3VO-O) yields a top drift value of

866 mm, which is less than closed configurations having larger number of outriggers (5VO-C and 4VO-C).

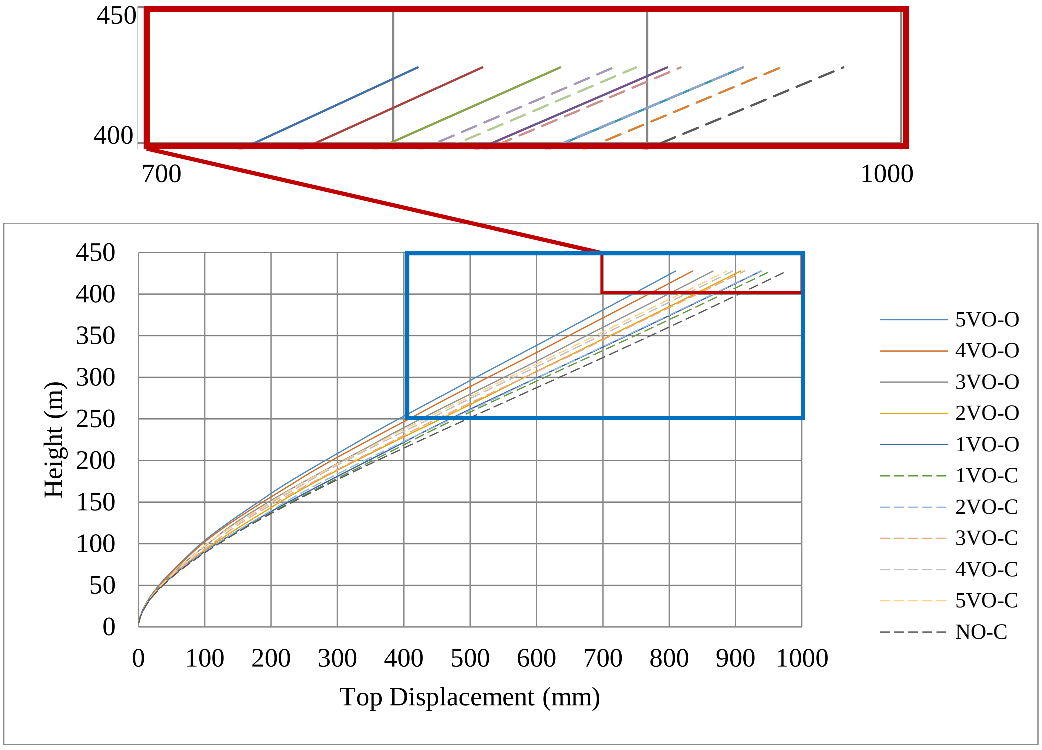


Figure 4.3. Virtual outrigger (VO) models with closed (C) and perforated (O) façades

Models with 5 and 4 sets of outrigger and closed façade (5VO-C and 4VO-C) performs better than the models having 2 and 1 sets of outriggers with perforated façade (2VO-O and 1VO-O), although their efficiency get reduced with increasing number of outriggers. Same observations are also valid for braced outrigger models with and without perforated façade (BO-O and BO-C).As shown in Table 4.3, braced outrigger models with perforated façade (BO-O) can reduce top drifts up to 22.5% compared to no outrigger with closed façade (NO-C) model. The results given in Table 4.3 also show that the reduction in top drift of 5BO-O model is 5.3% more than 5VO-O model.

Table 4.3. *Top drifts of virtual and braced outrigger models with and without perforated façades and reduction in top drift compared to NO-C model*

Model	Top drift (mm)	Percent	Model	Top drift (mm)	Percent
5BO-O	758	-22.5	**5VO-O**	810	-17.2
4BO-O	791	-19.1	**4VO-O**	835	-14.6
3BO-O	829	-15.2	**3VO-O**	866	-11.4
5BO-C	850	-13.1	**5VO-C**	887	-9.3
4BO-C	863	-11.7	**4VO-C**	896	-8.4
2BO-O	869	-11.1	**2VO-O**	908	-7.2
3BO-C	887	-9.3	**3VO-C**	914	-6.6
2BO-C	904	-7.5	**2VO-C**	938	-4.1
1BO-O	926	-5.2	**1VO-O**	938	-4.0
1BO-C	944	-3.4	**1VO-C**	953	-2.5
NO-C	978	0.0	**NO-C**	978	0.0

As seen in Figure 4.3, 2 levels of virtual outriggers with perforated façade (2VO-O) model have slightly lesser top drift value than 3 levels of virtual outrigger without perforated façade (3VO-C) which means that instead of using 3 level of outriggers with closed façade, one may use 2 levels of virtual outriggers with open façade for the same reduction in top drift. The relationship between 3VO-C and 2VO-O models is given in Figure 4.4.

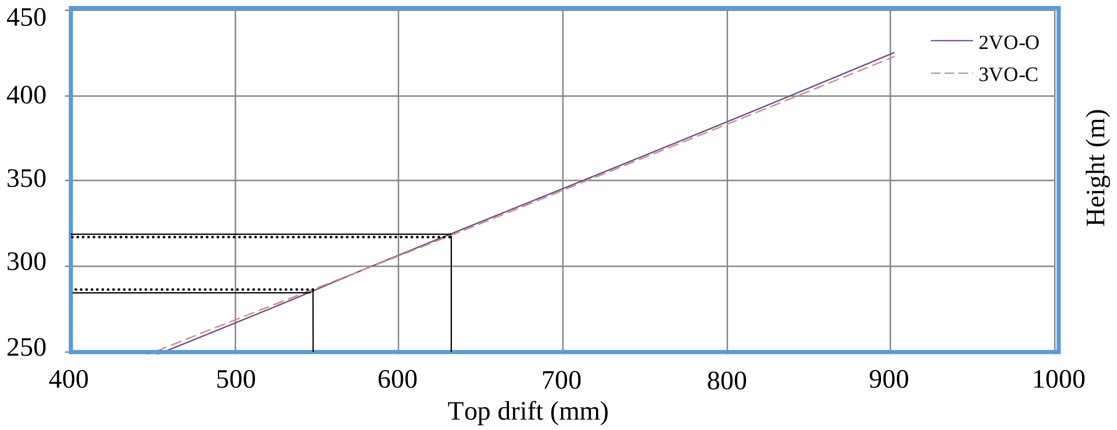


Figure 4.4. Upper story drift values of 3 levels of virtual outrigger with closed façade (3VO-C) and 2 levels of virtual outrigger with perforated façade (2VO-O) models

The top drift value of 2 levels of virtual outriggers with perforated façade (2VO-O) surpass model with 3 levels of outriggers with closed façade (3VO-C) approximately at 300 meter height as presented in Figure 4.4. However, as the building height increases, wind escape floors' height increases relatively. Hence, mean wind profile for different regions might affect these results. Note that, these results and heights are valid for 427.5 m height tall building with the same levels of wind escape floors.

Brace outrigger (BO) models have least top drift values among different outrigger typologies studied in first phase. Results of brace outrigger models are fairly similar to virtual outrigger models as shown in Table 4.3. In braced outrigger case, 2 levels of braced outrigger with perforated façade (2BO-O) intersects with 3 levels of braced outrigger model with closed façade (3BO-C) at approximately 150 m height shown in Figure 4.5.

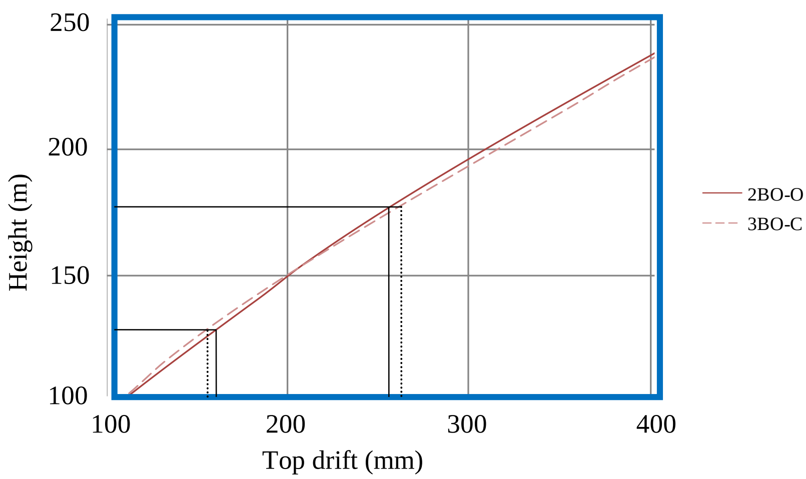


Figure 4.5. Upper story drift values for 2 and 3 levels of brace outrigger (2BO and 3BO) with and without perforated façade (O and C) respectively

Figure 4.6 shows overturning core moments of 2 challenging models as 2BO-O and 3BO-C. The core moments at ground floor are almost identical each other. The overturning moment of 2 levels of outriggers with perforated façade model (2BO-O) is lesser than 3 levels of outriggers without perforation (3BO-C) due to wind escapes.

On the other hand, the fraction points at wind escape floors are differentiate as expected. The similar graph is drawn for 3VO-C and 2VO-O models and same configuration is valid for them.

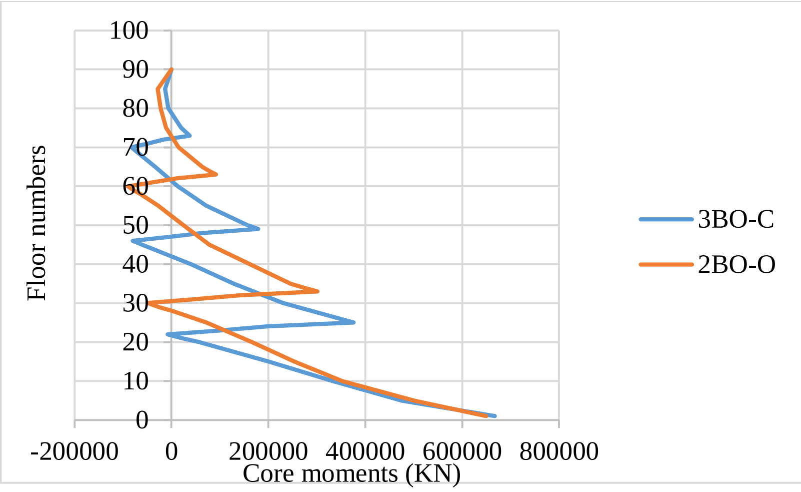


Figure 4.6. Overturning core moments of 2 and 3 levels of brace outrigger (2BO and 3BO) with and without perforated façade (O and C) respectively

Two types of outrigger with alternative number of wind floor openings are compared in Table 4.3. Also, a model of no outrigger with closed façade (NO-C) is included to those models as a reference of the reduction in top drift values. Models with 5 and 4 levels of brace outrigger (5BO-O and 4BO-O) are the ones effectively reduce the top drift of the case study building. 5 levels of virtual outrigger model with perforated façade (5VO-O) follows 5BO-O and 4BO-O and has less top drift compared to 3 levels of braced outrigger model (3BO-O). Note that, using 5 levels of wind escape floors distributed equally through the building height improve the building performance by providing up to 9.8% reduction in top drift compared to model without openings (NO-C).

Table 4.4. *Top drift comparisons of models having alternative number of wind escape floor*

Model	**Top drift (mm)**	**Percent Reduction**
5BO-O	758	-22.5
4BO-O	791	-19.1
5VO-O	810	-17.2
3BO-O	829	-15.2
4VO-O	835	-14.6
3VO-O	866	-11.4
2BO-O	869	-11.1
5NO-O	882	-9.8
4NO-O	903	-7.6
2VO-O	908	-7.2
3NO-O	927	-5.2
1VO-O	938	-4.0
2NO-O	942	-3.6
1BO-O	926	-5.2
1NO-O	961	-1.7
NO-C	978	0.0

Model with 5 levels of brace outrigger and perforated façade (5BO-O) has the closest ratio of 1/564 between studied models as indicated in Section 1.3, for providing occupant comfort. Besides, LERA Peer review (2011) reveals that 432 Park Avenue building is modeled on ETABS with 2 and 3 sets of outrigger options and the drift index values are 1/271 and 1/262, respectively. These results are compared to pre-study results of reference building model with 3 and 2 sets of outriggers and drift indexes are found to be fairly similar. Thus, the models analyzed in this thesis are expected to provide reliable results.

All models' (used in the second phase) overturning moments are illustrated in Figure 4.7. The overturning moments increase significantly with decreasing number of outriggers coupled with wind escape floors. On the other hand, models with closed have fairly similar overturning moment values as excepted.

Since virtual outrigger models are less stiff than brace outrigger models, the overall overturning moment results of virtual models are higher than brace outrigger models.

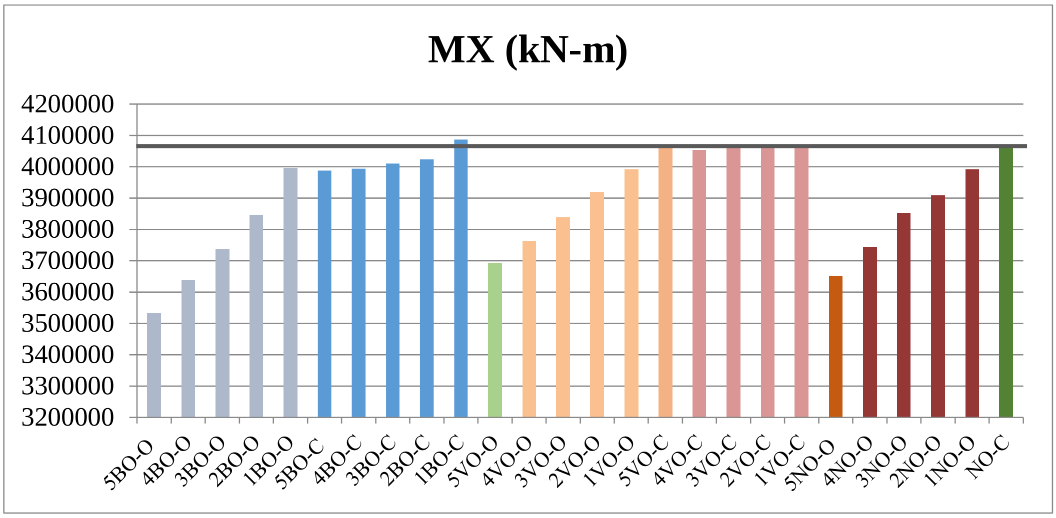


Figure 4.7. Overturning moments (OM) of Brace, Virtual and No outrigger (BO, VO and NO) models with perforated (O) and closed (C) façades

4.3. Evaluation on results

This study involves two phases for optimization of outrigger numbers and location with wind escape floors in a tall building. In this context, the first phase consists of 8 models with different outrigger typologies. Brace outrigger and virtual outrigger types reduce top drift of the building more than other typologies as shown in Figure 4.1. As presented in Table 4.2, overturning moments of the building are also less in these types of outriggers (BO-O and VO-O) with perforated façade compared to others such as shear wall outrigger with closed façade (SW-C), reference building with perforated façade (RB-O) and no outrigger with closed façade (NO-C). The reduction of top drift values is likely to be associated with the stiffness of the building and reducing wind induced loads. Hence, the models with brace and virtual outriggers (BO and VO) are chosen for the second phase of the study.

In the second phase of the study, 26 models are generated from brace and virtual outriggers with perforated and closed façades in order to determine its optimum location and number. Table 4.3 shows that 5 sets of brace outriggers with perforated façade (5BO-O) reduce top drift value mostly and its drift index is found as 1/564.

As shown in Figure 4.4, 2 sets of virtual outriggers with perforated façade perform better than 3 sets of virtual outrigger with closed façade in terms of top drift. In order to increase leasable area in super tall buildings, wind escape floors with two sets of outriggers can be preferred. Moreover, 4 sets of brace outriggers with closed façade top drift values resembles those of 2 sets of brace outriggers with perforated façade as shown in Figure 4.5. Therefore, using 2 sets of brace outriggers with perforated façade can reduce the cost and construction time with increasing architectural (leasable) area. Since the façade condition is perforated in both situations, the stiffness difference between brace and virtual outrigger is the reason of these results. According to overturning moments, which are directly related, to base shear, 5 BO-O is again shows better performance compared to other 25 models.

CHAPTER 5

CONCLUSION

5.1. Summary of research

The motivation of this thesis study is to reduce the number of unoccupied floor levels in super slender tall buildings by optimizing the arrangement of outriggers and wind escape floors.

A comprehensive literature survey is done about super slender tall buildings having wind escape floors as well as their structural systems to better understand the relationship between outriggers and wind openings as systems increasing the building performance against wind effects. As the scope of the study, the subject structural system and its relation with wind escape floors have been identified by this literature survey. Thereafter, a sample model which inspired from 432 Park Avenue building is generated with ETABS (ver. 16) software.

The literature survey reveals the fact that, the structural system and wind escape floors have to be compatible with each other for an improved system efficiently. Therefore, conducted study is settled into two stages. First phase is dedicated to the identification of efficient outrigger typology that can be used with wind escape floors and analytical models are generated within this context. The more convenient outrigger typologies are chosen from the first phase and further scrutinized within second phase. Analytical models with two types of outriggers, namely braced outrigger and virtual outrigger, are modeled with closed and perforated façades in alternative numbers through the height of the building. Additional building models without outriggers but only with perforated façades are generated to investigate the sole contribution of wind escape floors.

All in all, the results reveal the fact that using wind openings coupled with outrigger floors has a great potential for increasing building performance and providing occupant comfort by reducing top drift without further sacrificing of leasable areas.

5.2. Main Outcomes

Based on this study, following outcomes can be summed:

- The performance of tall building structural systems increases as the number of outriggers coupled with perforated façade increases. The efficiency of outriggers decreases as the number of outrigger levels increases whereas the wind load on the structure decreases as the number or the elevation, or both, of wind escape floors increases.
- 5 levels of braced outriggers coupled with wind escape floors reduce along wind storey drift up to 22.5% compared to the model without outrigger members and perforated façade.
- Overturning moments of models with perforated façade are found to be increased gradually where the number of outriggers is decreased due to the increasing wind load acting on the building as well as the reduced stiffness of the system.
- Outrigger typology has an influence on minimizing lateral movement of a supertall building. As the stiffness and strength, namely the efficiency, of the outrigger system is subject to change according to the outrigger typology, the lateral drift performance of the structure also changes with wind escape floors coupled with certain type of outriggers.
- Among alternatives, braced outrigger and virtual outrigger system coupled with wind escape floors performed better in terms of top drift.
- Models having 3 or more sets of outriggers (both virtual and braced) with perforated façades performed better than the models having 5 levels of outriggers with closed façade in terms of top drift.

- 2 levels of braced or virtual outriggers with perforated façade take the advantage of wind escape floors and have less along wind top drift values than 3 sets of outriggers coupled with closed façades. Thus, tall buildings leasable area can be increased by using perforated façades with certain type of outriggers instead of 3 sets of outriggers with closed façade.
- If it is intended to optimize leasable areas in plan, 2 levels of outriggers (both braced and virtual) with perforated façade have better performance than 3 levels of outriggers with closed façade in terms of top drift.
- Top drift is the least at 5 levels of braced outrigger which means that this model performs structurally and aerodynamically better than other all models studied in the thesis.
- Architects take into consideration that wind escape floors used with outriggers in super slender tall buildings can improve building performance and by this way, fewer floors are occupied by structural elements.

5.3. Limitation and Assumptions

The study has some limitations and assumptions which are explained below:

The used wind load calculations are based on ASCE 7-10 (2010) direct procedure which ignores vortex shedding and across wind loads acting on to building. Thus, the study is limited with static analysis process in context of along wind loading and independent from time variant.

Although, there is a tuned mass damper at upper floors in real building, it is ignored while generating analytical models. Thus, all models studied in this thesis scope are parametric models different from reference building.

There are three types of concrete grade which are used in reference buildings slabs in different floor ranges. However, is another assumption for parametric models used in the study. The slabs of the all models are generated with only one concrete grade in order not to increase the number of variants which effect the structural system of the building.

The corner columns of reference building located between ground and 7th floors showed in Section 3.1.3, Figure 3.2. are exception for generated models. The corner columns cross sectional areas are kept the same with parametric models but they are configured different in shape. Also, different column sizes are used throughout the height of the reference building, but this has been ignored in generic models for eliminating the effect of changing column dimensions on comparisons.

As indicated in Section 4.2, the top drift values of the reference building revealed by Lera Peer Review Report in 2011 are not identical with the results of the reference model (RB-O) with 5 levels of outriggers due to the differences indicated above (Tuned mass damper, different sizes of columns and concrete grade of slabs).

5.4. Recommendation for Further Studies

In order to investigate alternative ways of reducing the along wind story drift of slender tall buildings without increasing the number of unoccupied floors, an analytical study is conducted primarily focused on optimizing outrigger system and wind escape floor configurations. Tube systems having outriggers are the main subject of this study as tube systems inherently maximize the structural depth, a major requirement for super slender tall buildings. In future studies, the scope of this research can be extended to other structural systems, particularly outriggered frame systems. Besides, since the findings of this study rely on a building model having a certain height and aspect ratio, similar analyses can be made for other heights (i.e. mega tall buildings which are more than 600m) and aspect ratios. In this thesis study, only one type of outrigger coupled either with wind escape floors or closed façade has been used throughout the height of the building. Hybrid alternatives where a certain type of outrigger with closed façade at lower levels of the building can be used together with another type of outrigger coupled with wind escape floors at upper levels can be investigated as the subject of a future study.

This thesis study has been conducted through analytical models where the wind load applied to the structure has been calculated by ASCE7-10 based approach. The directional procedure used in this study is applicable to regular-shaped buildings of all heights for determining the design along wind loads. Nevertheless, it ignores the building response due to across-wind loading or vortex shedding. Such aspects should be considered by using wind tunnel procedure which is quite time consuming and expensive, and thus unfavorable to an optimization study by making use of dozens of models. Considering that issue, an analytical approach has been followed in this thesis study where an optimization is used to reduce the number of alternatives that can be easily used later in wind tunnel tests. This way a reasonable number of alternatives can be further scrutinized by considering other effects such as vortex shedding, across-wind loading and story acceleration. This task is the subject of an ongoing research project in which the author of this thesis is working as a researcher.

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