A STUDY ON TALL BUILDINGS AND AERODYNAMIC MODIFICATIONS AGAINST WIND EXCITATION

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Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

A STUDY ON TALL BUILDINGS AND
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The purpose of this thesis is to create basic design guidance for tall buildings and their aerodynamic modifications as a resource for architects, engineers, developers, and students. It aims to make a contribution to and strengthen particularly the architect's understanding of tall building design, that requires a high level of interdisciplinary approach, by providing a broad overview of the "tall building" with its general concepts; to demonstrate the importance of human element as a critical component in the design of tall building by clarifying the wind forces and resulting movements which cause discomfort to building occupants and create serious serviceability issues; and to show the significance of aerodynamic modifications as an effective design approach in terms of mitigating wind excitation. In order to achieve these purposes, firstly, a comprehensive literature survey, which includes the definition, emergence and historical background, basic planning and design parameters, and lateral load considerations of tall buildings is presented. Following a structural classification of the tall buildings, wind excitation, its negative effects on occupant comfort and serviceabilty issues, and the methods to control wind excitation are studied. Finally, the significance of aerodynamic modifications against wind excitation, which include modifications of building's cross-sectional shape and its corner geometry, sculptured building tops, horizontal and vertical openings through-building, are presented from the scholarship on this topic.

Keywords: Tall Building, High-rise Building, Skyscraper, Wind, Wind Excitation, Aerodynamic Modification.

ÖZ

YÜKSEK BİNALAR VE RÜZGAR ETKİSİNE KARŞI AERODİNAMİK MODİFİKASYONLARI ÜZERİNE BİR ÇALIŞMA

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Bu tezin amacı, yüksek binalar, ve onların aerodinamik modifikasyonları ile ilgili olarak mimarlar, mühendisler, müteahhitler ve öğrenciler için temel bir tasarım rehberi oluşturmaktır. Yüksek binalarla ilgili genel kavramlar üzerine geniş bir yelpaze açarak, özellikle mimarların yüksek seviyede disiplinlerarası yaklaşım gerektiren yüksek bina tasarım anlayışına katkıda bulunmak ve onu geliştirmek; bina kullanıcılarını rahatsız eden ve önemli ölçüde kullanışlılık problemleri yaratan, rüzgar kuvvetlerini ve onların sebep olduğu olumsuz etkileri açıklayarak, yüksek bina tasarımının temel bir unsuru olan insan faktörünün önemini belirtmek; yüksek binalardaki rüzgar etkisini azaltması açısından, etkili bir tasarım yaklaşımı olarak, aerodinamik modifikasyonların önemini anlatmak, tezin amaçlarındandır. Bu amaçlara ulaşmak için, öncelikle, yüksek bina tanımı, onun ortaya çıkışı ve tarihsel arka planı, temel tasarım ve planlama parametreleri, ve maruz kaldığı yatay yükler ile ilgili bölümleri içeren, geniş bir literatür araştırması sunulmaktadır. Daha sonra, yazar ve tez yöneticisi tarafından önerilen yüksek binaların yapısal sistemlerine ilişkin sınıflandırmanın ardından, rüzgar etkisi ve onun bina kullanıcılarına ve bina kullanışlılığa ilişkin olumsuz yönleri, ve bu olumsuzlukları gidermek için kullanılan metotlar anlatılmaktadır. Son olarak, binaların kesitleri, köşe ve bitiş geometrileri, ve üzerindeki yatay ve dikey açıklıklara yönelik iyileştirmeleri içeren, aerodinamik modifikasyonların önemi üzerinde durularak, bununla ilgili, literatürdeki mevcut araştırmalara yer verilmiştir.

Anahtar Kelimeler: Yüksek Bina, Gökdelen, Rüzgar, Rüzgar Etkisi, Aerodinamik Modifikasyonlar.

To My Parents

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INTRODUCTION

1.1 Introduction

Man has always built monumental structures for the gods, including temples, pyramids and cathedrals which pointed to the sky; however, today's monuments, i.e. tall buildings, symbolize power, richness, prestige, and glory. The major difficulty, from the ancient efforts to reach heaven with the Tower of Babel to the world's tallest building – Taipei 101, has been to overcome the limitations of nature with human ingenuity.

Tall buildings, which are usually designed for office or commercial use, are among the most distinguished space definitions in the architectural history of American urbanism in the twentieth century. They are primarily a reaction to the rapid growth of the urban population and the demand by business activities to be as close to each other as possible. Architects' imaginative reinterpretations of the building type, the inadequacy and high cost of land in urban areas, the desire to prevent the disorganized urban expansion, the need to preserve significant agricultural production, the concept of skyline, influence of cultural significance and prestige, have all contributed to force buildings upward.

Until the introduction of modern metal frame construction, advent of electricity, fireproofing, and most importantly elevator, tall building actually was not practical. These technological innovations were first utilized in the Home Insurance Building (1885), and by the advances in these innovations, tall buildings become more and more practical.

Today, it is virtually impossible to imagine a major city without tall buildings. Tall buildings are the most famous landmarks of cities, symbols of power, dominance of human ingenuity over natural world, confidence in technology and a mark of national pride; and besides these, the importance of tall buildings in the contemporary urban development is without doubt ever increasing despite their several undeniable negative effects on the quality of urban life.

The feasibility and desirability of tall buildings have always depended on the available materials, the level of construction technology, and the state of development of the services necessary for the use of the building. Therefore, advances in structural design concepts, analytical techniques, and a more sophisticated construction industry, in conjunction with the high-strength lightweight materials have made it possible to construct very tall, much more slender and lightweight buildings at a surprisingly low cost premium compared to conventional construction. However, every advance in height comes with a new difficulty and hence the race toward new heights has not been without its challenges as well. Understandably, the increased flexibility makes contemporary tall buildings much more vulnerable to environmental excitations such as wind, which leads to horizontal vibration.

The tall buildings are designed primarily to serve the needs of the occupancy, and, in addition to the satisfied structural safety, one of the dominant design requirements is to meet the necessary standards for the comfort of the building users and the serviceability. In this context, since wind can create excessive building motion, the dynamic nature of wind is a critical issue, negatively affecting occupancy comfort and serviceability. Moreover, the human response to building motion is a very complicated phenomenon concerning both physiological and psychological features. Furthermore, excessive building motion can, create noise and crack partitions, damage non-structural elements such as curtain walls, cause glasses to break, reduce fatigue life, malfunction of the elevators and equipments, and result in structural damages or even collapse. Therefore, the extreme vibration is a greater concern for both users as well as designers of modern tall buildings, and excessive acceleration experienced at the top floors during frequent windstorms should be kept within acceptable limits to minimize discomfort for the building occupants and to avoid these kinds of undesirable events.

Many researches and studies have been done in order to mitigate such an excitation and improve the performance of tall buildings against wind loads. Hence, different design methods and modifications are possible, ranging from alternative structural systems to the addition of damping systems in order to ensure the functional performance of flexible structures and control the wind induced motion of tall buildings.

An extremely important and effective design approach among these methods is aerodynamic modifications in architecture, including, modifications of building's cross-sectional shape and its corner geometry, sculptured building tops, and horizontal and vertical openings through-building. By changing the flow pattern around the building, aerodynamic modifications in building shape, i.e. an appropriate choice of building form, could moderate wind responses when compared to original building shape.

Tall buildings are gigantic projects demanding incredible logistics, and management and influence building industry, national economy, and require enormous financial investment. A careful coordination of the structural elements and the shape of a building which minimize the lateral displacement, may offer considerable savings.

Nowadays, the challenge of designing an efficient tall building has considerably changed. The conventional approach to tall building design in the past was to limit the forms of the buildings to a rectangular prism mostly, but today, much more complicated building geometries could be utilized. In addition, planned and designed buildings today by means of sophisticated computer technology, have little or no historic precedent, and thus structural engineers can come up with daring structural solution.

On the other hand, the architects must be aware of the fact that, tall building design is a very complicated issue and requires an extraordinarily high level of coordination and collaborative study among different disciplines; namely early integration of aerodynamic shaping, wind engineering considerations, the selection of structural system and the control of building response to dynamic wind excitations, play a vital role in the design of tall buildings.

Since the wind forces and resulting movements in tall building design can be moderated by proper shaping of the building, an iterative process of shaping, wind tunnel testing, detailed analysis, and then re-shaping of the building can make dramatic changes in the level of forces experienced by the building. When successful, the structure becomes the architecture and the architecture becomes the structure, and the viability of a project is determined by these issues as they have an effect on the cost and constructability of the project. When the tall buildings, especially those constructed in the last decades are investigated, it will be seen that the effective building shape factor is remarkably taken into consideration in the design of the tall buildings.

1.2 Objective and Scope

The main objective of this research is to contribute to the development of the design guidance for tall buildings in relation to aerodynamic modifications to control wind excitation as a reference for architects, engineers, developers, and students.

The study shows that aerodynamic shaping of a building has a great importance in the design of the tall buildings and architects must be aware of this fact when designing a tall building. Thus, at the early stages of the planning of tall buildings, it must be certainly integrated with the other design disciplines.

In this research, *the concept of tall building*, which include the definition, emergence and historical background, basic planning and design considerations, and lateral loads; *structural systems*; *wind excitation*; and *aerodynamic modifications of tall buildings,* are studied.

In *chapter 2*, definition, evolution and historical background, and lateral loads of tall buildings are provided in order to familiarize the reader with the concept of tall building.

In *chapter 3*, structural systems of tall buildings are summarized and a structural classification for the tall buildings is proposed by the authors.

In *chapter 4*, the importance of wind excitation for tall buildings is clarified and discussed.

In *chapter 5*, the aerodynamic modifications of tall buildings, with some available researches in the literature are presented.

Chapter 6 summarizes the conclusion of this research.

CHAPTER 2

GENERAL CONSIDERATIONS ON TALL BUILDINGS

2.1 Definition of Tall Building

As the notion of size or appearance of tallness is a relative matter, and not consistent over time and place, it is difficult to define or distinguish the 'tall building', 'high-rise building' or 'skyscraper' just in terms of size. Unfortunately, there is no consensus on what comprises a tall building or at what magical height, or number of stories, buildings can be called tall. The terms all mean the same type of building which is built extremely high – in which skyscraper is a more assertive term. Although the high-rise building has been accepted as a building type since the late 19th century, tall buildings have been constructed since ancient times for several purposes and, therefore, the history of tall buildings is much older than a century. According to Ali and Armstrong (1995, p.143):

> The tall building can be described as a multistory building generally constructed using a structural frame, provided with high-speed elevators, and combining extraordinary height with ordinary room spaces such as could be found in low-buildings. In aggregate, it is a physical, economic, and technological expression of the city's power base, representing its private and public investments.

Beedle (1971) defines the tall building by stating: The multistory building can be generally described by the need of extra operation and technical measures because of its actual height, instead of by its overall-height or the number of stories. Furthermore, Ali and Armstrong (1995, p.9) by referring to Beedle (CTBUH, Group CH, 1978) state that:

> The typology is "a building in which 'tallness' strongly influences planning, design and use," or "a building whose height creates different conditions in the design, construction, and use than those that exist in 'common' buildings of a certain region and period.

From the structural design point of view, it is simpler to define a building as tall when its structural analyses and design are in some way affected by the lateral loads, particularly by sway caused by such loads (Taranath, 1998). A building is described as tall for an architect, when tallness becomes a concern affecting planning, esthetics, and environment. On the other hand, a building is considered as tall for a structural engineer, when the system must be modified to make it satisfactorily economical to carry lateral loads resulting from wind and earthquakes. Ada Louise Huxtable (1984, p.63) points out that "The tall building is the landmark of our age; the skyscraper and the twentieth century are synonymous".

Skyscraper is a word usually used to describe a very tall building, the 'very' is a comparative adverb dependent on time, while 'tall building' and 'high-rise building' are the terms depending on place. The word skyscraper was first applied to tall buildings in 1883, when the magazine American Architect published a letter saying, "America needs tall buildings; it needs skyscrapers" (Giblin, 1981, p.1). The essence of the skyscrapers combines ordinary spaces for many kinds of daily activities with an extraordinary height. Because of the lack of habitable interior spaces, the Eiffel Tower or the Washington Monument cannot be categorized as skyscrapers. "…a skyscraper as a 'super tall building' … a beam cantilevered from the earth" ('William LeMessurier's super tall structures: ...', 1985, p.144). As Leeuwen (1988) states, a skyscraper is the realization of both its technica1 enigma and its utopian-cosmopolitan objective. Francisco Mujica (1977, p.25) states that "The modern skyscraper is a building of great height constructed on a steel skeleton and provided with high speed electric elevators". According to his definition, the modern skyscraper rests on three fundamental inventions: passenger elevators, steel skeleton construction, and electricity. Leeuwen (1988, p.3) by referring to Starett (1928) argues:

> A skyscraper must be constructed on a skeletal frame (universally of steel) with the characteristics of having columns in the outside walls, rendering the exterior we see as a continuous curtain of masonry penetrated by windows.

Consequently, the use of the terms 'tall building', 'high-rise building', and 'skyscraper' have common associations, and depending on time and place, the concept of height varies in relation to the progress of technology and the desires of society.

2.2 The Emergence and the Historical Background of Tall Building

In this section, the emergence and the historical background of tall building, mostly in U.S.A. (the birthplace of tall building), the Far East in particular for recent history, and of course, Turkey are investigated. Because of its reaction and strict attitude against this 'American building type', Europe is not studied in detail.

“No symbol to the modern era are more convincing than the gravity defying vertical shafts of steel, glass, and concrete, that are called *‘skyscrapers’* ” (Harbert, 2002, p.1). As Greek temples and Gothic cathedrals are the representative building types of their respective periods, tall buildings and skyscrapers are seen as the best representative examples of industrialized society. They have compounded the human instinct to build ever higher, ego and competition, and the economic needs of coping with the density of urbanization.

In the 1890s, a 10-story building was considered as a skyscraper, yet just 40 years later, the Empire State Building with its 102 stories was constructed. Since their emergence over 120 years ago, these buildings have risen from 10 to over 100 stories, and what was once considered to be an American urban phenomenon, now dominates the skyline of almost every large city throughout the world.

As a product of culture, architecture sensitively reacts to the changes in the social and economic conditions of a specific era. If a society experiences a radical change, architecture also invents a new style or a special building type to respond to that change. The emergence of the skyscraper in Chicago was also a response to this kind of transformation resulting from a boom in economy, and the rise of the value of the urban space. As building activity grew more intense and the development of business corporations forced the concentration of offices in city centers with the growing capitalism, a new type of building with an enormous volume became a necessity, much of which it was extraordinary in form and technique. New ideas about tall buildings emerged with these extensive social and economic changes.

Tall buildings were both the pioneering challenges in the 19th century for architects and engineers; and also the symbols of new prosperity and advertisement for the rising capitalist class. Therefore, they began to be regarded as the most advanced symbols of modern society. Besides these factors, technical innovations in building systems have also played a greater role, much more than they did for any other building type, for the development of tall buildings. The rise of the skyscraper as an American building type could not have occurred without technical innovations in building systems. In the late 19th century, two technological developments, the introduction of the elevator and the modern metal frame construction, namely the development of higher strength and structurally more efficient materials like wrought iron and subsequently steel, paved the way for the development of the modern skyscraper, and the race for tallness started. The advances including fire proofing methods, electric lighting, advanced telecommunications and electronics, improved mechanical ventilation and cleaning technologies as well as new footing and foundation systems, have also contributed to the birth of the skyscraper.

After the Great Fire of Chicago (1871), which provided the opportunity for rebuilding the downtown area, more durable fireproof materials and techniques began to be utilized instead of wood and unprotected iron frame of the past. On the other hand, despite their excellent strength and fire resistance, brick and stone masonry suffered from the disadvantages of weight and extremely large vertical structural elements, when compared to the gross floor area. Finally, toward the end of the 19^{th} century, masonry construction reached its peak in Chicago with the construction of the 17-story, and 64 m high *Monadnock Building* (1891) (Figure 2.1). This building had 2.13 m thick load-bearing masonry walls at ground level. It was the last tall building in the city in terms of employing massive load-bearing masonry walls. Hence, before the building designers and architects could attempt to carry masonry walls even to further heights, the skyscraper appeared.

Most historians agree that the first skyscraper was William Le Baron Jenney's 10-story high *Home Insurance Building* (Figure 2.2) (two stories were added later) of 1884-1885. The design of this building initiated the innovative use of the structural steel frame for building multiple stories efficiently and created a model for future tall building designs. Since this initial improvement, the next generation of the skyscrapers has reached 150 stories - 15 times the number of stories in Jenney's building.

Figure 2.1 Monadnock Building, Chicago, U.S.A. (Bennett, 1995)

Figure 2.2 Home Insurance Building, Chicago, U.S.A. (Bennett, 1995)

2.2.1 The developments in America and the Far East

The architects and historians present a similar chronology with different number of phases, generally based on the changes of the design trends and the major architectural movements, for the history of the skyscrapers and their developments. For example, While Winston Weisman specified seven phases from 1849 to 1970 (Weisman, 1970), Cesar Pelli (1982) and Ada Louise Huxtable (1984) identified four skyscraper ages: ‘the functional’, ‘the eclectic’, ‘the modern’ and ‘the postmodern’ period. The historical background in this study utilizes and relies on the classification of Bennett (1995) which includes seven phases:

1- the functional period (1880-1890);
2- the eclectic period (1900-1920);
3- the art deco period (1920-1940);
4- the international style (1950-1970);
5- the super tall period (1965-1975);
6- the social skyscraper period (1970-1980);
7- the postmodern period (1980 -).

Throughout ***the functional era*** (1880-1890), there were great advancements in the technology of tall building: light, steel skeleton and a façade of terracotta or stone were utilized instead of heavy masonry construction. These innovations were essential before the buildings of more than five stories became feasible. With this lighter structure, it was possible to make larger areas of glass, and the buildings of this period were well-engineered and economical, with little decoration. Moreover, decoration and glass bay windows characterized the high-rise buildings by the end of the period. Basically, the early skyscraper was seen as an economic phenomenon in which business was the engine that triggered innovation. With the Home Insurance Building, *William Le Baron Jenney* opened a new chapter in building science. Together with him, *Daniel Burnham* with *the Reliance Building* (Figure 2.3); *John Wellborn Root* with *the Monadnock Building*; and, most important of all, *Louis Henry Sullivan,* known as the architectural father of the skyscraper, with his masterpieces such as the *Auditorium Building* and *Carson Pirie Scott Building* were the four dominant men of the era. They also played an active role in establishing the significant architectural movement, which is known as the Chicago School. *Tacoma Building* (1889) by Holabird and Roche, and *the Manhattan Building* (1890) completed by Jenney were among the other important tall structures in Chicago. Besides them, the 92 m high *Masonic Temple* (1895) (Figure 2.4) with a whole steel skeleton frame by Burnham and Root in Chicago was the tallest building of the period.

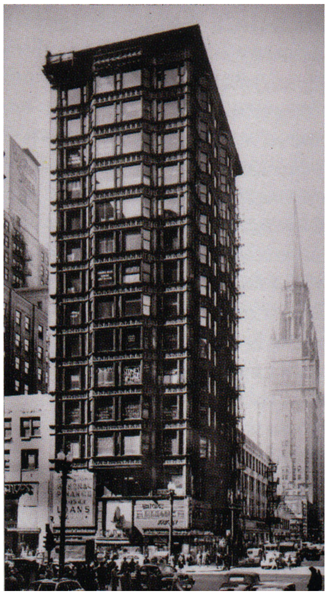


Figure 2.3 Reliance Building, Chicago, U.S.A.
(Bennett, 1995)

Figure 2.4 Masonic Temple, Chicago, U.S.A.
(Bennett, 1995)

During the first decade of ***the eclectic period*** (1900-1920), building design became progressively highly decorated. The Gothic and Renaissance motifs imported from Europe replaced the restrained elegance and order of the Chicago skyscraper. *Flatiron Building* (1903) (Figure 2.5) by Daniel Burnham, and *Woolworth Building* (1913) (Figure 2.6) by Cass Gilbert were the significant examples of this dynamic style. Moreover, 241 m high Woolworth Building was the tallest building in the world at that time. Many significant skyscrapers were produced in the second decade of the 20th century. Owners of the buildings and their architects started to search for new architectural styles which sought to combine height and decoration in a way that would reflect the owner's prosperity and position. Decorations taken from many styles such as Gothic Cathedrals, Palladian villas, Greek temples, Renaissance palaces, and French chateaux, were utilized in the skyscrapers of this era with great creativity and skill. However, some designs such as the most famous – *The Equitable Building* was not well-integrated into its immediate environment which led to the 1916 regulations that were established to control the irrelevant and undesirable excesses. From that time onwards, building shapes had to be set back to restrict their shadows as their height increased. With the 213 m high *Metropolitan Life Tower* (1909), historical references reached a new limit; and in spite of the several debates, the form of this building inspired some others for instance *the Bankers Trust Company Building* (1912) and *the Customs House Tower* (1915). On the other hand, New York's *Municipal Building* (1913) was also considered innovative owing to being well-interacted with its surroundings.

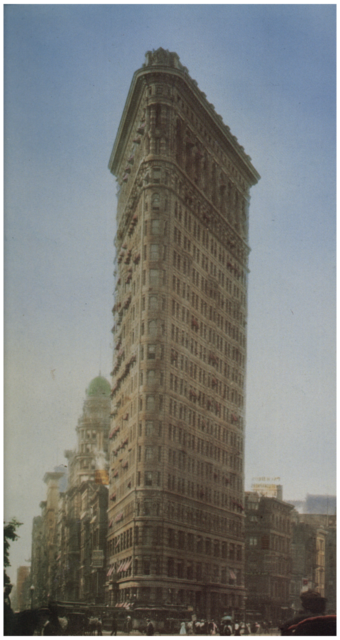


Figure 2.5 Flatiron Building, New York, U.S.A. (Bennett, 1995)

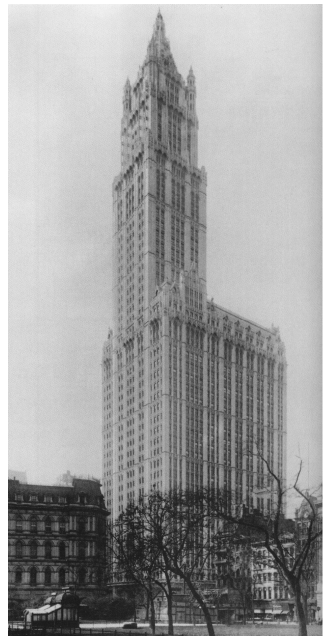


Figure 2.6 Woolworth Building, New York, U.S.A. (Zaknic et. al. 1998)

The art deco period (1920-1940), which had also a European origin in the 1920s and developed into a main style by the 1930s, involved a great mixture of various approaches, combining past European fashion, Mayan, Aztec, and Chinese architecture, and the modern influences of Cubism, Futurism, and Expressionism. American skyscrapers in this period were regarded as highly esthetic structures by the public. Yet, while Art Deco was the dominating style of the era, there was a growing reaction among the architects to refuse the derivative design of eclecticism and to prefer pure forms. *Tribune Tower* (1925) (Figure 2.7), *the New York Telephone Building* (1926) and *American Radiator Building* (1924) were among the landmark buildings of this period. Over the decades, technological innovations in the structural systems, building materials, elevator designs, ventilation, lighting, and heating systems made 100-story high skyscrapers possible and enhanced their comfort standards. The 283 m tall *Manhattan Company Bank Building* became the tallest building in the world in 1930s. Within a month, however, the 319 m tall *Chrysler Building* (Figure 3.4) by William Van Allen contributed to the race for the world's tallest building. The 381 m tall *Empire State Building* (1931) with 102 stories was the Chrysler Building's immediate challenger for the title of the tallest building in the world and had kept this title for four decades (Figure 3.5). These two buildings left an undeniable mark on the urban landscape - one which still endures today. *The Rockefeller Center* (Figure 2.8), however, was the greatest development ever undertaken. For its time, it was the largest multi-use urban project in terms of its sheer size, vision, and harmony within its context.

Figure 2.7 Tribune Tower, Chicago, U.S.A.
(Bennett, 1995)

Figure 2.8 Rockefeller Center, New York, U.S.A.
(Bennett, 1995)

The international style (1950-1970) was actually developed in Europe and then spread to America by several European master architects, for example by *Mies van der Rohe* and *Walter Gropius*. With the Great Depression and the 2nd World War, American life became more rational and pragmatic. Thus, economical, functional and usually box-shaped buildings constructed with glass, steel and concrete became more important in this period. The international style could be described by a complete absence of ornament and by forms in which the effects of mass were decreased for the sake of an effect of the purity of the form. Architectural expression was decreased to the essence of the structural form, depending on shape and scale to get elegance and beauty. *The Lever House* (1952) (Figure 3.2) by S.O.M was a notable building of this era. However, Rohe's 38-story high *Seagram Building* (1958) (Figure 2.9) was undeniably one of the most remarkable monuments of the period. Rohe's *Lake Shore Drive Apartments* (1952), *Inland Steel Building* (1958), *the Chase Manhattan Bank Building* (1963), S.O.M.'s *Brunswick Building* (1965), Ponti's *Pirelli Building* (1958) (Figure 2.10) with hexagonal glass façade in Italy and *the CBS Building* (1965) by Eero Saarinen were the other prominent buildings of the period.

Figure 2.9 Seagram Building, New York, U.S.A. (86)

Figure 2.10 Pirelli Building, Milan, Italy (Bennett, 1995)

During the mid-1960s, namely in the beginning of ***the super tall period*** (1965-1975), there were great innovations in the technology of tall buildings. The buildings with the glass-box look were beginning to disappear. The 1960s and 1970s became an era of discussion about different styles. On one side were the Modernists and on the other were the early Postmodernists. While architects were discussing the future of architecture, several new structural systems have been introduced with the objective of accomplishing economically-competitive and aesthetically-pleasing tall buildings without sacrificing safety. Thus, the design of tall buildings took a giant leap in the 1960s with the works of the brilliant engineer Fazlur Khan, who pioneered super tall structures including two of the most innovative tall buildings ever seen; the 344 m high *John Hancock Center* (1969) (Figure 5.6) with an exterior braced tube in Chicago; and the 443 m high *Sears Tower* (1974) (Figure 5.10) with a bundled tube. The record for height was initially broken by the 417 m high *World Trade Center Twin Towers* (Figure 3.10) in New York by Minoru Yamasaki in 1972, however, just two years later, the Sears Tower took this much popular title back to Chicago – it had been since 1895. In addition to these, 229 m high *Maine Montparnasse* in Paris and the 285 m high *First Bank Tower* in Toronto were also built in this period.

In ***the social skyscraper period*** (1970-1980), architects searched for a social character in tall buildings. According to Bennett (1995, p. 72):

> Skyscrapers could no longer exist as isolated tower, each one cut off from the street and community of which it was a part. But what was needed was a style that would make tall buildings more appealing, linking them to the urban landscape and making them part of the community, without sacrificing their corporate identities.

The IDS Center (1972) by Philip Johnson and John Burger in Minneapolis, *Pennzoil Place* (1976) (Figure 2.11) in Houston, Hugh Stubbins's *Citicorp Center* (1977) (Figure 3.16) in New York, and *the Xerox Center* (1980) (Figure 2.12) by Helmut Jahn in Chicago were significant buildings of this period.

The postmodern period (1980 -) with its incorporated color, sculptured form, and ornamentation, is a reaction to the Modernism, or International Style. But the selection criterion for a style was wide open, and thus a type of modern eclectic approach emerged. This approach, which is still developing its own identity, is utilized not only in North America but also in Europe and the Far East, where many of today's skyscrapers are being built (Bennett, 1995). *Philip Johnson* with *AT&T Building* (1985) (Figure 2.13) and *PPG Place* (1984), *William Pederson* with *333 Wacker Drive* (1983) (Figure 2.14) and *DG Bank* (1993), *Cesar Pelli* with *One Canada Square* (1991) and *Petronas Towers* (1997) (Figure 5.3), and *Norman Foster* with *the Honk Kong Bank* (1991) (Figure 2.15) are significant names of this period. *First Interstate Bank Tower* (1985), *Central Plaza* (1992), *Landmark Tower* (1993), *Trump Tower* (1983), I. M. Pei's *Bank of China* (1988), and the *CNG Tower* (1983) by Kohn Pederson Fox are also among the important buildings of the period. On the other hand, as some of the world's fastest-growing economies are to be found in Southeast Asia and China, this region became the birthplace of a new generation of super-tall buildings. Namely, while the building type was not welcomed with open arms in Europe, the momentum of skyscraper dominance has shifted in the 1990s from Chicago and New York City to Southeast Asia and China in particular. The tall building was accepted as a symbol of technological, economic, and political dominance in these geographies. Consequently, these countries will presumably soon overtake New York and Chicago as the leaders in the field of the tall building industry and design, and the majority of the next generation skyscrapers are most likely to be built in the Far East, even though some tall buildings are still being planned in the West. In this race, Cesar Pelli's 452 m high *Petronas Towers* in Malaysia, which took the title of world's tallest building from *the Sears Tower* in 1998, was the world tallest building until the construction of 508 m high *Taipei 101* in Taiwan (2004) (Figure 2.16).

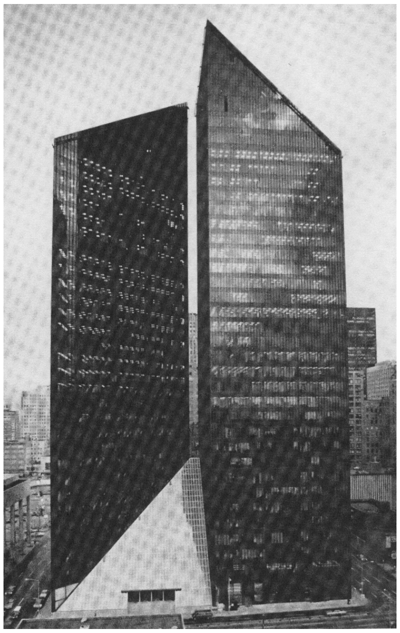


Figure 2.11 Pennzoil Place, Houston, U.S.A.
(Huxtable, 1984)

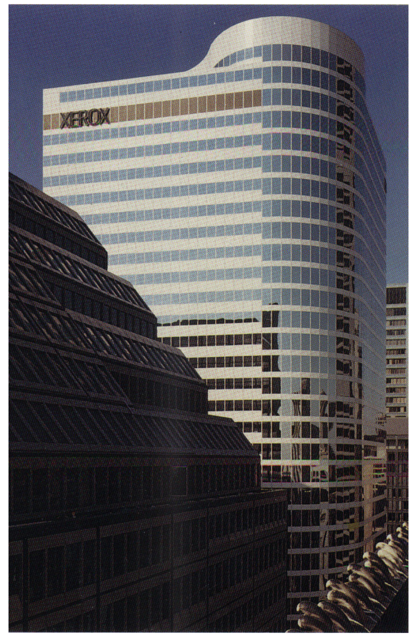


Figure 2.12 Xerox Center, Chicago, U.S.A.
(Bennett, 1995)

Figure 2.13 AT&T Building, New York, U.S.A.
(Bennett, 1995)

Figure 2.14 333 Wacker Drive, Chicago, U.S.A.
(Bennett, 1995)

Figure 2.15 Honk Kong Bank, Honk Kong, China (Bennett, 1995)

Figure 2.16 Taipei 101, Taipei, Taiwan (93)

In conclusion, for over a hundred years, tall buildings have been an integral part of the urban landscape. The technological innovations, economic growth, and rapidly increasing populations gave rise to tall buildings. Besides these factors, economics, and in many cases ego and politics, have traditionally been the driving forces in the rise and fall of tall buildings. Moreover, the evolution of tall buildings had several distinct periods, each marked with different solutions according to the developing technology, and different social needs and changes. Hence, tall building seems to have been not only a symbolic feature, but also a functional and economic one. If sensitively built, it is appreciated by every developing industrial society.

2.2.2 The developments in Turkey

In Turkey, the construction of tall buildings became widespread only after the 2nd World War. Since the 1950's, tall buildings with 20 or more stories, have been more frequently constructed. Firstly, they were built for hotel and commercial occupancy, and then for various functions such as residential, student accommodation, and business.

In the 1948 regulations, the maximum building height was defined as 21 m, in regard to the width of the street it fronted. In the period between the 1950's and mid-1970's, the tall buildings, most of which served as hotels and for commercial use, which were constructed were under 25 stories. The 13-story high *Ulus Business Center* (Ankara, 1958) (Figure 2.17), the 24-story high *Emek Business Center* (Ankara, 1962) (Figure 2.18), the 18-story high *Ankara Grand Hotel* (Ankara, 1960) (Figure 2.19), the 20-story high *Ankara Stad Hotel* (Ankara, 1968), and the 29-story high *Turkey İş Bank Tower* (İstanbul, 1970) were the important buildings of this period in Turkey.

Figure 2.17 Ulus Business Center, Ankara (100)

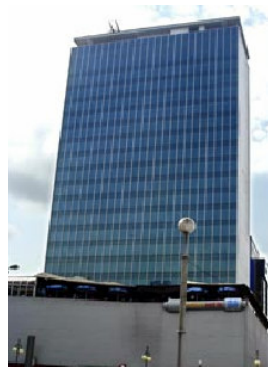


Figure 2.18 Emek Business Center, Ankara (29)

During the period between 1975 and 1985, the height of the buildings was increased up to 30 stories, thanks to the technological advancement, but for economic, and politic reasons, many of the projects could not be constructed. 28-story high *Hacı Ömer Sabancı Dormitory* (Ankara, 1984) (Figure 2.20) is the most significant building of this era.

Figure 2.19 Ankara Grand Hotel, Ankara (7)

Figure 2.20 Hacı Ömer Sabancı Dormitory, Ankara (37)

Since 1980's, however, the economy and the business capacity of Turkey have expanded due to its policy with foreign countries, and hence particularly in Ankara and İstanbul, the number of the tall buildings have increased in parallel to these developments. After 1985, projects with 30 to 50 stories have been designed by the help of technological improvements, such as the tubular system and the climbing formwork system. During the period between 1985 and 1990, many projects were realized especially in Ankara, İstanbul, İzmir, Antalya, and Mersin. The 23-story high *Ankara Hilton Hotel* (Ankara, 1988) (Figure 2.21), the 33-story high *İzmir Hilton Hotel* (İzmir, 1991) (Figure 2.22), the 25-story high *Nova Baran Center* (İstanbul, 1988) are the significant buildings of this period.

Figure 2.21 Ankara Hilton Hotel, Ankara (8)

Figure 2.22 İzmir Hilton Hotel, İzmir (49)

Since 1990's, the projects, which were at the design phase in 1980's, could have been realized. 39-story high *Akbank Tower* (İstanbul, 1993) (Figure 2.23), 32-story high *Halkbank Headquarter* (Ankara, 1993) (Figure 2.24) are such examples to these projects. 29-story high *Sheraton Hotel* (Ankara, 1991), 36-story high *Dikmen Valley Towers* (Ankara, 1996), 26-story high *Armada Tower* (Ankara, 2002) (Figure 2.25), 34-story high *Beybi Giz Plaza* (İstanbul, 1996), and 40-story high *Polat Tower Residence* (İstanbul, 2001) are the examples of tall buildings of the recent time. Moreover, the 175 m high *Mersin Trade Center* (Mersin, 1987) (Figure 2.26) with 49 stories was the tallest building of Turkey for 13 years (1987-2000) until it lost this title to 52-story high *İş Bank Tower 1* (Figure 2.27) in İstanbul with 181 m height. On the other hand, 300 m high mixed-use tower complex - *Dubai Towers* (Figure 2.28), is planned to be constructed in İstanbul in 2008.

Figure 2.23 Akbank Tower, İstanbul (4)

Figure 2.24 Halkbank Headquarter, Ankara (38)

Figure 2.25 Armada Tower, Ankara (9)

Figure 2.26 Mersin Trade Center, Mersin (74)

Figure 2.27 İş Bank Tower 1, İstanbul (48)

Figure 2.28 Dubai Towers (proposed), İstanbul (26)

Consequently, when compared to other countries, the tall building issue in Turkey appears to have a shorter history. Today, with a rather limited range of technological possibilities compared to other more advanced countries, architects of Turkey, construct tall buildings with different architectural expressions by using same technology.

2.3 Planning and Design of Tall Buildings

Tall buildings are designed primarily to provide the needs of the occupancy, whether single use or mixed-use, which include different types of functions such as commercial, business, hotel, residential, recreational, parking and like. That is, the "human centered design", which means that the design should focus on people and be done for the people, is the keyword in the design of tall buildings. Their design should be based on an appropriate internal layout for the building and how the building can contribute positively to the neighborhood, community and city where it is located. Furthermore, while for the occupiers, the tall buildings provide comfortable and convenient workplace or living space, it maximizes potential land values and offer long term investment growth for developers and investors.

As the world economies expand, building designers are faced with the challenges of leading future developments to meet the needs of occupant comfort, safety, and building protection as well as conservation of the environmental quality in the built environment. In the design of tall buildings, these improvements required a multi-disciplinary effort, in which designers must understand how their efforts will integrate to the efforts of other design team members such as structural, mechanical, electrical, and environmental engineers, to create an overall project, which will be attractive, economical, energy efficient, and flexible in meeting the needs of occupants.

An important phase of research in the design of tall buildings is the exploration of the optimum design of building components. These components, such as floor construction, columns, bracing, skin, and mechanical systems, are strongly related to each other, in such a way that, a change in one component or building system generally affect many others. For example, a change in the floor depth will alter the building height, and therefore the overall structural, architectural, and mechanical costs of the building increase.

2.3.1 Basic planning considerations

Basic planning considerations for tall building design include the following parameters (Ali and Armstrong, 1995):

- planning module;
- lease span;
- ceiling height;
- floor-to-floor height;
- depth of structural floor system;
- elevator system;
- core planning;
- parking.

Planning module, namely the space one needs for living, changes according to the culture and the economic class. In design of residential tall buildings, the space allowed per person for normal living functions varies significantly among nationalities and cultures. For instance, while in the United States, the average living area per person is 24 to 28 m^2, in Germany 108 m^2 is allowed for rented apartments (2 to 5 persons) or 21.6 to 54.0 m^2 per person (Ali and Armstrong, 1995). Moreover, Ali and Armstrong (1995) by referring to Rubanenko (1973) state that, in average 73% net living area requires 27% traffic area.

Lease span, described as the distance from a fixed interior element such as building core to exterior window wall, is another important criterion for good interior planning. There are no international standards to determine lease span depths. These depths change depending on the function of the space, and acceptable lease span is determined by office layouts, hotel room standards, and residential code requirements for outside light and air. Usually, the depth of the lease span should be between 10 and 14 m for office functions, except where very large single tenant groups are to be accommodated. Lease span for hotels and residential units range from 6 to 9 m (Ali and Armstrong, 1995).

Ceiling height (Figure 2.29) is also an important factor in building planning. Commercial functions require a variety of ceiling heights ranging between 2.7 and 3.7 m. While office functions necessitate ceiling heights of approximately 2.5 to 2.7 m, residential and hotel functions require ceiling heights of 2.4 to 2.7 m (Ali and Armstrong, 1995).

As another planning criterion *floor-to-floor height* (Figure 2.29), which is a function of the necessary ceiling height, the depth of the structural floor system, and the depth of the space required for mechanical distribution, determines the overall height of the building, and affects the overall cost. A small increase or decrease in floor-to-floor height, when multiplied by the number of floors and the area of the perimeter enclosure by the building, can have a great effect on many systems such as the exterior, structural, mechanical system, and the overall cost.

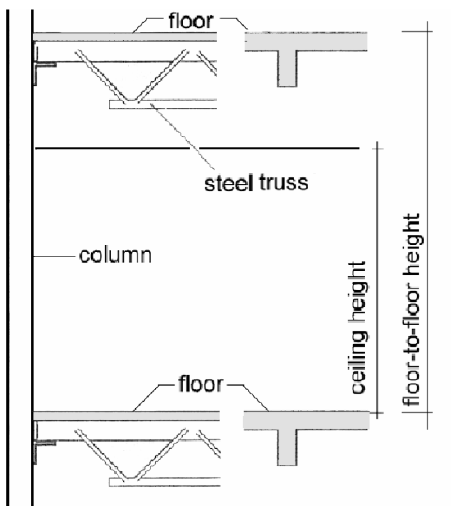


Figure 2.29 Ceiling height and floor-to-floor height

Depth of structural floor system plays an important role for planning considerations in tall buildings, and varies broadly depending on the floor load requirements, size of the structural bay, and type of floor framing system. In steel systems, increasing the structural dept will, up to a point, result in decreased weights of rolled sections, and with the use of trusses there is the possibility of even saving more weight. As they permit the passage of ducts, trusses provide structural depth without a proportional increase in floor-to-floor height.

Elevator is another major component for good interior planning. In the design of an elevator system, waiting interval, elevator size and speed interpretation of program criteria, areas to be served, the population density of the building, and the handling capacity of the system at peak periods, must be considered. This becomes even more complicated for mixed-use projects. For preliminary planning, one elevator per 4645 m^2 of gross area is a rule of thumb for estimating the number of elevators needed. Besides this, the net usable area varies from one elevator zone to another and from floor to floor, and should average from 80 to 85% over the entire building (Ali and Armstrong, 1995). The sky-lobby concept is an important and innovative approach in elevator system design. This concept uses high-speed express shuttle cars to transport passengers from the ground level to a lobby higher up in the building for transfer to local elevator zones so that the area used for elevator shafts and lobbies on the lower floors of the building is reduced.

Core planning is another significant issue for planning considerations. A typical floor in a tall building contains a perimeter zone, an interior zone, and a core zone. While *perimeter zone* is described as an approximately 4.5 m or 5 m deep area from the window wall with access through the interior zone, *interior zone* is defined as the area between the perimeter and the public corridor. On the other hand, *core zone* consists of those areas between elevator banks which become rentable on floors at which elevators do not stop. *Central core*, which is generally used in the buildings with a rectangular plan, and *split core*, which is generally used in the building with a relatively square plan, is the most typical core arrangements. Cores accommodate elevator shafts, mechanical shafts, stairs, and elevator lobbies. Core elements that pass through or serve every floor should be located, so that they can rise continuously, and thus avoid expensive and space-consuming transfers. In order to obtain better space efficiency, designers must give special attention to core planning.

Parking is another planning requirement, which varies according to different functions such as business, residential, and like. When parking facility provided within the footprint of the building, it has a great impact on the plan and the structure. Because of this reason, this is an undesired situation, and if possible, it should be avoided. If it is inevitable, the structural bay should be well arranged to obtain efficient space use for parking and functional areas, and the core elements should be effectively located to minimize interference with car parking and circulation. Mechanical ventilation is one other important concern for the user of parking facility, and pedestrians.

2.3.2 Basic design considerations

The basic design considerations for a tall building include the following parameters:

- the cultural, political, and social aspects of the city where the building will be located;
- a strong relationship with the city;
- the master plan and an appropriate site selection;
- sustainability;
- safety and security issues;
- learning about the possibilities and limitations of technology.

When a tall building is designed, the cultural, political, and social aspects of the city where the building will be located must be taken into consideration. The design team should also be aware of the codes, regulations, zoning requirements, and life safety issues of the different countries.

The tall building, which can be described as a vertical city, has a very strong relationship with the city, which could be defined as the mother city. The mother city's population, character, landmark value, location, infrastructure, and transportation system, have a great effect on the new vertical city itself. By making use of such information, the location of a tall building in the mother city could be determined and its negative effects on that city could be minimized.

The master plan is one of the significant design considerations for tall buildings, in which well-performed site analysis include, automobile, traffic and pedestrian impact, accessibility, minimal blockage of view, and minimizing the building shadows to neighboring buildings. Besides this, an appropriate site selection also includes the consideration of reuse or rehabilitation of existing buildings, and physical security. The location of tall buildings within an urban area affects the amount of day lighting, and may even create wind tunnels.

Sustainability is also a key element in tall building design. This concept is based on the following objectives: optimization of site potential, minimization of energy consumption, protection and conservation of water, use of environmental-friendly products, enhancement of indoor environmental quality, and optimization of operational and maintenance practices. Day lighting, natural shading, energy efficient and photovoltaic facades, wind power systems, and the sky garden concept are also the main parameters for a more sustainable tall building design.

Designing a safe and secure tall building has always been a primary goal for owners, architects, engineers, and project managers. There is an increased concern on these issues for tall building design especially after the disastrous 9/11 incident. Natural disasters, acts of terrorism, indoor air quality, hazardous materials, and fire are very significant and immediate safety issues to be considered in the design.

Learning about the possibilities and limitations of technology is critical for the success of the project. New technology and new building materials are being introduced at a fast rate; it is important to track these changes. The different demands of the ever changing nature of business and lifestyle also force us to be aware of the technological changes.

2.3.3 Urban design considerations

Another important subject in the development of tall buildings is their impacts on urban life. These buildings have a great influence on the skyline of the city and its physical, social, and economic systems; and also on the scale and context of the urban environment. Whether standing alone or blending into the urban context, the larger a building's mass, the greater its impact on the city. Although tall buildings play a vital role in the shaping of the modern urban area, they are often considered as uninvited guests in the urban landscape because of their enormous size, visual blockage and huge shadows. The urban design considerations for a tall building include the following parameters:

- the impact on the city's existing urban fabric and the historical heritage
- the impact on the capacity of the city's public services
- the impact on the street life in terms of their base
- the impact on the microclimatic environment of the city block and its surroundings
- the impact on city skyline identity

Tall buildings can also have an impact on the city's existing urban fabric, its environmental ecology, and historical heritage. When these huge structures fill up a whole city block, a human-scale landscape including conventional low-rise buildings is damaged. Furthermore, if they are located in a historic context, their harmony with the surroundings becomes an important subject. Significant public spaces, historic landmarks, and fine-grained urban fabric can be blocked out under these gigantic structures. Moreover, the construction of tall buildings often causes the removal of historic buildings or a disharmony with the historic context. Facade harmony and building material are significant features to provide continuity in a historic context. In that respect, the analogy or repetition of design element from the existing historic buildings can be a strategy for a successful contextual design of a new tall building. Therefore, a tall building needs to resolve the issue of massing and how the scale of the tower as a whole will relate to the image of the city, the neighboring structures, and the historic context.

Tall buildings also have a remarkable impact on the capacity of the city's public utilities and services, such as, its telephone lines and exchanges, water supply system, refuse collection and disposal, electrical supply and load shedding, sanitary system and discharge, and its postal services. They may dramatically affect the roads and other infrastructures in a city, such as transportation systems, and increase or create congestion in the surrounding movement systems as well.

The base and lower floors of the tall buildings are important spaces, since they serve the street life. However, while changing the scale and form of the street level, tall buildings increase the congestion of pedestrian and vehicular traffic. Most importantly than the design of a tall building must resolve how the building joins the ground to meet the street and its pedestrian life, the existing land use, and the character of the block where it is located. Its base may include retail spaces, public plazas, and cafes to generate social interaction, and "humanize" the scale at the street level of the building.

Other urban design considerations include the impact of the tall building on the microclimatic environment of the city block and its surroundings. The open spaces of modern cities are subjected to the strong winds, and gloomy shadows created by surrounding tall buildings. These shadows may considerably change the character of the area, which affects the microclimate as well as block out vistas. Moreover, pedestrians are subjected to the danger of strong wind channeled down these rising canyons of buildings.

Skyline identity of tall buildings is another important issue for the urban design. Tall buildings are assumed as high level icons for the city. While their base serves the street life, their top generally serves the city skyline. At the tall building's skyline, its uppermost termination, the architect has greater opportunities for aesthetic expression.

Despite all their negative effects, it is impossible to think of contemporary cities without tall buildings. Since the restriction of height and profile by building codes or zoning laws and researching historical precedents are not enough to solve the problems discussed above, more successful solutions, in which the design process of a tall building aims for and attempts to keep the environmental disturbances at a minimum, should be found by the architects and city planners for tall buildings which present entirely new forms, users and technological problems.

2.4 Lateral Loads on Tall Buildings

From the structural design point of view, due to its height, a tall building could be described, as one that is more affected by lateral loads created by wind or earthquake actions compared to other building types. Thus, loads acting on tall buildings are different from those on low-rise buildings in terms of accumulation into much larger structural forces, and the increased importance of wind loading. Wind loads on a tall building act not only over a very large surface, but also with greater amount at the greater heights, and with a larger moment arm than on a low-rise building. Even though the wind loads on a low-rise building generally have a minor affect on the design and structural configuration, they can play a vital role for the selection of the structural system in a tall building.

Depending upon the mass and shape of the building, and the region, although, the wind load is very important in the design of tall buildings, in seismic regions, inertial loads from the shaking of the ground also play an important role. Furthermore, in contrast to vertical loads which can be estimated roughly from previous field observations, lateral loads, namely the wind and earthquake loads, on buildings are fairly unpredictable, and cannot be assessed accurately. However, with the help of modern materials and computer analysis today, engineers can calculate the forces acting on a building much more precisely, and determine the best structural design.

2.4.1 Wind effects on tall buildings

The wind is the most powerful and unpredictable force affecting tall buildings. Tall building can be defined as a mast anchored in the ground, bending and swaying in the wind. This movement, known as *wind drift*, should be kept within acceptable limits. Moreover, for a well-designed tall building, the wind drift should not surpass the height of the building divided by 500 (Bennett, 1995). Wind loads on buildings increase considerably with the increase in building heights. Furthermore, the speed of wind increases with height, and the wind pressures increase as the square of the wind speed. Thus, wind effects on a tall building are compounded as its height increases. Besides this, with innovations in architectural treatment, increase in the strengths of materials, and advances in methods of analysis, tall building have become more efficient and lighter, and so, more vulnerable to deflection, and even to swaying under wind loading.

Since the effects on nearby buildings and land configuration can be significant issues, a tall building should be considered with its surrounding in designing for the wind. The swaying at the top of a tall building induced by wind may not be seen by a passerby, but its effect may be a concern for those occupying the top floors.

Despite all the engineering sophistication performed with computers, wind is still a complex phenomenon, mainly owing to two major problems. Unlike dead loads and live loads, wind loads change rapidly and even abruptly, creating effects much larger than when the same loads were applied gradually, and that they limit building accelerations below human perception. Although the true complexity of the wind and the acceptable human tolerance to it have just begun to be understood, there is still a need to understand more the nature of wind and its interaction with a tall building, with particular reference to allowable defections and comfort of occupants.

2.4.1.1 Nature of wind

Wind, which is created by temperature differences, could be described as an air motion, generally applied to the natural horizontal motion of the atmosphere. The vertical motion, on the other hand, is termed as a *current*. Air close to the surface of the earth moves three-dimensionally, in which horizontal motion is much greater than the vertical motion. While the vertical air motion is significant particularly in meteorology, the horizontal motion is important in engineering. The surface boundary layer concerning the horizontal motion of wind extends upward to a certain height above which the horizontal airflow is no longer affected by the ground effect. Most of the human activity is performed in this boundary layer, and hence how the wind effects are felt within this zone is of great concern in engineering.

Wind is a very complex phenomenon owing to the many flow situations resulting from the interaction of wind and structure. In wind engineering, on the other hand, simplifications are made to find meaningful predictions of wind behavior by distinguishing the following features:

- variation of wind speed with height;
- turbulent and dynamic nature of wind;
- vortex-shedding phenomenon;
- cladding pressures.

2.4.1.1.1 Variation of wind speed with height

An important characteristic of wind is the variation of its speed with height (Figure 2.30). The wind speed increase follows a curved line varying from zero at the ground surface to a maximum at some distance above the ground. The height at which the speed stops to increase is called the *gradient height,* and the corresponding speed, the *gradient wind speed* (Taranath, 1998). This important characteristic of wind is a well understood phenomenon that higher design pressures are specified at higher elevations in most building codes. Additionally, at heights of approximately 366 m from the ground, surface friction has an almost negligible effect on the wind speed; as such the wind movement is only depend on the prevailing seasonal and local wind effects. The height through which the wind speed is affected by the topography is called *atmospheric boundary layer* (Taranath, 1998). The wind speed profile within this layer is in the domain of turbulent flow and could be mathematically calculated.

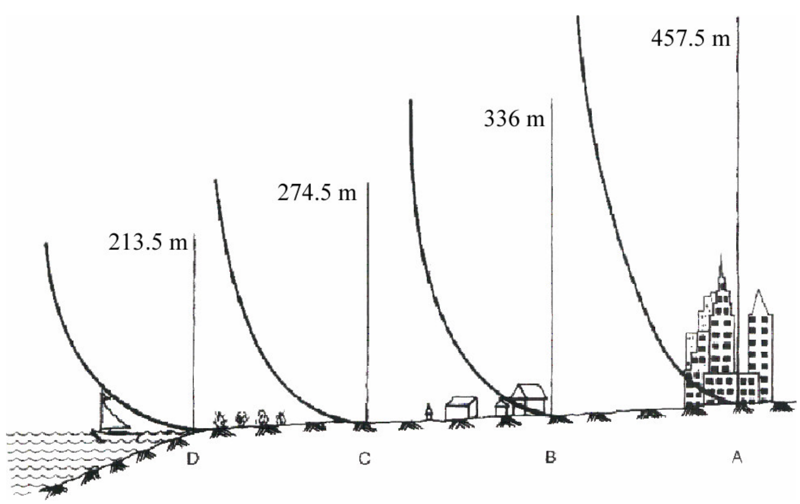


Figure 2.30 Variation of wind speed with height (Taranath, 1998)

2.4.1.1.2 Turbulent and dynamic nature of wind

Wind transfers some amount of its energy to the object that it hit on its path. The measure of the amount or energy transferred is called *the gust response factor*. Terrain roughness and variety of the height above ground, affect wind turbulence (also known as gustiness) (Taranath, 1998). Wind loads related with gustiness or turbulence, change rapidly and even abruptly unlike the mean flow of wind with static characteristic. Furthermore, the motion of wind is turbulent. Turbulence can be described as, any movement of air at speeds greater than 0.9 to 1.3 m/s, resulting in random movement of air particles in all directions (Taranath, 1998). The scale and intensity of turbulence can be related to the size and rotating speed of eddies (a circular movement of wind) that create the turbulence. Additionally, the flow of a large mass of air has a larger overall turbulence than that of a small mass of air. Consequently, from the structural engineer's point of view, the wind speed can be considered to include two components; a mean speed component increasing with height and a turbulent speed fluctuation.

2.4.1.1.3 Vortex-shedding phenomenon

Along wind and across wind are two important terms, also discussed in Chapter 4, used to explain the vortex-shedding phenomenon. Along wind or simply wind is the term used to refer to drag forces. The across wind response is a motion, which happens on a plane perpendicular to the direction of wind.

When a building is subjected to a wind flow, the originally parallel wind stream lines are displaced on both transverse sides of the building (Fig 2.31), and the forces produced on these sides are called vortices.

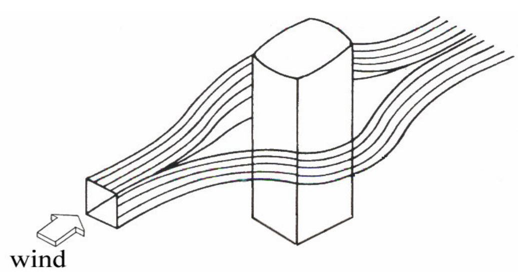
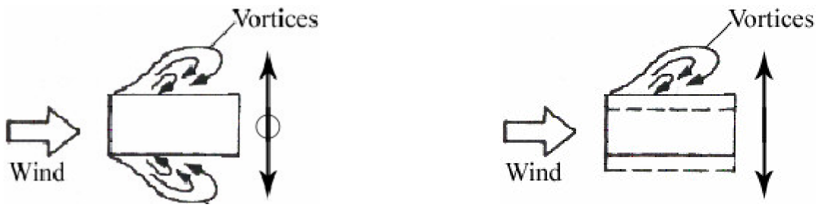


Fig 2.31 Simplified wind flow

At low wind speeds, the vortices are shed symmetrically (at the same instant) on either transverse side of the building (Fig 2.32a), and so building does not vibrate in the across wind direction.



(a) (b)

Fig 2.32 Vortices in different wind speed conditions: (a) vortices in low speed of wind (there is no vibration in the across wind direction); (b) vortices in high speed of wind – vortex-shedding phenomenon (there is vibration in the across wind direction)

On the other hand, at higher wind speeds, the vortices are shed alternately first from one and then from the other side. When this occurs, there is an impulse both in the along wind and across wind directions. The across wind impulses are, however, applied alternatively to the left and then to the right. This kind of shedding which causes structural vibrations in the flow and the across wind direction is called *vortex-shedding*, a phenomenon well known in fluid mechanics (Taranath, 1998). This phenomenon of alternate shedding of vortices for a rectangular tall building is shown schematically in Figure 2.32b.

2.4.1.1.4 Cladding pressures

The cladding design for lateral loads is a very significant subject for architects and engineers. Even though the broken glass resulting from the exterior cladding failure may be a less important consideration than the structural collapse during an earthquake, the cost of replacement and risks for pedestrians require careful concentration in its design.

Wind forces play a major role in glass breakage, also affected by solar radiation, mullion and sealant details, tempering of the glass, double or single glazing of glass, and fatigue. Breaking of large panels of glass in tall buildings can badly damage the neighboring properties and injure the pedestrians. Glass, and indeed any other cladding material, is not assessed with strength criteria, and hence glass can not be purchased according to yield strength criteria unlike concrete or steel.

Consequently, the selection, testing, and acceptance criteria for glass must definitely be based on statistical probabilities rather than on absolute strength. The glass industry has tried to solve this problem.

2.4.1.2 Wind tunnel engineering

Appreciation of wind loads in design started when the Eiffel Tower was completed to mark the occasion of the Paris exhibition in 1889. On the other hand, research for the wind effects on tall buildings started only during the design of the Empire State Building. Later, with the greater complexity of engineering systems brought about by the 2nd World War, wind engineering analysis developed rapidly. After the collapse of the Tacoma Narrows Bridge in 1940, a comprehensive study of the wind effect on structures was performed. Yet, the impact of turbulent flow on wind tunnel measurements was not understood until 1958, since when the techniques for modeling the turbulent wind effects have noticeably improved.

Within the past 20 years, the field of wind engineering has experienced a remarkable growth and has become a main discipline for assessing the wind load impacts on tall buildings. The wind tunnel approach is a sophisticated method to estimate design wind loads and to understand the complex action of wind in the design of very tall buildings. In order to determine the expected loads under both service-level and extreme wind conditions, scaled models of tall buildings are usually tested in commercial wind tunnels during design stage.

In the first level of tall building design, namely *the survivability limit states check* related to the extreme wind loadings, the building is checked if the wind tunnel's predicted loads for 50 or 100-year wind storms can be safely carried or not. However, this test may not always give the governing design scenario for the building. In the second stage, namely *the serviceability design parameter check,* the non-structural elements and mechanical services of the tall building are tested in terms of their drifts or displacement for more frequent 10-year event. A third and final limit state is the *habitability limit state*, quantified in terms of structural accelerations expected by the wind tunnel for service-level winds. Limiting structural accelerations can reduce occupant discomfort, ensuring that the structure is functional from a human as well as a mechanical perspective. This limit state is often critical for tall building projects (Kijewski and Kareem, 2003).

2.4.1.2.1 Wind tunnel tests

Even though wind tunnel tests still have several uncertainties due to the complicated characteristics of the natural wind, wind tunnel results for today's engineers are the-state-of-the-art in tall building design. Although wind tunnel model testing has gained a broader acceptance, the existing codes are also enough to comprehend the action of wind for many conditions (Taranath, 1998). In addition, it is necessary to determine the situations where the wind tunnel tests are necessary to obtain reliable structural performance. Wind tunnel model studies usually specify lower wind loads than those given in the codes and result in more economical designs as well.

Although it is difficult to determine the buildings that require wind tunnel tests, the buildings which appear to have an unusual sensitivity to wind, generally fall outside common practice. Wind tunnel tests can be a requirement for extraordinary aerofoil shaped buildings that are torsionally flexible even if their height is not an important design criterion. As a rule of thumb, the wind tunnel test can also be required for prismatic shaped buildings up to 40-50 stories high. Furthermore, the building models for wind tunnel tests are made to scales which differ from 1/100 to 1/1000 depending on the size of the building, and the size of the wind tunnel, with a scale of 1/400 being common.

A complete analysis of the wind effects on buildings (i.e. by wind tunnel tests) can be done through four experimental approaches: *the local wind climate study*, which can be obtained from the meteorological data of the location and can also be used to determine the distribution probability of the wind speed, *the aeroelastic modeling*, which is very important in determining wind induced dynamic effects on buildings*, the pressure measurement,* which is very significant for not only the design of the structural elements and cladding but also for the energy calculations; and *the wind environmental study,* which helps in town planning (Baskaran, 1993).

2.4.1.2.2 Pedestrian wind studies

With the introduction of tall buildings, the wind environment around them has become a significant technological and social problem. The shape of the building or structure may create inhospitable or even dangerous wind environmental conditions for pedestrians at street level. Moreover, several accidents have been reported with the most serious one related to two elderly British ladies who died from skull injury after being blown over by the winds in the vicinity of high-rise buildings (Stathopoulos et. al. 1992). Pedestrians who walk past tall, smooth-skinned skyscrapers may be subjected to what someone has called the “Mary Poppins syndrome,” referring to the tendency of the wind to lift the pedestrian literally off his or her feet. Another effect of this phenomenon, which has been frequently observed, is known as the “Marilyn Monroe effect,” referring to the billowing action of ladies’ skirts in the turbulence of wind around and in the vicinity of the buildings (Taranath, 1998).

The wind conditions around a building are affected by many factors such as, the ambient wind statistics, local topography, building mass, nearby foliage, and the closeness of similarly tall structures. All these can influence the resulting winds around the base of a new building and at elevated levels on balconies and terraces. Moreover, even though the acceptable wind speed is 5 m/s for most outdoor activities, this speed is too high for recreational areas, parks, or similar places. For these areas, additional wind breaks can be a necessity. Acceptable wind speeds depend not only on the activity of the person subjected to the wind, but also on his age as well (Houghton and Carruthers, 1976).

The quality of the wind environment at the base is considerably affected by design of a building. For example, a shear curtain wall all way down to the ground level in a rectilinear floor plan design can deteriorate street-level winds by allowing the high-elevation, faster winds to flow down the face of the structure, called *downwash* (Figure 2.33a), which is accelerated around the ground-level corners after the wind reaches the ground (Figure 2.33b). This is particularly true for buildings much taller than the surrounding buildings. In such cases, in order to prevent this kind of flow and protect sidewalk area around the entrance, large canopies are commonly used, particularly in office buildings (Figure 2.33c). Furthermore, if there is sufficient land, large podiums are also utilized for the same purpose (Figure 2.33d). Moreover, an arcade or an open, columned plaza under a building frequently creates undesired wind conditions (Figure 2.33e). A recessed entry provides low winds at door locations (Figure 2.33f) while a corner entry may increase wind concentration at building corner (Figure 2.33g).

Because of the innumerable variations resulting from location, orientation, shapes, and topography, it is impossible to find an analytical solution to this problem. Therefore, actual field experience and results of wind tunnel studies are utilized to qualitatively recognize situations negatively affecting the pedestrian comfort within a building complex. Besides this, model studies can provide reliable estimates of pedestrian level wind conditions based on considerations of both safety and comfort. For a successful design of a building at the pedestrian level, planners, designers, and developers are becoming increasingly aware of the potential for pedestrian-level problems, and generally acknowledge that design assistance is required to predict the microclimate that will be negatively affected by a design proposal.

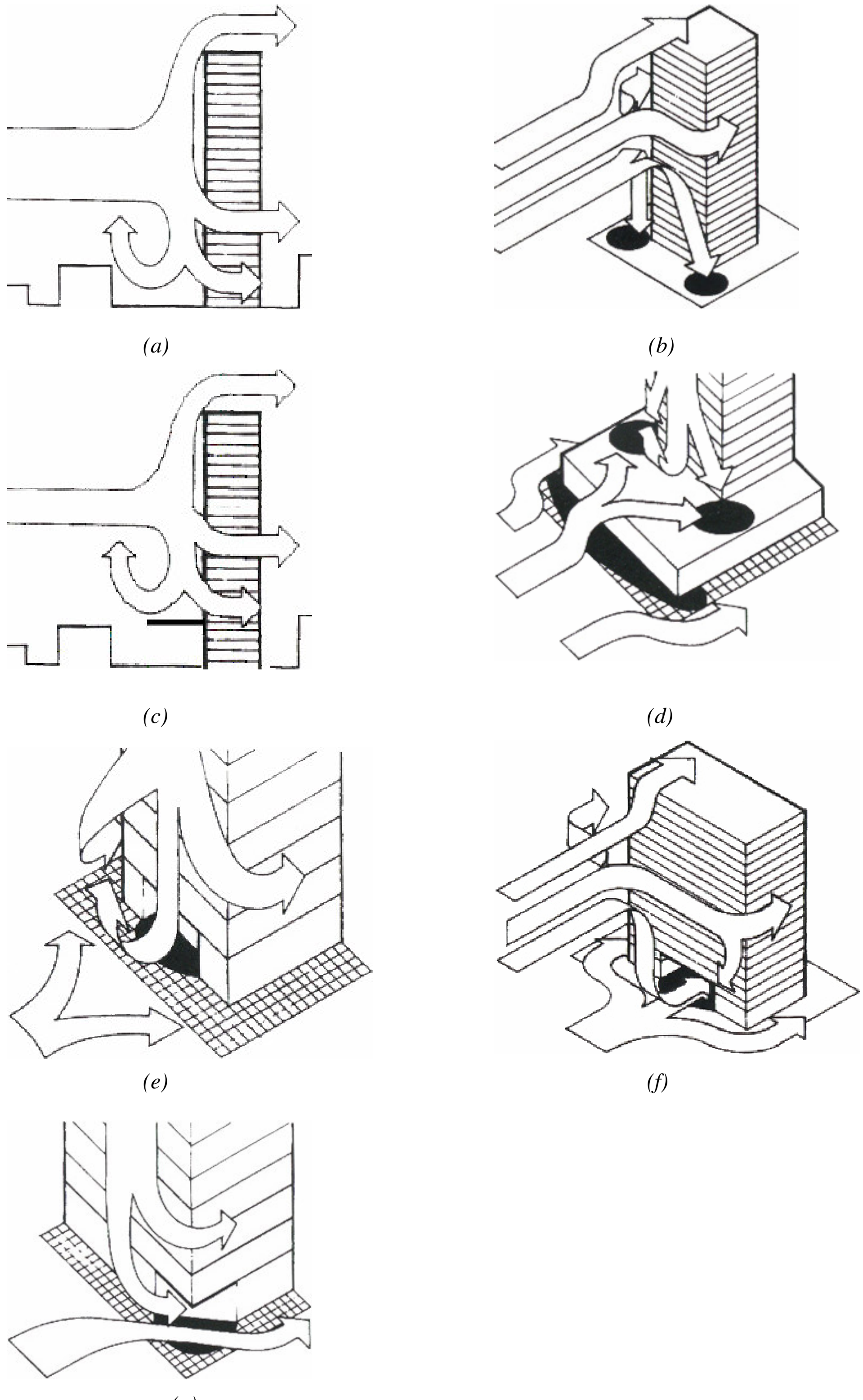


Figure 2.33 Design considerations for pedestrian wind studies: (a) downwash to street level; (b) high wind areas at the ground-level corners; (c) a large canopy; (d) large podiums; (e) recessed entry; (f) an arcade or an open columned plaza under a building; (g) corner entry (Taranath, 1998)

2.4.2 Earthquake effects on tall buildings

As earthquakes can happen almost anywhere, some measure of earthquake resistance in the form of reserve ductility and redundancy should be built into the design of all structures to prevent catastrophic failures. Moreover, during the life of a building in a seismically active zone, it is usually expected that the building will be subjected to many small earthquakes, including some moderate ones, one or more large ones, and possibly a very severe one.

Building massing, shape and proportion, ground acceleration, and the dynamic response of the structure, influences the magnitude and distribution of earthquake forces. On the other hand, if irregular forms are inevitable, special design considerations are necessary to account for load transfer at abrupt changes in structural resistance.

Therefore, two general approaches are utilized to determine the seismic loading, which take into consideration the properties of the structure, and the past record of earthquakes in the region. When compared to the wind loads, earthquake loads have stronger intensity and shorter duration.

The general philosophy of earthquake-resistant design for buildings is based on the principles that they should (Smith and Coull, 1991):

- resist minor earthquakes without damage;
- resist moderate earthquakes without structural damage but accepting the probability of non-structural damage:
- resist average earthquakes with the probability of structural as well as non-structural damage, but without collapse.

2.4.2.1 Nature of earthquake

The earth’s outer layer is composed of plates ranging in thickness from 32 to 241 km. The plates are in constant motion, riding on the molten mantle below, and normally traveling at the rate of a millimeter a week, which is equivalent to the growth rate of a fingernail. Hence, this motion causes continental drift and the formation of mountains, volcanoes, and earthquakes. As a complex phenomenon, earthquake has just begun to be understood. Thanks to the analytical studies of earthquake response of buildings, experimental studies performed both in the laboratory and in the field, much of destruction and loss of life resulting from earthquake are tried to be prevented.

2.4.2.2 Design considerations

The intensity of vibration of the earth's surface at the building site depends on following factors (Taranath, 1998):

- amount of energy released;
- distance from the center of the earthquake to the structure;
- character and the thickness of foundation material.

During an earthquake, the magnitude of seismic loads on the structure depends on the following factors (Taranath, 1998):

- building mass;
- the dynamic properties of the building;
- the intensity, duration and frequency content of ground motion and soil structure interaction.

Although, the magnitude of earthquake can be predicted on a regional basis from the probability theories, there are too many unknowns to be able to predict quantitatively and with any degree of certainty the ground vibration of some unknown future earthquake. Moreover, despite the advancements in earthquake engineering during the last three decades, many uncertainties still exist.

The plan layout of a building plays a vital role in its resistance to lateral forces and the distribution of earthquake forces. Experience has shown that the buildings with an unsymmetrical plan have a greater vulnerability to earthquake damage than the symmetrical ones (Taranath, 1998). Therefore, symmetry in both axes, not only for the building itself but also for the arrangement of wall openings, columns, and shear walls is very important. For a building with irregular features, such as asymmetry in plan or vertical discontinuity, assumptions different from the buildings with regular features should be used in developing seismic criteria.

If irregular features are inevitable, special design considerations should be used to account for the unusual dynamic characteristics, and the load transfer and stress concentrations that occur at abrupt changes in structural resistance. Asymmetry in plan can be eliminated or improved by separating L-, T-, and U-shaped buildings into distinct units by use of seismic joints at junctions of the individual wings. Considering the effect of lateral forces on the structural system from the start of the layout could save substantial time and money without detracting considerably from the building usefulness or appearance.

The systems to provide resistance to seismic lateral forces, rely basically on a complete, three-dimensional space frame; a coordinated system of moment frames, shear walls or braced frames with horizontal diaphragms.

The local soil condition is also an important factor for the seismic motion. For instance, harder soils and bedrock will effectively transmit short-period vibrations while filtering out longer-period vibrations as opposite to softer soils which will transmit longer-period vibrations (Taranath, 1998).

A list of features that can be utilized to minimize the earthquake damage is as follows (Taranath, 1998):

1- Provide details which allow structural movement without damage to non-structural elements, such as piping, glass, plaster, veneer, partitions and like. To minimize this type of damage, special care in detailing, either to isolate these elements or to accommodate the movement, is required.

2- Breakage of glass windows can be minimized by providing adequate clearance at edges to allow for frame distortions.

3- Damage to rigid non-structural partitions can be largely eliminated by providing a detail at the top and sides which will permit relative movement between the partitions and the adjacent structural elements.

4- In piping installations, the expansion loops and flexible joints used to accommodate temperature movement and are often adaptable to handling the relative seismic deflections between adjacent equipment items attached to floors.

5- Fasten free-standing shelving to walls to prevent toppling.

In the earthquake-resistant design, because of quite low probability, there is no need to consider the simultaneous action of wind and earthquake loads. Furthermore, there is no record that an extreme wind and earthquake loads stroke a building at the same time. It is expected, as in the case of wind loads, that under the action of moderate earthquake loads, the building structure will remain within the elastic range.

By means of the probabilistic methods, in which all possible earthquakes in the area are considered, the seismic hazards at a site can be assessed. Thanks to this approach, the associated shaking at the site and the probabilities of these occurrences can be determined. However, given the current limited knowledge and understanding of the earthquake process, all assessments of earthquake hazard are inherently uncertain.

2.4.2.3 Tall building behavior during earthquakes

Since the seismic motions of the ground result in vibration in the structure, the behavior of a tall building can be described as a vibration problem during an earthquake. The damage in a building results from the inertial forces caused by the vibration of the building mass. An increase in the mass has two adverse effects for the earthquake design. First, it causes an increase in the force, and second, it can result in buckling and crushing of vertical elements such as columns and walls.

On the other hand, even though the duration of strong motion is a significant measure, it is not explicitly utilized as a design criterion at present. In order to prevent distress in structural members and architectural components lateral deflections resulting from seismic loads should be limited. For the design of the non-structural elements, sufficient clearance or flexible supports are important criteria to accommodate the predictable movements.

Seismic motion response of tall buildings is to some extent generally different than low-rise buildings. The magnitude of inertia forces generated by an earthquake depends on the building mass, ground acceleration, the nature of foundation, and the dynamic characteristics of the structure (Figure 2.34). Although tall buildings are more flexible than low-rise buildings, and usually experience accelerations much less than low-rise ones, a tall building subjected to ground motions for a prolonged period may experience much larger forces if its natural period is near that of the ground waves (Taranath, 1998).

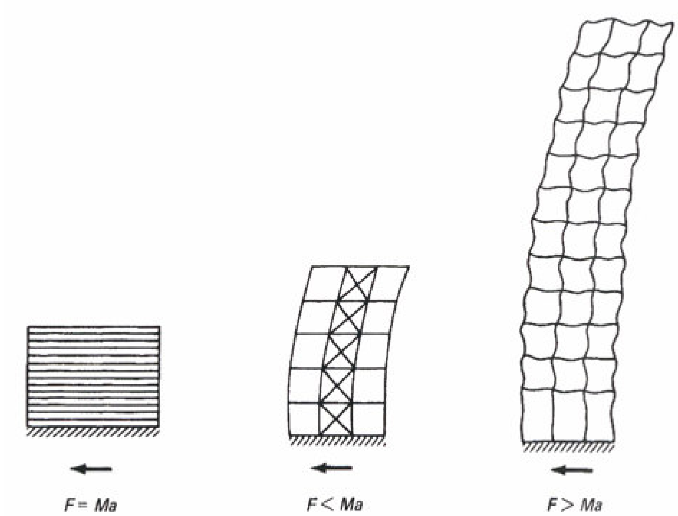


Figure 2.34 Schematic representation of seismic force (Taranath, 1998)

2.4.2.4 Damping and seismic separation

The conventional approach to improving the safety and serviceability of structures is to increase the structure's capacity by enlarging the member section and providing sufficient ductility for the structure. Utilization of damping devices is another method to mitigate the dynamic response of the building.

Based on external energy requirement, damping devices used in earthquake engineering can be classified in two broad categories: *active* and *passive devices*. While in the passive devices, no external energy supply is required and the control mechanisms move along with the main structures, in the active devices, the dynamic responses of the structures are controlled with the introduction of external energy into the structure. Besides this, the degree of damping depends on the construction materials, type of connections and the presence of non-structural elements.

In addition, seismic separation approach can also be utilized. Because of different modes of response, adjoining buildings or adjoining sections of the same building can strike each other. In such cases, building separations or joints should be used to allow adjoining buildings to respond independently to earthquake induced motion.

CHAPTER 3

STRUCTURAL SYSTEMS FOR TALL BUILDINGS

3.1 Structural Systems for Tall Buildings: Lateral Load Resisting Systems

The key idea in conceptualizing the structural system for a slender tall building is to think of it as a beam cantilevering from the earth. From the structural engineer's point of view, because of their incredible height, lateral loads resulting from wind or earthquake actions play an important role in the structural design of tall buildings.

As a general rule, when other things being equal, the taller the building the more necessary is to identify the proper structural system for resisting lateral loads, in which the rigidity and stability requirements are often the dominant factors in the design. Moreover, the selection of the structural system of a tall building involves the following factors:

- economic criteria related to the budget of the project;
- function of the building;
- internal planning;
- material and method of construction;
- external architectural treatment;
- planned location and routing of the service systems;
- height and proportions of the building.

Consequently, the effect of lateral loads must be considered from the very beginning of the design process, and the structural systems need to be developed around concepts associated entirely with resistance to these loads. Over the past three decades, with the help of modern materials and computer analysis, a notable development has been achieved in the structural engineer's ability to improve appropriate building systems. The structural engineer has also developed a much more complete understanding of these forces of nature. Basically, there are three main types of buildings: *steel buildings*, *reinforced concrete buildings*, and *composite buildings*.

3.1.1 Steel, reinforced concrete and composite tall buildings

Even though the application of steel in structures can be traced back to Bessemers steel-making process (1856), its application to tall structures received its stimulus from the 300 m high Eiffel Tower (1889) (Taranath, 1998). Furthermore, the role of steel members which used to carry only gravity loads in the early structures, has been entirely upgraded to include wind and earthquake resistance in systems ranging from the modest portal frame to innovative systems involving outrigger systems, interior and exterior braced frames, and like. Today, structural steel could be utilized in a variety of structures from low-rise parking areas to 100-story high skyscrapers. Most of the tallest buildings in the world have steel structural system, due to its high strength-to-weight ratio, ease of assembly and field installation, economy in transport to the site, availability of various strength levels, and wider selection of sections. Innovative framing systems and modern design methods, improved fire protection, corrosion resistance, fabrication, and erection techniques combined with the advanced analytical techniques made possible by computers, have also permitted the use of steel in just any rational structural system for tall buildings.

Although concrete as a structural material has been known since early times, the practical use of reinforced concrete was only introduced in 1867 (Ali and Armstrong, 1995). The invention of reinforced concrete increased the significance and use of concrete in the construction industry to a great extent. Particularly, because of its moldability characteristics, and natural fireproof property, architects and engineers utilize the reinforced concrete to shape the building, and its elements in different and elegant forms. Besides this, when compared to steel, reinforced concrete tall buildings have better damping ratios contributing to minimize motion perception and heavier concrete structures offer improved stability against wind loads. New innovations in construction technology, methods of design and means of construction, have all contributed to the ease of working with concrete in the construction of tall buildings. Moreover, high strength concrete and lightweight structural concrete allow using smaller member sizes and less steel reinforcement. Similar to steel or composite construction, reinforced concrete offers a broad range of structural systems for tall buildings. According to Ali (2001, p.13):

> Structural systems which go beyond the traditional post-and-beam construction of the Ingalls Building and the introduction of high-strength concrete mixes have together allowed reinforced concrete skyscrapers to grow to heights of the Petronas Towers and the Jin Mao Building never dreamed of in Elzner's and Ransome's day.

All tall buildings can be considered as composite buildings since it is impossible to construct a functional building by using only steel or concrete. That is, in a critical sense, using mild steel reinforcement can make a concrete building a composite structure, and in the same way, reinforced concrete slabs can make a steel building, a composite building. In this study, buildings having reinforced concrete beams, columns, and shear walls are accepted as reinforced concrete (or concrete) buildings, and in the same way, buildings having steel beams, columns and bracings are accepted as steel buildings. Namely, the frame and bracing or shear walls – but not the floor slabs – are the determining parameters for the building type. A concrete column became more economical than a pure steel column thanks to the introduction of high and ultra-high-strength concrete with compressive strength up to 181 MPa in 1960 (Taranath, 1998). Besides the economic feature, moldability, high stiffness and insulating, and fire-resisting quality of concrete, have all contributed to realize its structural combination with steel which has merits of high strength-to-weight ratio especially for seismic zones, fast construction, long span capacity, ease of assembly and field installation. While reinforced concrete is mostly used in apartment, condominium, and hotel buildings, where the underneath of floor slab is often used as finished ceiling, either steel or reinforced concrete can be utilized for office buildings with no need of hung ceilings, depending upon the in-place cost of the frame and/or the speed of construction. Concrete and steel systems evolved independently of each other until 1969, the year in which the composite construction, basically described as a steel frame stabilized by reinforced concrete, of a 20-story building was done by Dr Fazlur Khan (Taranath, 1998).

Both steel and concrete constructions have advantages and drawbacks. Thus, a perfect structural system is one that overcomes the drawbacks and makes use of the advantages of both materials in a unified superior system. Moreover, without composite construction, many of our contemporary tall buildings may never have been constructed in their present form today. On the other hand, here, the term composite system means any and all combinations of steel and reinforced concrete elements and is considered synonymous with other definitions such as mixed systems, hybrid systems, etc.

In this research, taking into consideration the studies in the literature (Taranath, 1998; Gaylord and Gaylord, 1979; Fintel, 1974; Smith and Coull, 1991) the following classification is proposed by the authors for the structural systems of tall buildings:

1- *Frame (rigid frame) systems;*
2- *Braced frame and shear walled frame systems;*
3- *Outrigger - belt truss systems;*
4- *Framed tube systems;*
5- *Braced (exterior braced) systems;*
6- *Bundled tube systems.*

3.1.1.1 Frame (rigid frame) systems

Rigid frame systems are utilized in both steel and reinforced concrete construction. Rigid frame systems for resisting lateral and vertical loads have long been accepted for the design of the buildings. Rigid framing, namely moment framing, is based on the fact that beam-to-column connections have enough rigidity to hold the nearly unchanged original angles between intersecting components. Figure 3.1 shows typical deformations of a rigid frame under lateral load.

Owing to the natural monolithical behavior, hence the inherent stiffness of the joist, rigid framing is ideally suitable for reinforced concrete buildings. On the other hand, for steel buildings, rigid framing is done by modifying the joints by increasing the stiffness in order to maintain enough rigidity in the joints.

For a rigid frame, the strength and stiffness are proportional to the dimension of the beam and the column dimension, and inversely proportional to the column spacing. Columns are placed where they are least disturbing to the architecture, but at spacing close enough to allow a minimum depth of floor. Thus, in order to obtain an efficient frame action, closely spaced columns and deep beams at the building exterior must be used.

Thanks to its simplicity, convenience of making rectangular arrangements, being able to place on the exterior, or throughout the interior of the building, the rigid framing is advantageous in the construction of the tall buildings. However, it is not very popular since the requirements usually limit the number of interior columns for the frame action. Moreover, especially for the buildings constructed in seismic zones, a special attention should be given to the design and detailing of joints, since rigid frames are more ductile and less vulnerable to severe earthquakes when compared to steel braced or shear walled structures.

In buildings up to 30 stories, frame action usually takes care of lateral resistance except for very slender buildings. For buildings with 30 stories and more, the rigidity of the frame system remains mostly insufficient for lateral sway resulting from wind and earthquake actions (Taranath, 1998). *Lever House* (1952) (Figure 3.2) in New York, built with steel is a good example of the frame system.

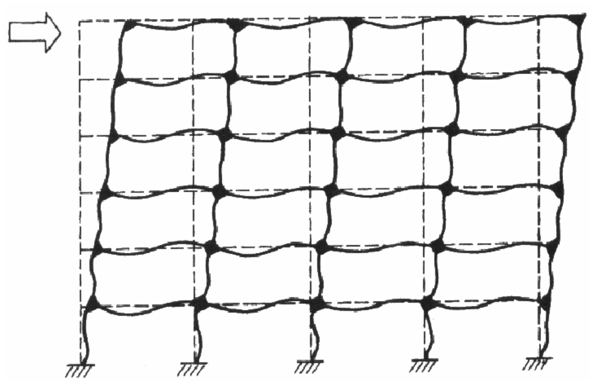


Figure 3.1 Response of rigid frame to lateral loads (Taranath, 1998)

Figure 3.2 Lever *House,* New York, U.S.A. (Bennett, 1995)

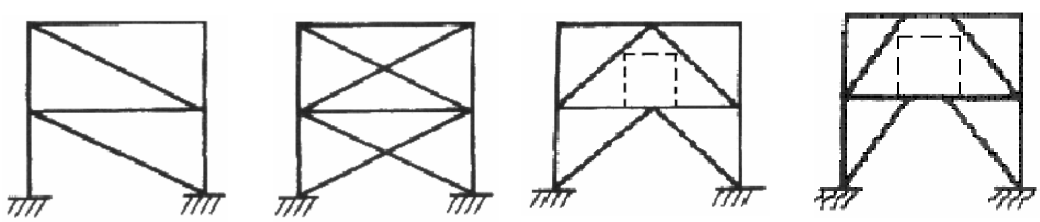
3.1.1.2 Braced frame and shear walled frame systems

Rigid frame systems are not efficient for buildings taller than 30 stories, because lateral deflection due to the bending of columns causes the drift to be too large (Taranath, 1998). On the other hand, introduction of steel bracing or shear walls, which interact with the frame, increases the total rigidity of the building, and the resulting system is named as *braced frame*, or *shear walled frame system*. While braced frame system is utilized in steel construction, shear walled frame system is utilized in both reinforced concrete and composite construction. These systems are stiffer when compared to the rigid frame system, and can be used for buildings up to 50 stories (Smith and Coull, 1991).

3.1.1.2.1 Braced frame systems

Braced frame systems are utilized in steel construction. This system is a highly efficient and economical system for resisting horizontal loading, and attempts to improve the effectiveness of a rigid frame by almost eliminating the bending of columns and girders, by the help of additional bracings. It behaves structurally like a vertical truss, and comprises of the usual columns and girders, essentially carrying the gravity loads, and diagonal bracing components so that the total set of members forms a vertical cantilever truss to resist the horizontal loading.

Depending on architectural and structural characteristics, braces can be classified as four main groups as shown in Figure 3.3. These are, *diagonal*, *X*, *K*, and *Knee bracings*. The K and Knee bracing systems are more efficient than diagonal and X bracing systems, since in the latter systems, floor beam spans full length between the columns, resisting in larger bending moments. What's more, K and Knee bracings offer greater freedom in the use of open space, since it is possible to fit door and windows.



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

Figure 3.3 Types of braced frame systems: (a) Diagonal – less available space; (b) X – the least available space; (c) K – openings possible; (d) Knee – larger openings

Besides its advantages, bracing has several drawbacks which are inherently obstructive in the architectural plan, and can create problems in the organization of internal space and traffic as well as in locating window and door openings. Thus, the areas around elevator, stairs, and service shafts, where frame diagonals may be enclosed within permanent walls, are the most preferable places for the braces; and the arrangement of the bracing is generally dictated by the requirements for openings.

Historically, bracing has been utilized to stabilize the building laterally in many of the world's tallest structures, including *Woolworth Building* (1913) (Figure 2.6), *Chrysler Building* (1930) (Figure 3.4) and *Empire State Building* (1931) (Figure 3.5).

Figure 3.4 Chrysler Building,
New York, U.S.A. (24)

Figure 3.5 Empire State Building,
New York, U.S.A. (30)

3.1.1.2.2 Shear walled frame systems

Shear walled frame systems (Figure 3.6) are utilized in both reinforced concrete and composite construction. Shear walls, first used in 1940, may be described as vertical cantilevered beams, which resist lateral wind and seismic loads acting on a building and transmitted to them by the floor diaphragms. Shear walls are generally parts of the elevator and service cores, and frames to create a stiffer and stronger structure. These elements can have various shapes such as, circular, curvilinear, oval, box-like, triangular or rectilinear. Reinforced concrete's ability to dampen vibration and provide mass to a building makes it a good choice of material. Moreover, concrete's quality of sound absorption makes this system suitable for hotels and apartment buildings to reduce the transfer of noises from unit to unit. This system is, a milestone in the development of taller concrete buildings, and was seriously studied first by Fazlur Khan. Shear walled frame system has a wide range of use. Namely, it has been used for buildings as low as 10-story or as tall as 50-story or even higher buildings (Taranath, 1998).

For composite tall buildings, the selection of structural materials coming first in the construction is often determined by the choice of construction technique. In one version, concrete core is cast first, followed by the erection of the steel surrounding (Figure 3.7). Even though the structural steel framing may proceed slowly when compared to traditional steel building, the entire construction period can be decreased owing to the rapid installation of elevators, mechanical and electrical systems of the core while the construction outside the core proceeds at the same time. In another version, steel erection columns are utilized within composite shear walls to serve as erection columns, and steel erection proceeds as in a conventional steel building. After the steel erection has reached a certain level, concreting of core starts using conventional forming techniques. This system structurally behaves like a concrete building with shear walls resisting all the lateral loads. Use of rigid frames or other types of bracing around the building perimeter is an advisable method to neutralize the torsional effects. Since concrete shear walls are designed to resist all the lateral loads and some of gravity loads, the function of the steel surrounding designed as a simple framing is, to carry the gravity loads only. Composite metal deck with a structural concrete topping makes steel fabrication and erection simple.

Even though conventionally the core has been utilized to carry lateral forces, it has contribution also in resisting the vertical loads since a relatively small floor area is carried by the core. There are several methods to support the floors from the core depending upon the floor area and the number of levels, and of course, the economics of each method plays a vital role for the selection of a proper system. For instance: (1) floors can be hung from the top of the center core; or (2) the floor system can be cantilevered at each level (Taranath, 1998).

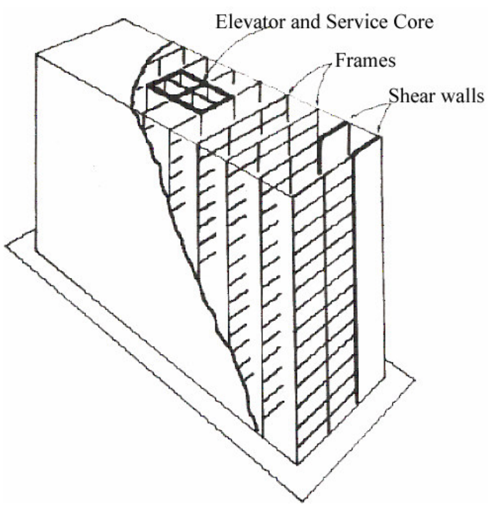


Figure 3.6 Representative shear walled frame structure (Smith and Coull, 1991)

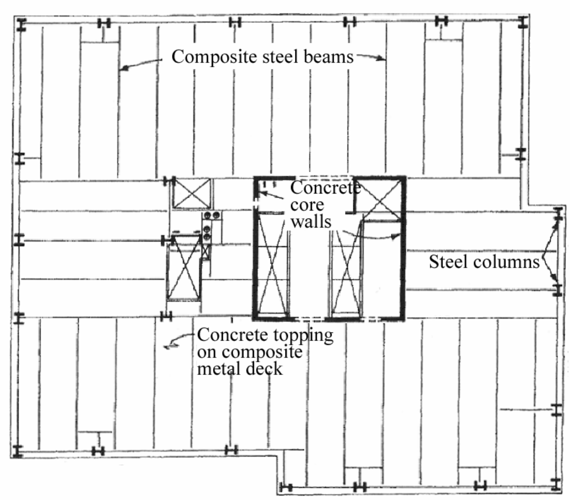


Figure 3.7 Typical floor plan of core structure with steel surrounds (Taranath, 1998)

3.1.1.3 Outrigger-belt truss systems

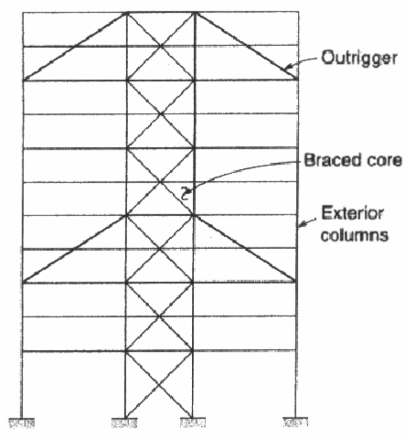
This system is a modified form of braced frame systems, and can only be utilized in steel. As an innovative and efficient structural system, the outrigger-belt truss system comprises a central core, including either braced frames or shear walls, with horizontal "outrigger" trusses or girders connecting the core to the external columns. If the building is subjected to the horizontal loading, the rotation of the core is prevented by the column-restrained outriggers. The outriggers and belt girder (Figure 3.9) should be at least one and often two stories deep to realize adequate stiffness. Thus, they are generally positioned at plant levels to reduce the obstruction they create.

The core may be centrally located with outriggers extending on both sides (Figure 3.8a) or it may be located on one side of the building with outriggers extending to the building columns on one side (Figure 3.8b). It is also possible to use diagonals extending through several floors to behave as outriggers (Figure 3.8c). Besides this, girders at each floor may be transformed into outriggers by rigid connections to the core and, if preferred, to the exterior columns as well (Figure 3.8d).

On the other hand, the efficiency of the system can be improved dramatically by placing it at certain strategic locations along the height of the building. Application of a "hat" or "cap" truss (Figure 3.8e-f) to bind the braced core to the peripheral columns is a method of enhancing the efficiency of the system. The tied columns, besides their usual function of carrying gravity loads, also facilitate supporting the overturning moments.

Depending upon the number of levels of outriggers and their stiffness the perimeter columns of an outrigger structure perform a composite behavior with the core. When compared to single outrigger structures multilevel outrigger structures have a significant increase in their effective moment of resistance. However, each extra level of outriggers enhances the lateral stiffness, but by a smaller amount than the previous added level so that 4 or 5 levels appears to be the economic limit.

Outrigger-belt structures can be used for buildings with over 100 stories. *First Wisconsin Center* (183m, 1974) (Figure 3.9) in U.S.A. and *Melbourne Tower* (proposed, 560 m, 2005) in Australia are excellent examples of this system.



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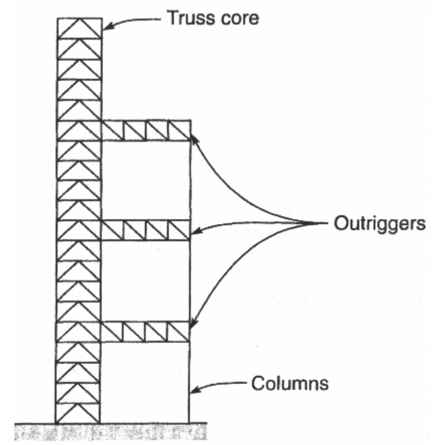

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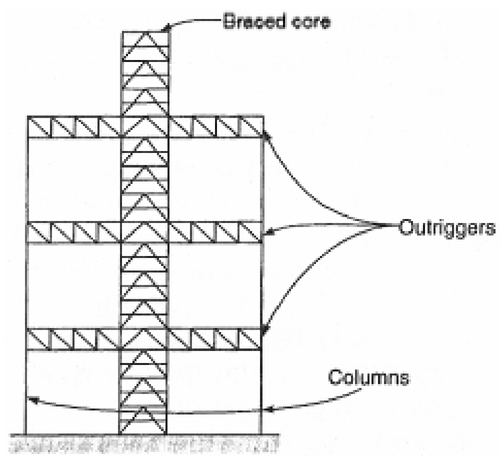

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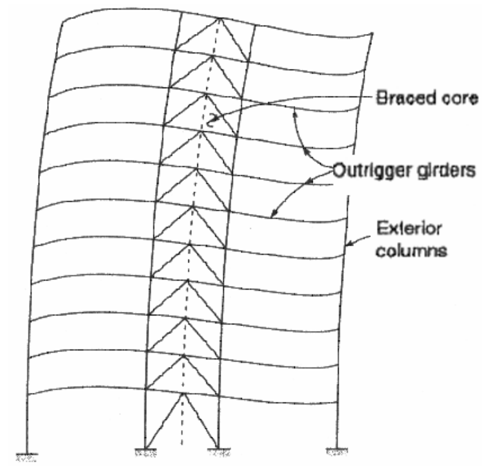

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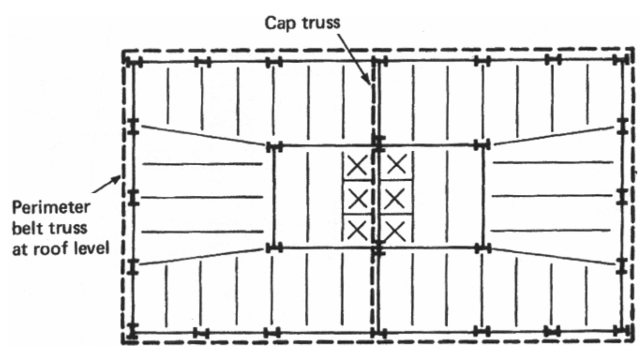

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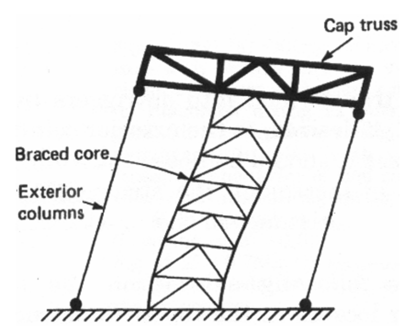


(f)

Figure 3.8 Different versions of outrigger structure:(a) outrigger structure with central core; (b) outrigger structure with offset core; (c) diagonals acting as outriggers; (d) floor girder acting as outriggers; (e) plan with cap truss; (f) behavior of the system with cap truss (Taranath, 1998)

Figure 3.9 First Wisconsin Center, Milwaukee, U.S.A. (Bennett, 1995)

3.1.1.4 Framed tube systems

Framed tube system, which is proper for steel, reinforced concrete and composite construction, represents a logical evolution of the conventional frame structure. Since braced frame and shear walled frame systems become inefficient in very tall buildings, framed tube becomes an alternative of these systems. Khan is generally credited for its invention in the 1960s. The primary characteristic of a tube is the employment of closely spaced perimeter columns interconnected by deep spandrels, so that the whole building works as a huge vertical cantilever to resist overturning moments. According to Smith and Coull (1991, p.44):

> Aesthetically, the tube's externally evident form is regarded with mixed enthusiasm; some praise the logic of the clearly expressed structure while others criticize the grid-like facade as small-windowed and uninterestingly repetitious.

It is an efficient system to provide lateral resistance with or without interior columns. The efficiency of this system is derived from the great number of rigid joints acting along the periphery, creating a large tube. Exterior tube carries all the lateral loading. The gravity loading is shared between the tube and the interior columns or walls, if they exist. Besides its structural efficiency, framed tube buildings leave the interior floor plan relatively free of core bracing and heavy columns, enhancing the net usable floor area thanks to the perimeter framing system resisting the whole lateral load. Because of the closely spaced perimeter columns, on the other hand, views from the interior of the building may be hindered.

The method of achieving the tubular behavior by using columns on close centers connected by a deep spandrel is the most common system because of the rectangular windows arrangement. Furthermore, the difficult access to the public lobby area resulting from the closely spaced column configuration at the base, could be overcome by using a large transfer girder or an inclined column arrangement.

Height-to-width ratio, plan dimensions, spacing, and size of columns and spandrels of the buildings, directly affect the efficiency of the system. Even though the tube form was developed originally for rectangular or square buildings, and probably its most efficient use is in those shapes, circular, triangular, and trapezoidal forms, could be employed as well. The drift limit of the tube changes consistent with its geometric and elastic properties.

Framed tube systems can be categorized into three groups:

1- the systems without interior columns, shear walls or steel bracings;
2- the systems with interior columns, shear walls or steel bracings;
3- the tube in tube systems.

When lateral sway is critical and starts controlling the design, the “framed tube” can be supplemented by a tube in the core to create “tube in tube” system, which can be constructed over 100 stories height. The 110-story high *World Trade Center Twin Towers* (1972) (Figure 3.10) with its “tube in tube” steel structure and *the DeWitt-Chestnut Apartment Building* (1965) (Figure 3.11) with its reinforced concrete structure are good examples of the framed tube system.

On the other hand, there are two popular versions used currently for this system for composite construction: one system utilizes composite columns and concrete spandrels while the other utilizes structural steel spandrels instead of concrete ones. In Figure 3.12 and 3.13 schematic plan and sections for the two versions are illustrated (Taranath, 1998).

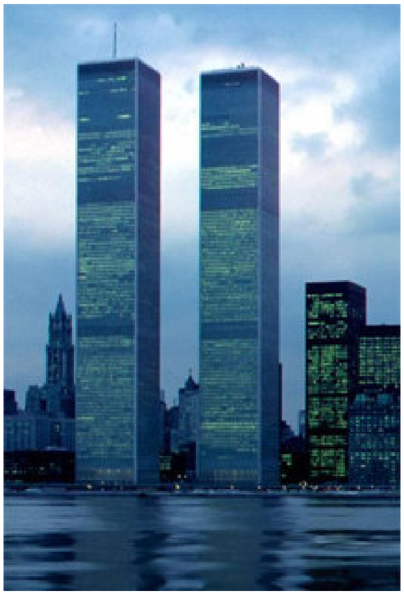


Figure 3.10 World Trade Center Twin Towers, New York, U.S.A. (103)

Figure 3.11 DeWitt-Chestnut Apartment Building, Chicago, U.S.A. (Ali, 2001)

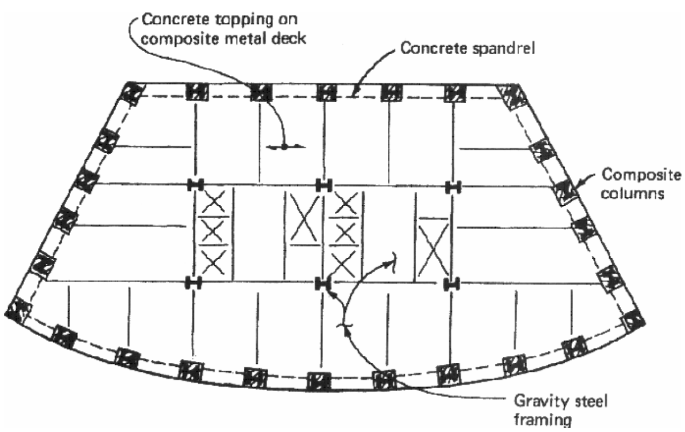


Figure 3.12 Composite tube with concrete spandrels: typical floor plan (Taranath, 1998)

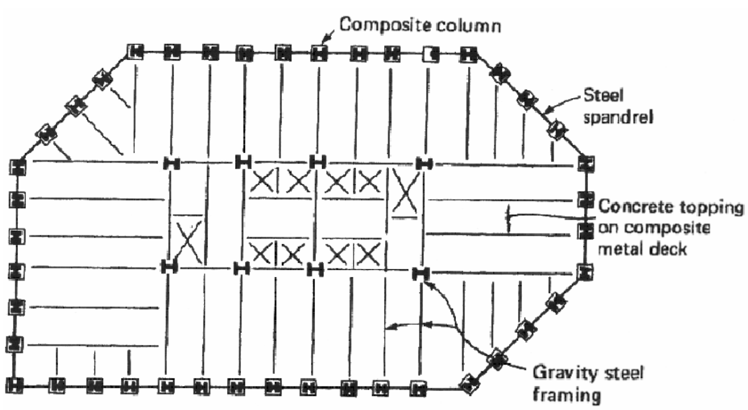


Figure 3.13 Composite tube with steel spandrels: typical floor plan (Taranath, 1998)

3.1.1.5 Exterior braced systems

This system can be utilized in steel, reinforced concrete and composite construction. By adding multistory diagonal bracings to the face of the tube, the rigidity and efficiency of the framed tube can be improved, thus the obtained system, the exterior braced tube, also known as diagonalized tube or trussed tube system, could be utilized for greater heights, and allows larger spacing between the columns. It offers an excellent solution by utilizing a minimum number of diagonals on each face of the tube intersecting at the same point as the corner columns. In steel buildings, steel diagonals, are used, while in reinforced concrete buildings, diagonals are created by filling the window openings by reinforced concrete shear walls to achieve the same effect as a diagonal bracing.

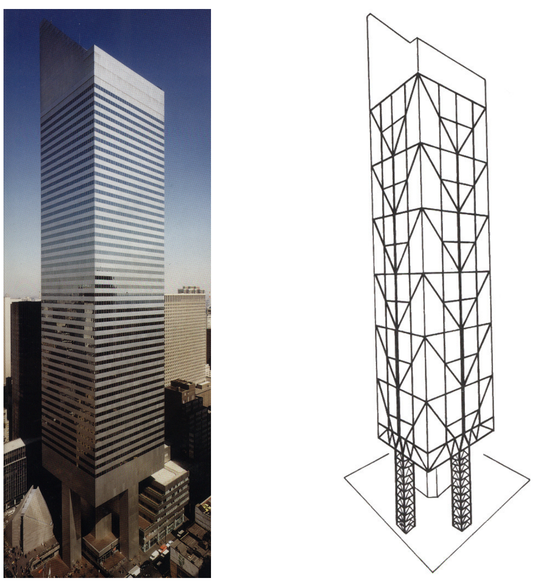
Although Fazlur Khan declared the principle of diagonal tube concept for concrete buildings in the 1970s, the realization of this idea took almost 15 years (Taranath, 1998). New York's *780 Third Avenue Building* (1985) (Figure 3.14) was the first reinforced concrete building to use this concept. *The Onterie Center* (Figure 3.15) in Chicago is another example of such a system in concrete.

On the other hand, the bracing guarantees that the perimeter columns act together in carrying both gravity and horizontal wind loads. Therefore, a very rigid cantilever tube is generated whose behavior under lateral load is very close to that of a pure rigid tube. This configuration is well suited for tall, slender buildings with small floor areas and was firstly used in a steel building, *the John Hancock Center* (1969) (Figure 5.6) by the great structural engineer Fazlur Khan, developer of trussed tube concept. *First International Plaza* and *Citicorp Center* (Figure 3.16a-b) are other excellent examples of this concept in steel.

An exterior braced tube eliminates the risk of the excessive axial load taken by the corner columns, one of the main problems in the framed tube, by stiffening the exterior frames. Although replacing vertical columns with closely spaced diagonals in both directions is the most effective exterior braced tube action, exterior braced tube system is not widely used due to its problems in curtain wall details. This system can be used for buildings with over 100 stories.

Figure 3.14 780 Third Avenue Building, New York, U.S.A. (1)

Figure 3.15 The Onterie Center, Chicago, U.S.A. (Ali, 2001)



(a) (b)

Figure 3.16 Citicorp Center, New York, U.S.A.: (a) an image of the building (Bennett, 1995); (b) structural representation of the building (Taranath, 1998)

3.1.1.6 Bundled tube systems

Bundled tube system is proper for steel, reinforced concrete and composite construction. A single framed tube does not have an adequate structural efficiency, if the building dimensions increase in both height and width. Namely, the wider the structure is in plan, the less effective is the tube. In such cases, the bundled tube, also known as modular tube, is preferred. This concept, being created by the need for vertical modulation in a logical fashion, can be defined as a cluster of tubes interconnected with common interior panels to generate a perforated multi-cell tube.

Since this system is originated from the arrangement of individual tubes, a variety of floor configurations could be achieved by simply terminating a tube at any desired height without sacrificing structural stiffness. This feature makes the setbacks with different shapes and sizes possible. It has advantages in structuring unsymmetrical shapes. Since the "bundled tube" design is derived from the layout of individual tubes, the cells can be in different shapes such as triangular, hexagonal or semicircular units. The disadvantage, however, is that the floors are divided into tight cells by a series of columns that run across the building width. Thanks to its larger spaced columns, and thinner spandrels, this system allows bigger window openings when compared the single-tube structure. Moreover, this system also makes the architectural planning of the building more flexible since any tube module can be dropped out whenever required by the planning of the interior spaces.

Two versions are possible using either framed or diagonally braced tubes, as well as a mixture of the two, as shown in Figure 3.17a, b. *One Peachtree Center* in Atlanta and *the One Magnificent Mile Building* (Figure 3.18) in Chicago are good example of a concrete bundled tube design. The best example of a steel bundled tube concept is *the Sears Tower* (Figure 5.10). In this building, the advantage of the bundled form was taken into consideration and some of the tubes are made disconnected, and the plan of the building was reduced at stages along the height.

Bundled tube concept has a broad application because of its modular quality. The tubes or cells can be organized in a variety of ways to create different massing; it can be utilized for a 30-storey high building as well as for ultra-tall structures with over 100 stories.

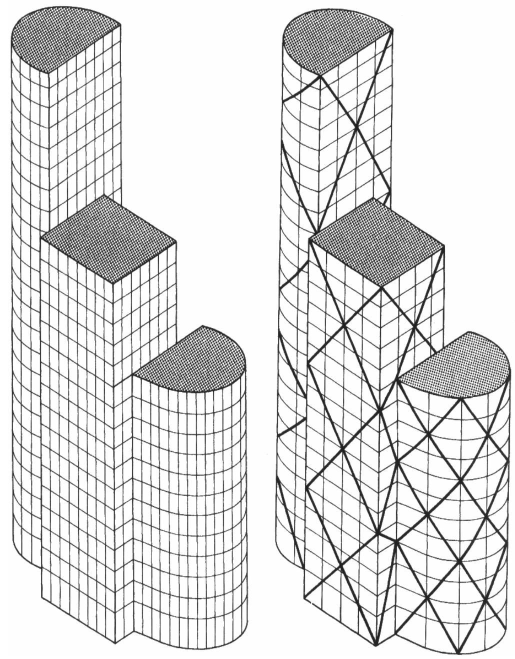


Figure 3.17 Bundled tube: (a) framed;
(b) exterior braced (Taranath, 1998)

Figure 3.18 The One Magnificent Mile Building,
Chicago, U.S.A. (Ali, 2001)

CHAPTER 4

WIND EXCITATION OF TALL BUILDINGS

4.1 Introduction

During the past three decades, many tall buildings have been built throughout the world. The development of new structural systems and materials makes these buildings much lighter, and more slender than their predecessors, yet they usually suffer from increased flexibility. These flexible structures are affected by vibration under the action of wind, which cause building motion. Therefore, high wind acting on the buildings has become one of the main challenges facing the designers, and so, the designers of the tall buildings must take into consideration the wind loads as well.

The response of a building to wind excitation depends on the following parameters:

- characteristics of the approach wind;
- building size and shape;
- distribution of mass and the stiffness;
- ability of the structural system to dissipate vibration.

On the other hand, the surrounding topography also influences such aerodynamic loads on tall buildings, and in this respect the neighboring buildings may increase or decrease wind loads, depending on the relative location to the measured building.

Although most buildings do not have safety problems during strong winds, wind excited motion may result in vibration of buildings that can cause discomfort to occupants and create serviceability problems. Furthermore, excessive motions can create noise, crack partitions, damage curtain walls, reduce the fatigue life, and cause malfunction of elevators. Thus, what constitutes the acceptable motion of a tall building has become the subject of a significant amount of research and considerable debate, and is continuously being modified with the introduction of new data.

4.2 Types of Wind Excited Motion

It has been observed that the motion of tall buildings occurs primarily in three modes of action: *along wind*, *across wind*, and *torsional modes*. For example, for a rectangular building with one face nearly perpendicular to the mean flow, the motion has been measured in the along wind and across wind directions as well as in the torsional mode. It has been recognized that for many tall buildings the across wind and torsional response may exceed the along wind response in terms of both serviceability and survivability designs (Kareem, 1985). Each mode of vibration is briefly reviewed below.

4.2.1 Along wind motion

Along wind (Figure 4.1) or simply wind is the term used to refer to drag forces. Under the action of the wind flow, structures experience aerodynamic forces including also the drag *(along wind)* force acting in the direction of the mean wind. Thus, the structural response induced by the wind drag is commonly referred to as the *along wind response*. The along wind motion primarily results from pressure fluctuations on windward (building's frontal face that wind hits) and leeward face (back face of the building). Therefore, most international codes and standards that utilize the "gust factor approach" are based on assumptions on the basis of climatological, meteorological, and aerodynamic considerations alone, but independent from the mechanical properties of the structure, such as mass distribution, flexibility, and damping. This procedure takes into consideration the following (Cho, 1998):

- the exposure of the building to the local wind environment;
- the dynamic and geometric properties of the building to determine "response factor";
- the coefficients from model measurements in wind tunnel boundary layers which simulate the turbulent characteristics of strong winds.

In order to use this approach satisfactorily, the building and its environment should be modeled in the wind tunnel. This is often complemented by a special meteorological study. By using wind tunnel, the following factors can be studied in significant detail:

- the response of the building to wind direction;
- topographic effects;
- the probability of extreme winds and deflections;
- the stress history, and the detailed dynamic of the building.

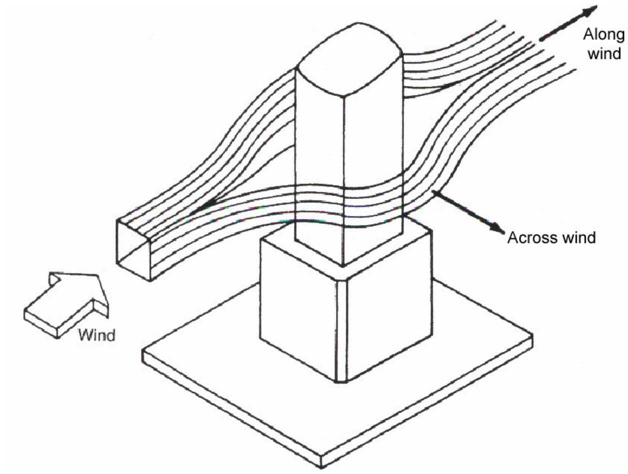


Figure 4.1 Simplified two-dimensional flow of wind (Taranath, 1998)

4.2.2 Across wind motion

While along wind or simply wind is the term used to refer to drag forces, across wind (Figure 4.1) is used to refer to transverse wind. The across wind response, is a motion in a plane perpendicular to the direction of wind. In the design of most modern tall buildings, the across wind response often dominates over the along wind response (Kwok, 1982). For instance, the wind tunnel test of the Jin Mao Building showed that its maximum acceleration in across wind direction at its design wind speed is about 1.2 times of that of the in along wind direction (Gu and Quan, 2004).

Buildings are very sensitive to across wind motion, and the sensitivity to the across wind motion may be particularly apparent as the wind speed increases. Wind induced instabilities of modern tower-like structures with exceptional slenderness, flexibility and lightly-damped features could cause considerably larger across wind responses. Besides this, while the maximum lateral wind loading and deflection are usually observed in the along wind direction, the maximum acceleration of a building loading to possible human perception of motion or even discomfort may occur in across wind direction (Taranath, 1998).

While the dynamic along wind loads can be predicted with reasonable accuracy using the gust factor approach, the estimation of across wind loads are usually obtained from wind tunnel tests with some special techniques because of their complex mechanism. So, the only accurate way to predict the across wind response is through a wind tunnel study.

As a designer, there are a number of approaches that can be used to minimize the across wind response (Scott et. al. 2005):

- *Rotating the building* so that its least favorable aspect does not coincide with the strongest wind direction can be very effective, as across wind sensitive buildings can see their peak responses change by 10 to 20% within a 10º wind direction change.

- *A rounded plan shape*. In practice, this means moving away from sharp-edged square plans as much as possible. Even small changes such as chamfered, rebated, or rounded corners can be very effective in reducing the across wind response (discussed in Chapter 5).

- *Tapering and stepping back the building shape with height*. Making the plan less regular assists in breaking up the correlation of vortex-shedding with height (also discussed in Chapter 5).

- *Introducing porosity at the corners*, particularly over the top sections of the building. This is commonly done through sky-gardens or refuge floors.

4.2.3 Torsional motion

The oscillations of tall buildings caused by wind action have been found to occur in the along wind and across wind directions, as well as in the torsional mode, which is more sensitive to a building's shape than to its general surroundings. Point of the application of resultant wind forces acting on the surface is the geometric center of that surface. On the other hand, the resultant of reaction forces passes through the stiffness center of the building structure. If the above forces are not on the same line, the resulting eccentricity creates torsional moments, and thus the torsional motion.

While in the design of tall buildings, methods for analytically estimating wind induced loads in the along wind direction are well developed and reliable or extensive experimental and theoretical works have been conducted for investigating across wind effects on tall buildings, this is not the case for wind induced torsional loads, because of their very complex nature. An additional complication is that torsional loads, like their sway counterparts, are really dynamic, rather than static in nature. Analytical methods for estimating torsional wind forces and building response are not revised yet. This lack of guidance can be a significant factor because torsional force and response may need to be considered in the design of tall buildings in many cases (Liang et. al. 2004).

Torsional motion is a special concern for a structural engineer for two reasons in particular. Torsional motion may damage cladding and anchors. Besides this, if a tall building is experiencing torsional motion and the occupants are looking out of the building and they lined up in front of the vertical parts of the windows with distant objects, the perceptible motion of the building is amplified. In order to overcome this adverse effect, the tube in tube construction and trussed cantilevering can be preferred in the design of tall buildings, in which these structural systems increase the torsional rigidity. Therefore, it is important to obtain knowledge of wind induced torsional forces on tall buildings.

4.3 Motion Perception: Human Response to Building Motion

The modern trend in building construction is one of ever-increasing height. With this trend, often accompanied by increased flexibility and low damping, buildings become even more susceptible to the action of wind, which governs the design of the lateral system. Thus, the skyscrapers of today sway and oscillate, in contrast to the heavy weight tall buildings of the past.

While major innovations in structural systems have permitted the increased lateral loads to be efficiently carried, the dynamic nature of wind is still a factor, causing discomfort ranging from mild discomfort to acute nausea to building occupants and posing serious serviceability issues. Furthermore, these motions with psychological or physiological effects on the occupants can make a building undesirable or even unrentable. Therefore, the design of very tall buildings is often driven by occupant comfort criteria, by limits to lateral acceleration.

According to Reed (1971), creaking noises that occur during the building motion may significantly increase the feeling of discomfort and should therefore be minimized by proper structural detailing. Moreover, it is more difficult to establish the criteria for occupants' comfort, since personal reactions to vibrations vary not only among individuals but also from position to position within the building.

Studies of human response to mechanical vibrations have been conducted generally by the aerospace industry (Simiu and Scanlan, 1986). Since the frequencies of vibration of interest in aerospace applications are relatively high, the usefulness of these studies in structural engineering is generally limited. Perception limits have been traditionally determined based on the response of the individuals to tests using motion simulators (Kareem et. al. 1999).

However, the subject of occupant tolerance to motion is a highly complex mix of engineering, physiology and psychology, and is not well understood, even by many wind engineering specialists. Although researchers have attempted to study this problem, there is no strong consensus on human comfort standards, for which there are many parameters including amplitude, speed, and acceleration, rate of change of acceleration, frequency, height, visual effect, and noise. To establish the criteria of human reaction to vibrations, the relationships among such parameters must be based on actual tests. There is substantial ongoing research and development in this area. The designers of tall buildings or flexible structures must be aware of this problem, and they should take it into account in their design.

4.4 Methods to Control Wind Excitation of Tall Buildings

In the light of human perception and serviceability concerns, many techniques have been developed to mitigate the unnerving motions induced by wind. The wind induced dynamic response of tall buildings can be controlled by global design modifications. These are: *increasing building mass* (not feasible or practical because of the resulting magnification of the seismic force, and the great additional cost), *increasing stiffness by using an efficient structural system*, *aerodynamic modifications in architecture*, and *addition of damping systems* including passive, active, hybrid and semi-active control. Besides these, if suitably designed, claddings, which are selected for weather resistance quality and pleasing appearance, can also provide a significant amount of damping.

4.4.1 Aerodynamic modifications in architecture

The wind induced motion of a tall building can be controlled either by reducing the wind loads or by reducing the response. A proper selection of building shape and architectural modifications can result in the reduction of motion by altering the flow pattern around the building. A building can be designed with smooth lines and curves so that it, like a plane, is highly aerodynamic, and that the wind will just move smoothly over it, without pushing too much. Therefore, aerodynamic modifications in architecture, which will be discussed in

Chapter 5, including modifications of cross-sectional shape of the building, its corner geometry, sculptured building tops, openings through building are also an extremely important and effective design tool to mitigate wind induced motion.

4.4.2 Wind resistant structural systems

Mass and stiffness are the two properties that influence the frequency of vibration of the building, and so directly relate to how much it sways. In order to mitigate this motion, increasing the mass is unfeasible and impractical because of its negative results. On the other hand, increasing the stiffness of the building, namely the proper selection of the structural system is one of the most efficient design approaches.

The resistance of tall buildings to wind as well as to earthquakes is the main determinant in the formulation of new structural systems that evolve by the continuous efforts of structural engineers to increase building height while keeping the deflection within acceptable limits and minimizing the amount of materials. An efficient structural system can provide an effective means of controlling structural response to wind in lateral and torsional directions. Outrigger-belt, framed tube, exterior braced and bundled tube systems are the most efficient structural systems against wind loading. These systems (discussed in detail in Chapter 3) are for buildings with more than 100 stories.

4.4.3 Addition of damping systems

In the design of tall buildings, engineers must assume a level of the natural damping in the structure to assess the building habitability during frequent wind storms. The actual damping in building structures is a difficult quantity to measure and varies according to the response levels, type of structural systems, cladding system and materials used for construction. Recognizing this uncertainty associated with estimating the natural damping in structural systems, engineers have introduced energy dissipating systems into the design of buildings. These devices are called "dampers" in short and like the dampers used for slowing down the closing of the doors they dampen the motion of the building. The addition of damping is then another approach towards the reduction of the effects of the wind induced motion on a tall building.

Damping systems can be mainly classified into two groups:

1- soil damping;
2- auxiliary damping.

Even though not marked for tall buildings, damping contributions may be obtained from the soil-foundation interaction, i.e. *soil damping*.

On the other hand, if the inherent damping is not adequate, *auxiliary damping devices* could be utilized, offering a relatively more predictable, adaptable, and reliable method of imparting additional damping to a system. The use of these systems is focused on the reduction of the acceleration response of the upper floors of a building. Since this type of motion has traditionally been a problem only in tall buildings, most applications of energy dissipating systems for occupant comfort control occur in buildings with over 40 stories, and located in turbulent environments.

Auxiliary damping devices, which become a part of the structural engineers' design vocabulary, were utilized in large scale structures such as *World Trade Center Twin Towers* (New York, U.S.A.) (Figure 4.2), *Citicorp Center* (New York, U.S.A.), *the John Hancock Center* (Chicago, U.S.A.), *Taipei 101* (Taipei, Taiwan) (Figure 4.3), and *the Millennium Tower* (Tokyo, Japan) (Figure 4.4).

Auxiliary damping sources can be basically categorized as two groups: *passive* and *active systems*. Moreover, these systems may be further subcategorized based on their mechanism of energy dissipation and their system requirements. These categories are *semi-active* and *hybrid systems*.

Passive control devices are systems which do not require an external power source. These devices impart forces that are developed in response to the motion of the structure, for e.g., viscoelastic dampers, tuned mass dampers, and tuned liquid dampers etc.

On the other hand, *active control systems* are driven by an externally applied force which tends to neutralize the unwanted vibrations. The control force generated is dependent on the feedback of the structural response. Examples of such systems include active mass dampers, active tendon systems etc.

The unique difference between a passive and an active control system is that the passive control does not make any real-time changes in the system, and so cannot destabilize a conservative system, no matter how serious are the physical implementation errors. Additionally, passive systems are usually favored over the active ones because of the uncertainty regarding the availability of power supply during extreme conditions, and the large power source needed to introduce control force.

Semi-active control systems are a class of active control systems for which the external energy requirements are orders of magnitude smaller than typical active control systems. Examples of such devices include semi active impact dampers, adjustable tuned liquid dampers, and controllable fluid dampers.

As an alternative system *hybrid control* implies the combined use of active and passive systems or semi-active and passive systems. Hybrid mass damper is an example of this type.

In the usual structural design practice, cladding, curtain walls and some interior partitions, referred to collectively as secondary systems, are not treated as load carrying members; however, if suitably designed, they may serve as passive dampers to help absorbing some of the vibratory energy, thus reducing the structural response to wind excitations.

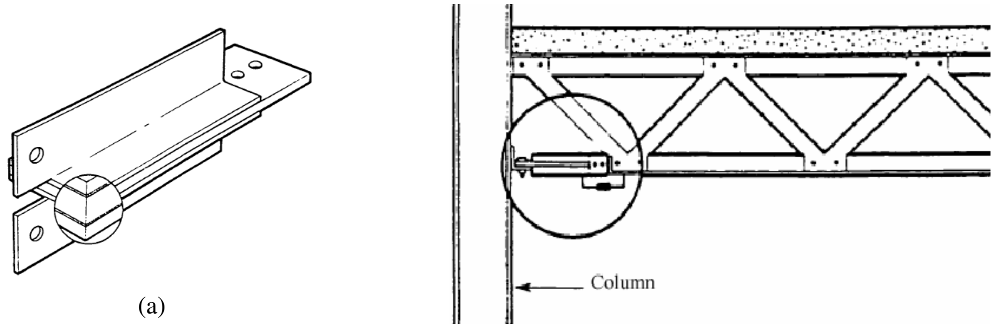


Figure 4.2 Viscoelastic damper in World Trade Center Twin Towers: (a) the damper; (b) the damper in place (Cho, 1998)

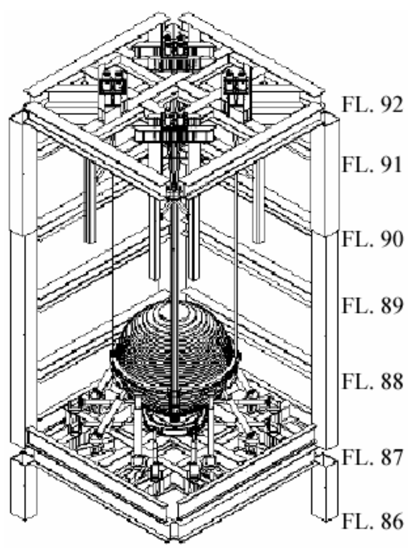


Figure 4.3 Tuned mass damper in Taipei 101 (Poon et. al .2004)

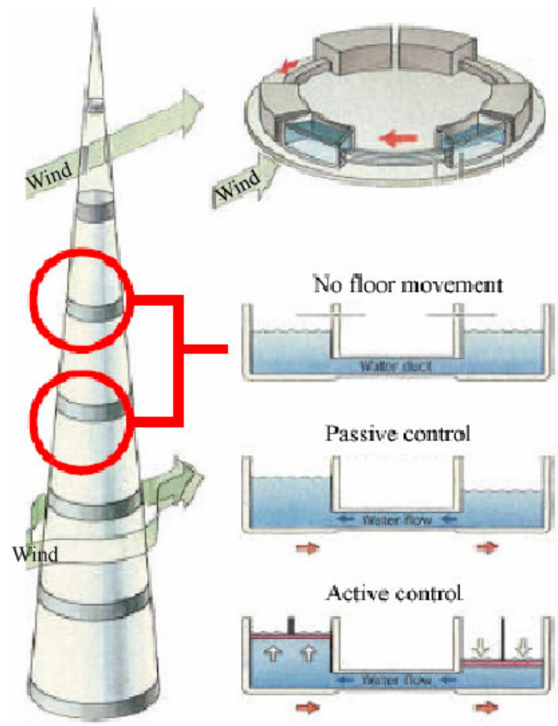


Figure 4.4 Auxiliary damping scheme for the Millennium Tower (Kareem et. al. 1999)

CHAPTER 5

AERODYNAMIC MODIFICATIONS OF TALL BUILDINGS AGAINST WIND EXCITATION

5.1 Introduction

As mentioned in the previous sections, modern tall buildings have efficient structural systems, and utilize high-strength materials, resulting in reduced building height, and thus, become more slender and flexible with low damping. These flexible buildings are very sensitive to wind excitation causing discomfort to the building occupants. Therefore, in order to mitigate such an excitation and to improve the performance of tall buildings against wind loads, many researches and studies have been performed.

Different strategies exist for the reduction of wind induced motion in tall buildings. One approach is to alter the dynamic properties of the structure, such as its mass, stiffness, and damping. Another approach is to reduce the actual excitation mechanism (i.e. vortex-shedding) with proper aerodynamic modifications, both active and passive. Active methods use spoilers from the building into the flow. Passive methods, which are broadly studied in this chapter, utilize fixed modifications in the building's geometry to disrupt the excitation process.

Early integration of aerodynamic shaping, wind engineering considerations, and structural system selections play a major role in the architectural design of a tall building in order to mitigate the building response to the wind excitations. A tall building, whose shape is unsuitable, often requires a great deal of steel or a special damping mechanism to reduce its dynamic displacement within the limits of the criterion level for the design wind speed.

Understandably, an appropriate choice of building shape and architectural modifications are also extremely important and effective design approaches to reduce wind induced motion by altering the flow pattern around the building. These aerodynamic modifications can be classified into three main groups:

1- *Modifications to building shape* including effect of tapered cross section, setback and sculptured top, and efficient building shapes;
2- *Modifications to corner geometry*;
3- *Addition of openings*.

5.2 Modifications to Building Shape

For an architect, besides the aerodynamic considerations, the determination of the building shape is governed by many factors:

- the site and occupancy requirements;
- structural necessities;
- aesthetics;
- control of traffic;
- acoustics requirements;
- space allocation;
- energy efficiency;
- general financial viability.

On the other hand, it is definitely observed that the selection of an efficient building form can provide a remarkable amount of reduction of the aerodynamic forces by changing the flow pattern around the building. Besides this, since the primary goal of accomplishing cost savings in a tall building structure is realized by minimizing the lateral displacement of the building caused by lateral loads, a careful coordination of the structural elements and the shape of the building may offer further substantial savings.

In order to control wind induced motion, modification to building shape, which includes utilizing *the effect of tapered cross section, setback and sculptured top*, and *efficient building shapes*, is one of the most effective design methods.

5.2.1 Effect of tapered cross section, setback and sculptured top

Many investigations for mitigating wind induced excitations of tall buildings have been carried out (Kim and You, 2002). Utilization of the tapering effect to control wind induced motion is one of the most effective design methods.

In their research, Kim and You (2002) evaluated the tapering effect for reducing along wind and across wind responses of a tall building, with several wind tunnel tests (Figure 5.1). In these tests, four types of building models, which have a different taper ratio ranging between %5, %10, %15 and one basic building model of a cross-section, were used. The effect of wind direction was also considered.

In the same study, wind tunnel model tests showed that:

- Modification of cross-sectional shape varied along with height has a tapering effect for reducing wind induced excitations of a tall building.
- The aerodynamic modification of a building shape changing the cross-section with height through tapering, which alters the flow pattern around the building, reduces wind induced excitations of tall buildings.
- Tapering effect has a more significant effect in across wind direction than that in along wind direction.

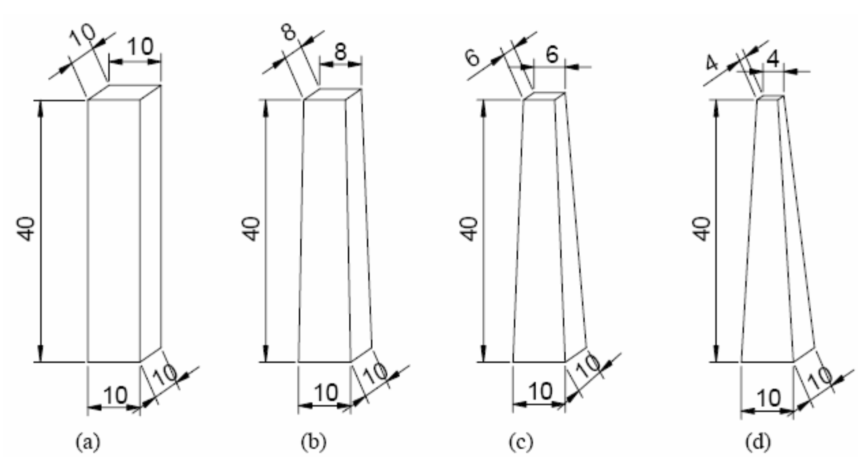


Figure 5.1 Dimensions of each model: (a) Type 1; (b) Type 2; (c) Type 3; (d) Type 4 (Kim and You, 2002)

In the study of Shimada and Hibi (1995), similar results were found. According to this study:

- Improved across wind responses have also been observed in tall buildings which vary in their cross-sectional shape with height or reduce their upper level plan areas, e.g. tapering effects, cutting corners, or dropping off corners progressively as height increases.

- Changing the cross sectional shape along the vertical axis, coupled with effective tapering, can be especially effective in reducing the across wind forces.

Some of the most elegant and notable structures incorporate a series of setbacks and tapering in their design, highlighting the height of the structure, but also serving for the practical aerodynamic purposes. *The Jin Mao Building* (Figure 5.2) and *the Petronas Towers* (Figure 5.3) are excellent examples of the utilization of such geometries. Further evidence of the aesthetic benefits of aerodynamic modifications is provided by the Jin Mao building, which uses setbacks to gently taper its façade. While the setbacks draw the eye's attention up towards the top of the structure, they more importantly, also gradually reduce and redefine the shape of the structure at the upper levels, where the effects of wind are most critical. Similarly, the benefits of tapering also were integrated into the design of the Petronas Towers. Moreover, the more sculptured a building's top is, the better it can minimize the along wind and across wind responses, as proved in this building.

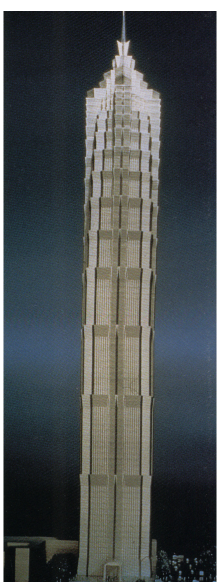


Figure 5.2 The Jin Mao Building, Shanghai, China (Bennett, 1995)

Figure 5.3 The Petronas Towers, Kuala Lumpur, Malaysia (Bennett, 1995)

In the study by Isyumov et. al. (1992) similar results about the sculptured building tops were also found. The wind induced loads and overall responses of an 85 storey (approximately 390 m) office tower project were tested. Tests were carried out for an initial configuration of the building geometry, and for the final configuration, which had a distinct new top in the form of an open pyramid. The original design was about a 360 m tall building with essentially a rectangular top, and the revised design was 390 m tall with the top consisting of a 53 m high triangular pyramid, open in the north-south directions and closed in the east-west directions (see photographs in Figure 5.4 and 5.5). According to this study:

- Changing the top of the building to an open pyramid has a markedly beneficial effect on the dynamic response, even though the total height of the building actually increases for the revised geometry.

- The dynamic response is quite sensitive to the aerodynamics of the top of the building.

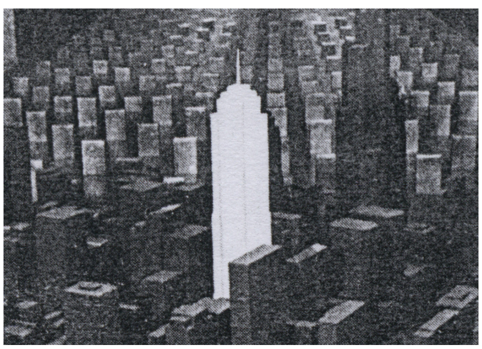


Figure 5.4 Original Design (Isyumov et. al. 1992)

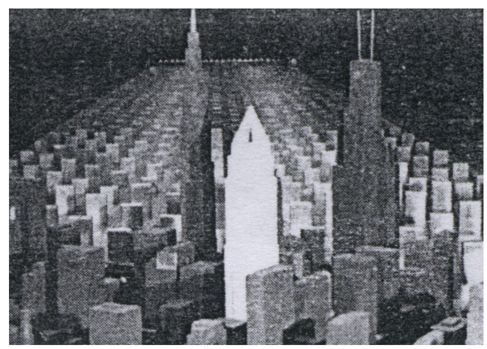


Figure 5.5 Revised Design (Isyumov et. al. 1992)

The John Hancock Center and *the First National Bank of Chicago* are other examples of the tapering effect utilization, where this effect created a smaller surface area at the higher levels, thus reducing the wind load. That is, tapering exterior frame by sloping exterior columns achieves a reduction in lateral drift as in the John Hancock Center (Figure 5.6) and the First National Bank of Chicago (Figure 5.7). The structural benefits are greatest when the taper extends the full height of the building. The reductions in lateral drift range from 10 to 50%, with the greatest influence in the taller and more slender buildings. A computer study showed that a slope of only 8% in the exterior columns produced 50% reduction in the lateral displacement of a 40-story building. A variation of the John Hancock Center's truncated pyramid is the 256 m high *Transamerica Building* (Figure 5.8) in San Francisco (Schueller, 1977).

Figure 5.6 The John Hancock Center, Chicago, U.S.A. (Bennett, 1995)

Figure 5.7 The First National Bank of Chicago, Chicago, U.S.A. (97)

Figure 5.8 The Transamerica Pyramid, San Francisco, U.S.A. (Bennett, 1995)

Moreover, the shape of *the Burj Dubai* is the result of the collaboration between SOM's architects and engineers to vary the shape of the building along its height, thereby minimizing wind forces on the building. In effect, each uniquely-shaped section of the tower causes the wind to behave differently, preventing it from becoming organized and minimizing lateral movement of the structure (Figure 5.9) (Baker, 2004) as in *the Sears Tower* (1974) in Chicago (Figure 5.10) (Ali and Armstrong, 1995).

Figure 5.9 The Burj Dubai, U.A.E. (Baker, 2004)

Figure 5.10 The Sears Tower, Chicago, U.S.A. (Bennett, 1995)

5.2.2 Efficient building shapes

It is a well known fact that the shape of the structures (other than rectangular blocks) has a substantial effect on the lateral resistance (Fintel, 1974). Namely, if the form of a tall building is limited to rectangular prisms, from the geometrical point of view, this form is rather susceptible to lateral drift. Other building shapes, which are discussed in the following paragraphs, are not as responsive to lateral force action as a rectangular prism. Having inherent strength in their geometrical form, they provide higher structural efficiency or allow greater building height at lower cost (Schueller, 1977).

A study performed by the structural engineers Skilling, Helle, Christiansen, and Robertson in the later 1960s shows that the circle is the superior shape for wind (Ali and Armstrong, 1995). A cylindrical form offers true tube geometry, providing three-dimensional structural action, and is aerodynamically highly efficient. *The Marina City Towers* (Figure 5.11) in Chicago is an example of this form. In addition to the structural advantage of three-dimensional action, the cylindrical building offers small surface area perpendicular to the wind direction, thus the magnitude of the wind pressure is greatly reduced, compared to what a prismatic building experiences. Building codes permit a reduction of the wind pressure design loads for circular buildings by 20% and 40% of the usual values for comparably sized rectangular buildings (Schueller, 1977). Another example is the circular tapered structure called *Millennium Tower* (Figure 5.12), over 792 m high, for Tokyo (Ali and Armstrong, 1995). The structure utilizes an aerodynamically favorable shape through its circular plan, coupled with the benefits of tapering with height, permitting it to perform efficiently in wind.

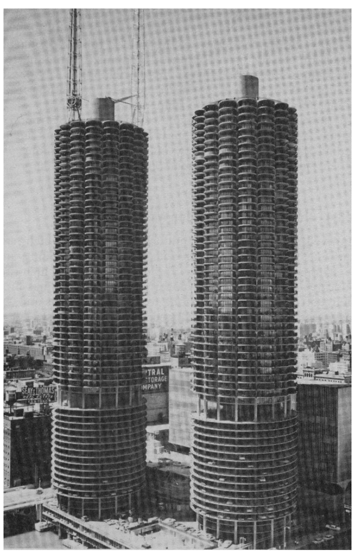


Figure 5.11 The Marina City Towers, Chicago, U.S.A. (Fintel, 1974)

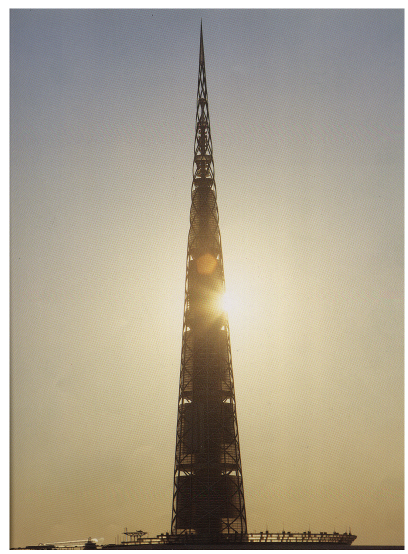


Figure 5.12 The Millennium Tower, Tokyo, Japan (Bennett, 1995)

The elliptical building offers advantages similar to the circular one. The architect of *the Le France Building* in Paris claims a 27% reduction of wind load attributable to the elliptical shape. Building codes offer a reduction of the wind load requirements by 20% and 40% of the values required for a rectangular building (Schueller, 1977).

The crescent shell form is also efficient in resisting lateral loads acting symmetrically on it. However, it is rather inefficient when considering asymmetrical loading, which produces torsional stresses (Schueller, 1977). The two crescent-shaped towers of *Toronto City Hall* (Figure 5.13) in Toronto is a notable example of this form.

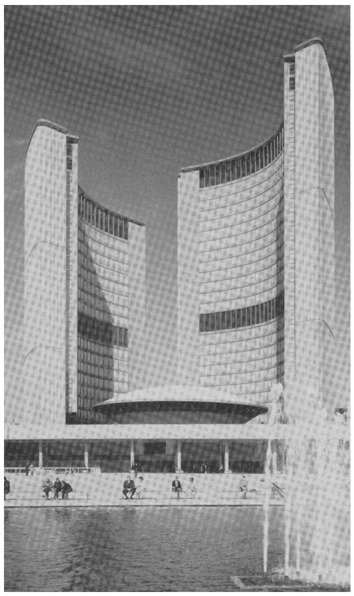


Figure 5.13 Toronto City Hall, Toronto, Canada (Fintel, 1974)

The triangular prism is another structurally efficient building form since it symbolizes a tripod-type configuration in plan. The 528-story high *Mile High Tower* (Figure 5.14) proposed by Frank Lloyd Wright had a plan of a double triangle. A double triangle is a very efficient form, and hence Wright's intuition for the Mile High Tower form was the ideal choice. *The U.S. Steel Building* (Figure 5.15) in Pittsburg and *The American Broadcasting Company Building* in Los Angeles are other examples of triangular tall building.

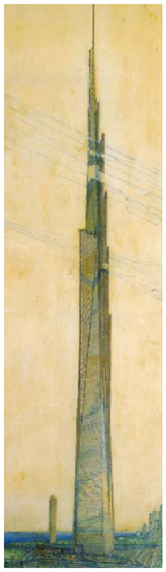


Figure 5.14 The Mile High Tower (proposed), Illinois, U.S.A. (98)

Figure 5.15 The U.S. Steel Building, Pittsburg, U.S.A. (99)

In the work of Hayashida and Iwasa (1990), the effects of building plan shape on aerodynamic forces and displacement response have been studied for super high-rise building with an assumed height of 600 m. Experiments have been carried out using models with eight kinds of building plan shapes of equal area (6400 m^2), equal building height (600 m), and equal density (125 kg/m^3). The maximum across wind displacement response in each model for two typical wind directions under the same conditions is shown in Figure 5.16.

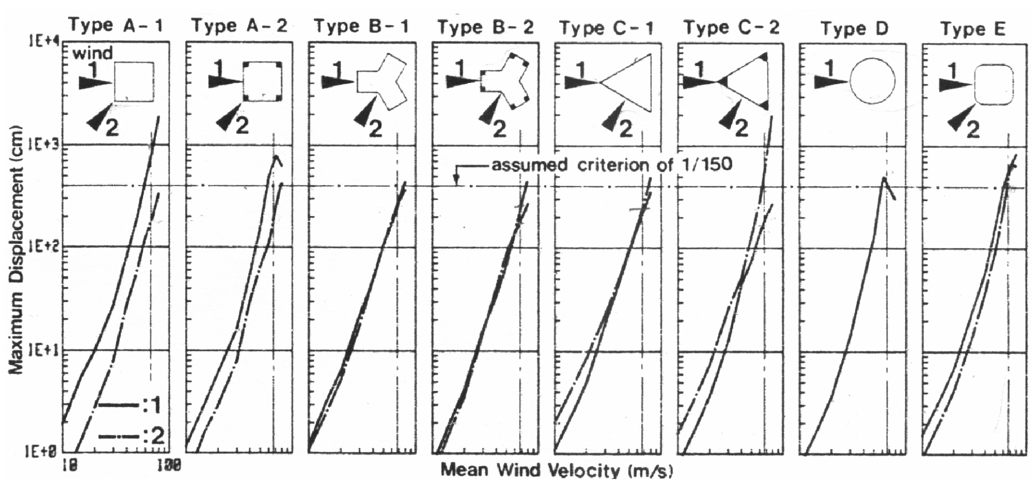


Figure 5.16 Maximum across wind displacement of different building shapes under two typical wind directions with reference mean wind speed (Hayashida and Iwasa, 1990)

The result of this study according to their displacement magnitude is shown below:

A-1 > A-2 > E > D > C-2 > B-1 > C-1 > B-2

Within the limits of this experiment and analysis for eight models and two typical wind directions, the models based on a square cross section, type A and E displayed a large displacement response than the other models. On the other hand, the cross section based on a triangular shape, such as type B or C, displayed a smaller response when compared to the other forms. From a comparison of the largest and smallest displacement, it is shown that the displacement of type A-1 was about three times higher than that of type B-2.

5.3 Modifications to Corner Geometry

The work by Kwok et. al. (1988) was performed to investigate the effect of different edge configurations such as slotted corners, chamfered corners or a combination of them on the wind induced response of a tall building with a rectangular cross-section. The aim of the study was to assess the effectiveness of modification to the building edges in reducing the along wind and across wind responses of the building. A number of building model configurations with combined sharp corners, slotted corners and chamfered corners were tested as shown in Figure 5.17. Results of this study showed that:

- Modification to the edge of a tall building with a rectangular cross-section has a significant effect on the excitation process and the response characteristic.

- Slotted corners and chamfered corners, and combinations of these, were found to be effective in causing significant reductions in both the along wind and across wind responses.

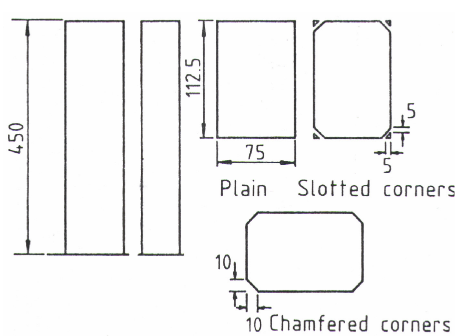


Figure 5.17 Sketches of the tall building models showing different configurations (Kwok et. al. 1988)

A similar study by Kwok (1988) was also performed to investigate the effect of building shape on the wind induced response of a tall building with a rectangular cross-section. In this study, results of the wind tunnel model tests showed that modification to the shape of a tall building with a rectangular cross-section has a significant effect on both the along wind and across wind excitation processes. It was found that horizontal slots, slotted corners and in particular chamfered corners caused significant reductions in both the along wind and across wind responses.

In the study of Kawai (1998), effects of corner cut, recession and roundness were investigated by wind tunnel tests for square and rectangular prisms. 15 square prisms and 11 rectangular prisms of side ratio of 1/2 with various corner modifications, as shown in Figure 5.18, were used. According to the tests, the following results were obtained:

- Small corner cut and recession are very effective to prevent aeroelastic instability for a square prism by increasing the aerodynamic damping, but large corner cut and recession promote the instability at low speed.

- Among the three corner modifications, the corner roundness is the most effective to suppress the aeroelastic instability for a square prism. The amplitude of the wind induced vibration reduces as the extent of the corner roundness increases.

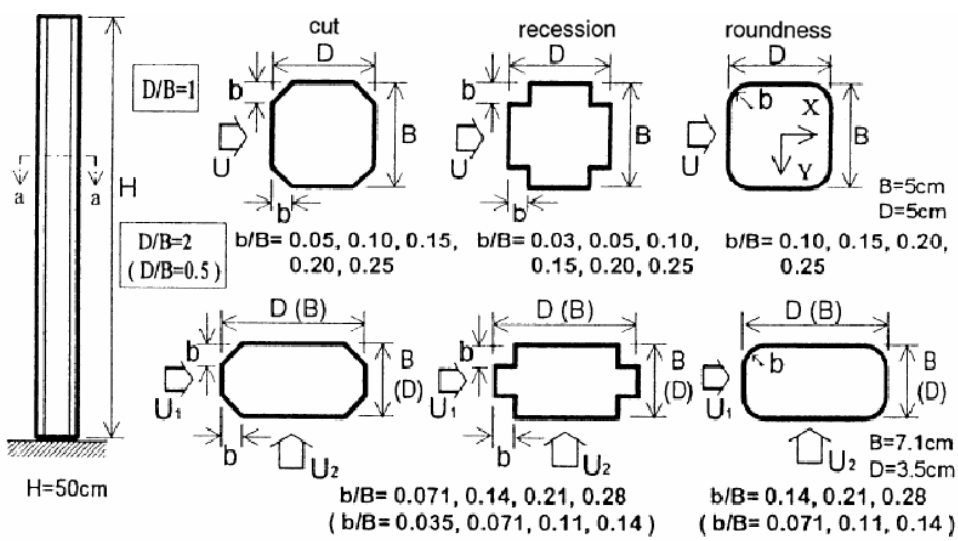


Figure 5.18 Sections of the models with corner cut, recession and roundness (Kawai, 1998)

Recent work by Kwok and Bailey (1984) showed that small fins, vented fins and slotted corners have a significant effect on the along wind and across wind responses of a square tower model.

Besides these results, the study of Kareem, Kijewski and Tamura (1999) shows that the modifications of corner geometry are effective to mitigate the wind induced motion of tall buildings. Initiatives to explore the effects of building shape on aerodynamic forces have confirmed the benefits of adjustments in building configurations and corners, as illustrated in Figure 5.19 (Hayashida and Iwasa, 1990; Hayashida et. al. 1992; Miyashita et. al. 1993; Shimada et. al. 1989). Investigations have established that corner modifications such as chamfered corners, horizontal slots, and slotted corners can significantly reduce the along wind and across wind responses when compared to a basic building shape (Kwok, 1995). Moreover, chamfers of the order of 10% of the building width produce up to 40% reduction in the along wind response and 30% reduction in the across wind response (Holmes, 2001). Significant rounding of the structure's corners, approaching a roughly circular shape, has been shown to improve the response of the structure significantly (Kareem et. al. 1999).

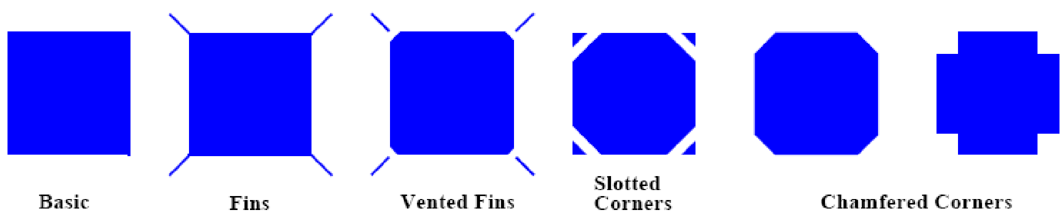


Figure 5.19 Aerodynamic modifications to square building shape (Kareem et. al. 1999)

Such modifications were applied to the 150 m high *Mitsubishi Heavy Industries Yokohama Building* (Figure 5.20a-b). To reduce the response, each of the four corners was chamfered, which consequently reduced the wind forces (Miyashita et. al. 1995).

Figure 5.20 (a) MHI Yokohama Building, Yokohama, Japan; (b) Its modified version (Kareem et. al. 1999)

In the study of Gu and Quan (2004), the building models with basic cross-section shapes, i.e., square, rectangular and corner-modified square cross-section shapes (concave corner and bevel corner) were tested. It was seen that both of these types of corner modifications have large effects on the across wind forces.

Corner modifications in *Taipei 101* (Figure 5.21) provide 25% reduction in base moment when compared to the original square section (Irwin, P. A. – the wind engineering consultant of Taipei 101).

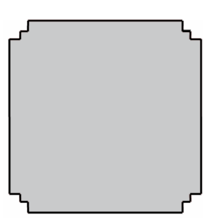


Figure 5.21 Corner modification in Taipei 101

5.4 Addition of Openings

The addition of openings (Miyashita et. al. 1993; Irwin et. al. 1998) to a building is another way of improving the aerodynamic response of that structure, though this approach, as in any other aerodynamic modification, must be used with care to avoid adverse effects. Openings through the building, particularly near the top, have been observed to significantly reduce vortex-shedding induced forces, and hence the across wind dynamic response, shifting the critical reduced wind speed to a slightly higher value (Dutton and Isyumov, 1990; Kareem, 1988). However, the effectiveness of this modification diminishes if the openings are provided at lower levels of the building (Tamura, 1997).

Utilization of openings through the building was applied to *the Shanghai World Financial Center* (Figure 5.22), which has a diagonal face shaved back with a 51 m aperture to reduce pressure at the top of the building. The design makes use of not only the advantages of openings through a building but also those provided by shifting and decreasing the cross section with increasing height, essentially tapering the 460 m tower (Kareem et. al. 1999). Although the shaving of the face of the structure has caused a loss of rental space in the upper floors, it serves as a priceless trademark for the building and provides a unique shape to the building’s upper plan.

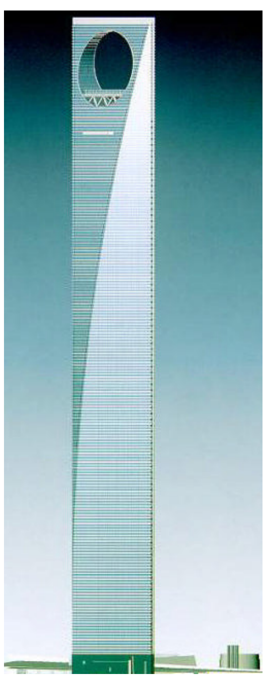


Figure 5.22 The Shanghai World Financial Center, Shanghai, China (Kareem et. al. 1999)

In the study of Dutton and Isyumov (1990), a wind tunnel model study was carried out to demonstrate how openings or gaps through a building can reduce the across wind response. The model allowed the following aerodynamic modifications to be made to its upper half:

i) “Along Wind Gap” – width D/6, located model centerline in plan

ii) “Across Wind Gap” – as in i), but with an across wind orientation.

Where *D* is the building width.

The results of this study are that:

- Introducing the gaps results in a pronounced reduction of the vortex-shedding induced forces and hence the across wind dynamic deflection of the building.

- A major reduction in the excitation and response occurs in the presence of the along wind gaps. The addition of identical gaps in the across wind direction results in a further smaller reduction response. Moreover, across wind gaps, if used alone, are not as effective as comparable along wind gaps.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

- All efforts performed by humans from the ancient times' primitive temples for the God(s) to today's state-of-the-art temples for commerce or even the tallest structure ever built, have served to realize the greatest dream ever seen by mankind to reach to the sky.

- There is not a definite description for "tall building", "high-rise building" and "skyscraper" in terms of height, or number of stories. Although the terms all mean the same type of building which is built extremely high, there is an implicit difference among them. Respectively, "skyscraper" is a more assertive term when compared to "tall building" and "high-rise building". On the other hand, according to the authors:

  - A building named as a "tall building" must satisfy all of the following conditions:

    - Its height has to surpass significantly its plan dimensions. In other words, this condition is directly related to the *slenderness ratio*.
    - It has to be much taller than the local (in which it is situated), but not necessarily the global context.

    Hence, the "tall building" is used in a local sense. The meaning of this term then varies according to place and not to time.

  - A building named as a "skyscraper", however, must satisfy all of the following conditions:

    - Its height has to surpass significantly its plan dimensions. In other words, this condition is directly related to the *slenderness ratio*.
    - It has to be much taller than other buildings in both the local and the global context.
    - It has to utilize the latest technological innovations of its respective period.

Additionally, a building can keep the title "skyscraper" throughout the period in which it was constructed or even keep this title beyond its respective period. If a building has taken the title of "the tallest building of the world" when it was constructed, it can become a worldwide popular building or an icon of its city, such as Empire State Building, Sears Tower, World Trade Center Twin Towers and like. Because of their global prominence, these buildings are called "skyscrapers" even today. Furthermore, these buildings become more than a skyscraper; they have become an unforgettable classic by keeping their fame beyond their respective period. Due to their universal popularity, their names are recognized more than as skyscrapers and the names of the cities where they are located are overshadowed by the names of these buildings. For example, the people who know the Sears Tower probably do not know in which city the Sears Tower is located. Hence, the "skyscraper" is a global term. It can be described as a "very tall building", where the 'very' is a comparative adverb dependent on time.

Because of not being taken into consideration the American origin of the "skyscraper", several buildings were called the "skyscraper" even tough they are not actually "skyscrapers". For example, often Emek Business Center (Ankara, 1962) is known as a "skyscraper" (in Turkish 'gökdelen') by Turkish people, since it was the first modern tall building in Turkey. However, when this building is assessed with American norms, it will be seen that it does not correspond to the meaning of skyscraper which is discussed above.

  - "High-rise building" and "tall building", on the other hand, are used synonymously.

- Despite all their negative effects, it is not possible to think of contemporary cities without tall buildings. Tall buildings are the most famous landmarks of cities, symbols of power, dominance of human ingenuity over natural world, confidence in technology and a mark of national pride; and besides these, despite several undeniable negative effects on the quality of urban life, the importance of tall buildings in contemporary urban development is without doubt ever increasing.

- Since the restriction of height and profile by building codes or zoning laws, and researching historical precedents were not enough to solve the problems created by tall buildings, more successful solutions are sought by the architects and city planners as these buildings introduce totally new form, user and technological problems. Architects, planners, engineers, and developers must develop a broad perspective for an understanding of the planning, design, and construction of tall buildings and their impact on a global scale.

- Thanks to the new innovations in construction technology, such as the advances in formwork, mixing of concrete, techniques for pumping, and types of admixtures to improve quality, reinforced concrete has gained more importance in high-rise construction. As a result of the rapid developments in concrete construction and technology, with every passing year, the use of concrete for tall buildings is becoming a constant reality. Besides this, due to the utilization of innovative structural systems and advanced design techniques, very little usable floor space is occupied by the structure. High strength concrete and lightweight structural concrete allow using smaller member sizes and less steel reinforcement. Furthermore, the floor erection cycle time for the reinforced concrete tall buildings is now almost comparable with that of the steel buildings. All these factors have contributed in making reinforced concrete an excellent alternative and a great challenger of steel in the construction of tall buildings. From the first reinforced concrete tall building, 15-storey high Ingalls Building to 610 m high Burj Dubai utilizing concrete strength up to 80 MPa (which is anticipated to be the next tallest building in the world upon completion in 2008), there has been a great evolution in reinforced concrete construction. Therefore, more and more concrete tall buildings shaping the skylines of major cities in the world will come to the building scene in the forthcoming years.

- Selection of reinforced concrete as a construction material can result from different reasons:

    - In some windy cities, the limiting sway requirement could be achieved only through the use of high strength concrete with super plasticizers as in Two Prudential Plaza (Chicago, U.S.A.).

    - In some countries, the building's sway from the wind forces would in fact be reduced with concrete, since the cycle of motion due to wind is longer than that of a steel building (which is lighter than the concrete building) and this longer period reduces the acceleration and thus decreases the sensation of sway that might be felt by the occupants as in Carnegie Hall Tower (New York, U.S.A.).

- Reinforced concrete is also selected because of its ability to support the loads while allowing the smaller floor-to-floor height as in the construction of Nations Bank Corporate Center (California, U.S.A.).

- In some cities, reinforced concrete is preferred over steel since local contractors are more experienced in reinforced concrete construction as in Malayan Bank (Malaysia).

- In Turkey reinforced concrete is a more preferred structural material than steel in the construction of tall buildings. The much more improved reinforced concrete industry and its great pressure on unwelcomed steel industry, the local contractors that are more familiar with reinforced concrete when compared to steel, have all contributed to make this material much more popular.

- The Far East is the birthplace of a new generation of super-tall buildings. While this building type was not welcomed with open arms in Europe, the skyscraper dominance has shifted in the 1990s from Chicago and New York to the Far East. European countries developed town planning regulations against tall buildings, which are seen as a symbol of the degeneration of traditional European city. Instead of becoming an unbeatable challenger for the race of building height as in the Far East, European planners try to design tall buildings with minimum disturbances to the natural environment and the city's existing urban fabric. In this context, it seems that the Far East has completely accepted the tall building as a symbol of technological, economic, and political dominance in order to take a better position in the international scene by showing their ability to compete with the western leaders in the field of tall buildings. Hence, the majority of the next generation of skyscrapers is most likely to be built in the Far East, although some tall buildings are still being planned in the West.

- Tall building design requires a unique collaboration particularly between the architect and the engineer. This interdisciplinary approach to resolving building planning, construction, and usage issues plays a vital role. Moreover, because of the scale and complexity of tall buildings, this teamwork often begins at the earliest stages of the design process and continues well into construction. On the other hand, for the skyscrapers of the next generation, the collaboration, in particular between the architectural, structural and aerospace engineering field without victimizing the architectural design, is gaining more and more importance.

- On the other hand, the race to build the tallest, introduces new obstacles to today's architects and engineers. Each step to the sky by means of the tallest buildings forces the designers to find innovations to overcome the newly emerging obstacles. One of the greatest problems of today's tall buildings is their vulnerability to environmental excitations such as wind, which leads to horizontal vibration. Thanks to the advent of high-strength lightweight materials, contemporary tall buildings are remarkably much more slender and lighter than their former precedents. Unfortunately, however, these improvements are often accompanied by increased flexibility and a lack of sufficient inherent damping. This undesired condition causes serious problems especially for the occupants of the building. If it is remembered that the main function of the building is to serve its users, the importance and seriousness of the problem is better understood. Understandably, under the action of wind and the excessive vibration, serviceability and occupant comfort are under a great threat. Hence, accelerations particularly at the top floors during windstorms should be kept within a tolerable limit to minimize discomfort of the occupants and to prevent damages on both structural and non-structural elements.

- Tall buildings are gigantic projects demanding incredible logistics and management. They influence building industry, national economy, and require enormous financial investment. A careful coordination of the structural elements and the shape of a tall building which minimizes the lateral displacement, may offer considerable savings.

- Many factors, such as aesthetics, functionality, and the requirements of city planning authorities, dictate the shape of a tall building. As the building becomes taller and slender, another factor, wind, enters into the picture. Usually, the structural engineer can design the main wind force resisting system to overcome the expected wind forces but some shapes will experience greater forces than others and thus could result in increased structural cost. The problem of excessive building motions and their effect on comfort of the occupants can be a more difficult one to solve in the case of very tall and slender buildings. Structural measures alone are sometimes inadequate in finding a practical solution to motion problems and other approaches such as special damping devices must be used in such situations. Therefore, an appropriate choice of building shape can result in a significant reduction of aerodynamic forces by changing the flow pattern around the building. This way of treatment can moderate wind responses when compared to the original building shape.

- Tall buildings cause accelerated wind at ground level, which may influence the comfort and safety of the pedestrians. The overall massing of the building and its orientation towards the prevailing wind are critical factors that dictate how much the impact will be.

- Because of the enormous variety of the possible shapes in building design and their different interactions with the surrounding structures, it is difficult to develop simple general rules for the preference of shapes as a tool for reducing wind related problems. In this respect, the wind tunnel testing is usually the best way for determining project specific wind loads and building motions.

- From the wind engineer's point of view, architectural modifications such as setback, tapering and sculptured building tops are very effective design methods of controlling wind excitation and many of the most elegant and notable buildings, such as the John Hancock Center, the Jin Mao Building, the Petronas Towers, and the Sears Tower, utilize these approaches.

- Architectural modifications to corner geometry, such as chamfered corners, slotted corners, rounded corners, corner cuts, can also significantly reduce wind induced response of buildings.

- Addition of openings completely through the building, particularly near the top, is another very useful way of improving the aerodynamic response of that structure against wind as in the Shanghai World Financial Center.

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