مجلة جامعة الملكة أروى العلمية المحكمة

QUEEN ARWA UNIVERSITY JOURNAL

Art and Analysis of high-rising building

Ali Saleh Mohammed Abdulrazaq [1]

[1]*Thamar University, Department of Civil Engineering, Assistant Professor*

2020

ISSN: *2226-5759*   ***ISSN Online:*** *2959-3050*   ***DOI:****10.58963/qausrj.v1i24.114*

Website: *qau.edu.ye*

Art and Analysis of high-rising building

Ali Saleh Mohammed Abdulrazaq
Thamar University, Department of Civil Engineering

Abstract: Tall building developments have been rapidly increasing worldwide. This paper reviews the evolution of tall building's structural systems and the technological driving force behind tall building developments. For the primary structural systems, a new classification – interior structures and exterior structures – is presented. While most representative structural systems for tall buildings are discussed, the emphasis in this review paper is on current trends such as modeling and analysis. Consideration of site specific lateral loading due to wind or earthquake loads along with vertical gravity loads is important for finding the behavior of the tall buildings. The design of tall buildings essentially involves a conceptual design, approximate analysis, preliminary design and optimization, to safely carry gravity and lateral loads. Analysis and design of buildings for static and dynamic forces is a routine affair these days because of availability of affordable computers and specialized programs which can be used for the analysis. Finally, the future of structural developments in tall buildings is envisioned briefly.

Keywords: Shear wall, Framing, Diagrid structures, Exterior structures, Interior structures, Outrigger systems, Dual Structural , Structural systems, Tall buildings, Finite Element Method

1.0 Introduction

Tall buildings emerged in the late nineteenth century in the United States of America. They constituted a so-called “American Building Type,” meaning that most important tall buildings were built in the U.S.A.

The function of tall buildings has been as commercial office buildings. Other usages, such as residential, mixed-use, and hotel tower developments have since rapidly increased. Tall building development involves economics, technology, aesthetics, politics, and municipal regulations[1, 4, 10, 11, 14].

#	City	Number of skyscrapers	Percentage
1	**Asia**	12,730	69%
2	**North America**	3,659	20%
3	**Europe**	888	5%
4	**South America**	637	3%
5	**Oceania**	433	2%
6	**Africa**	136	1%
Total		18483	

Table 1 *Tall Buildings in Regions (2020, based on most active cities in the regions reported in Emporis.com).*

Many tall buildings are built worldwide, especially in Asian countries, such as China, Korea, Japan, and Malaysia. Based on data published in the 1980s, about 49% of the world’s tall buildings were located in North America. The distribution of tall buildings has changed radically with Asia now having the largest share with 69%, and North America’s at 20% (**Table 1**). This data demonstrates the rapid growth of tall building construction in Asian during this period while North American construction has slowed. In fact, nine of the top ten tall buildings are now in Asia and only one, One World Trade Center is in North America, NY, USA. In the middle east the high-rising building is going to increase from time to time, the state is look as in **Table2**.

	Country	Height>50m	Percentage
1	**UAE**	3969	70.5%
2	**KSA**	315	6%
3	**Bahrain**	120	2%
4	**Qatar**	340	6%
5	**Oman**	20	0.3%
6	**Kuwait**	280	5%
7	**Lebanon**	6% 340	
8	**Syria**	60	1.1%
9	**Iraq**	100	1.7%
10	**Jordan**	80	1.3%
11	**Yemen**	7	0.1%
	TOTAL	5631	

Table 2. *Middle east country for high-rise building, height above 50m*

2.0 Developments of Structural Systems

Structural development of tall buildings has been a continuously evolving process. There is a distinct structural history of tall buildings similar to the history of their architectural styles in terms of skyscraper ages **Figure 1**. These stages range from the rigid frame, tube, core-outrigger to diagrid.

The primary structural skeleton of a tall building can be modeled as a vertical cantilever member with its base fixed in the ground. The structure has to carry the vertical gravity loads and the lateral load. The building must therefore have adequate shear and bending resistance and must not lose its vertical load-carrying capability.

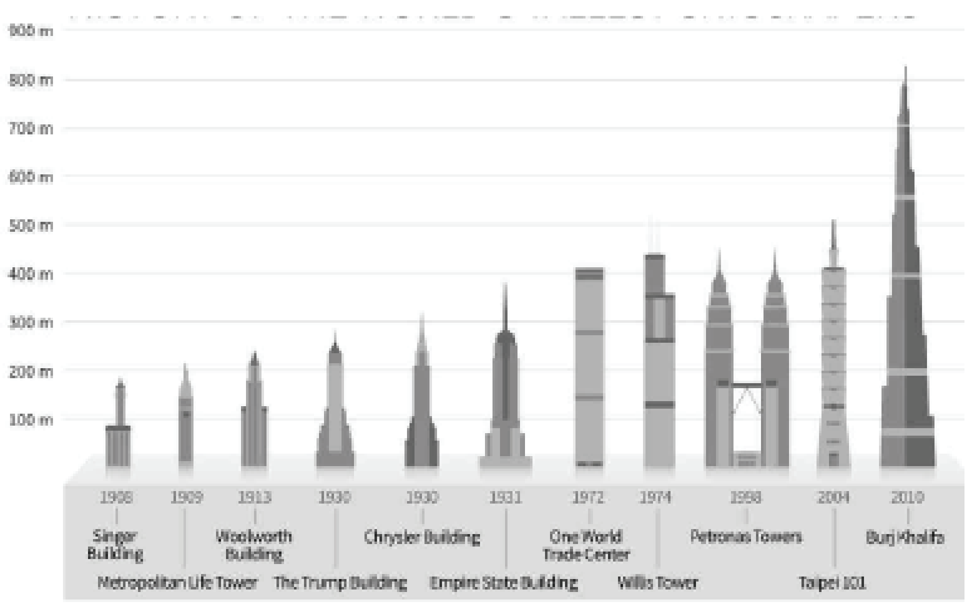


Figure 1 *Historical brief of tall building in the world*

The floor framing system usually carries almost the same gravity loads at each floor, although the girders along the column lines need to be progressively heavier towards the base of the building to carry increasing lateral forces and to augment the building's stiffness.

The column sizes increase progressively towards the base of the building due to the accumulated increase in the gravity loads transmitted from the floors above. Further to this, the columns need to be even heavier towards the base to resist lateral loads. The net result is that as the building becomes taller and the building's sway due to lateral forces becomes critical, there is a greater demand on the girders and columns that make up the rigid-frame system to carry lateral forces.

If we assume the same bay sizes, the material quantities required for floor framing is almost the same regardless of the number of stories. The material needed for floor framing depends upon the span of the framing elements, that is, column-to-column distance and not on the building height. The quantity of materials required for resisting lateral loads, on the other hand, is even more increased and would begin to exceed other structural costs if a rigid-frame system is used for very tall structures. This calls for a structural system that goes well beyond the simple rigid frame concept. Based on his investigations Khan argued that as the height increases beyond 10 stories, the lateral drift starts controlling the design, the stiffness rather than strength becomes the dominant factor, and the premium for height increases rapidly with the number of stories. Following this line of reasoning, Khan recognized that a hierarchy of structural systems could be categorized with respect to relative effectiveness in resisting lateral loads for buildings beyond the 20- to 30-story range (Khan, 1969)[19].

3.0 Classification of Tall Building Structural Systems.

Building types and elements Alberti (1992)[6] does mention the existence of various building types that has developed from the original shelter as specialization of functions. Generally buildings divided into two types: Public buildings with several functions, sacred as well as profane, and private buildings divided into two groups- those foremost citizens and those for common citizens **Figure 2**.

These different aspects are referred to as building systems. Beedle (1980)[9] defines four distinct building systems: Loading Systems, Physical Systems, Functional Systems, and Building Implementation Systems. These are seen in **Figure** 3. Under the "Physical Systems" heading are such i terns as foundation systems, structural framework, mechanical and service systems, and electrical systems. In general, the structural system of a building is a three dimensional complex assemblage of interconnected structural elements. The primary function of the structural system is to effectively and safely carry all the loads which act upon the building, and to resist sway by providing adequate stiffness. The structural system physically supports the entire building, and with it, all the other various building systems

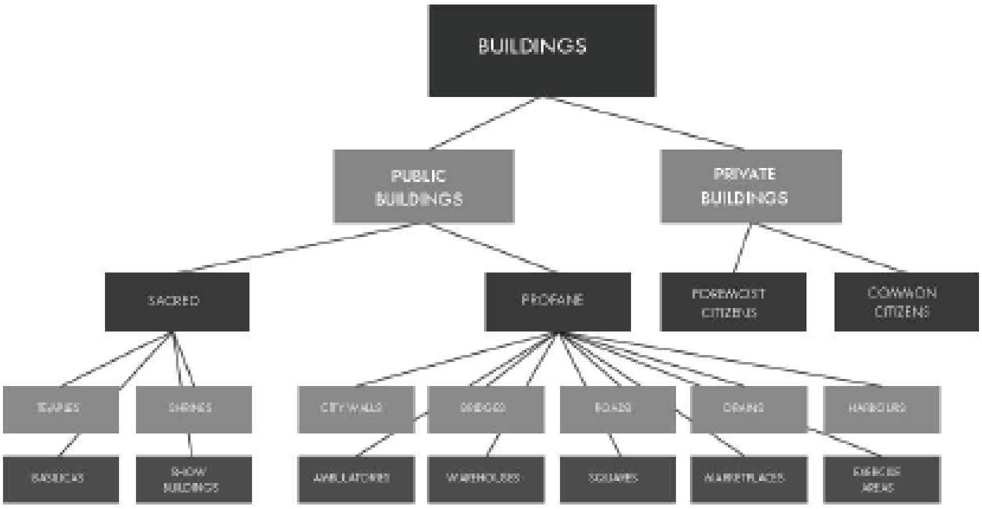


Figure 2 *Types of buildings and elements*

For the purpose of research, it is desirable to categorize the different aspects of tall buildings.

Loading Systems

Gravity
Temperature
Earthquake
Wind
Fire
Accidental Loading

Functional Systems

Utilization
Ecological
Site
Esthetics
Space Cognition

Parking
Ownership, Financing
Operation
Maintenance
Management

Access and Evacuation
Infiltration Protection
Environmental
Transportation
Energy Efficiency

Building Services
Communication
Security
Fire Protection
Urban Services

Physical Systems

Foundation
Structural Framework
Mechanical Systems
Electrical

Architectural
Fitting and Furnishings
Contents
Utilities

Building Implementation Systems

Need
Planning
Design
Construction
Operation
Demolition

Figure 3 *Tall Building Systems (Beedle, 1980)[9]*

Fazlur Khan in 1969 classified structural systems for tall buildings relating to their heights with considerations for efficiency in the form of "Heights for Structural Systems" diagrams [19,21].

Khan [17, 21] uses a material-oriented classification to discuss the different responses of various steel, concrete and mixed structural systems to lateral loads.(see **Table 3**).

Steel Structural Systems	**Concrete Structural Systems**
1. Rigid Frame	1. Frame
2. Shear Truss Frame	2. Shear Wall

3. Shear Truss Frame with Belt Trusses	3. Frame-Shear Wall
. 4. Framed Tube	4. Framed Tube
5. Column Diagonal Truss Tube	5. Tube-in-Tube
6. Bundled Tube	6. Modular Tube
7 . Truss Tube without Interior Columns	

Table 3 *High rise structural systems (Khan, 1974)*

This marked the beginning of a new era of skyscraper revolution in terms of multiple structural systems. Later, he upgraded these diagrams by way of modifications [20, 21](Khan, 1972, 1973). and developed these schemes for both steel and concrete **Figure 4** and **5.** (Ali, 2001; Ali & Armstrong, 1995; Schueller, 1986)[3, 7, 27]. Khan argued that the rigid frame that had dominated tall building design and construction so long was not the only system fitting for tall buildings.

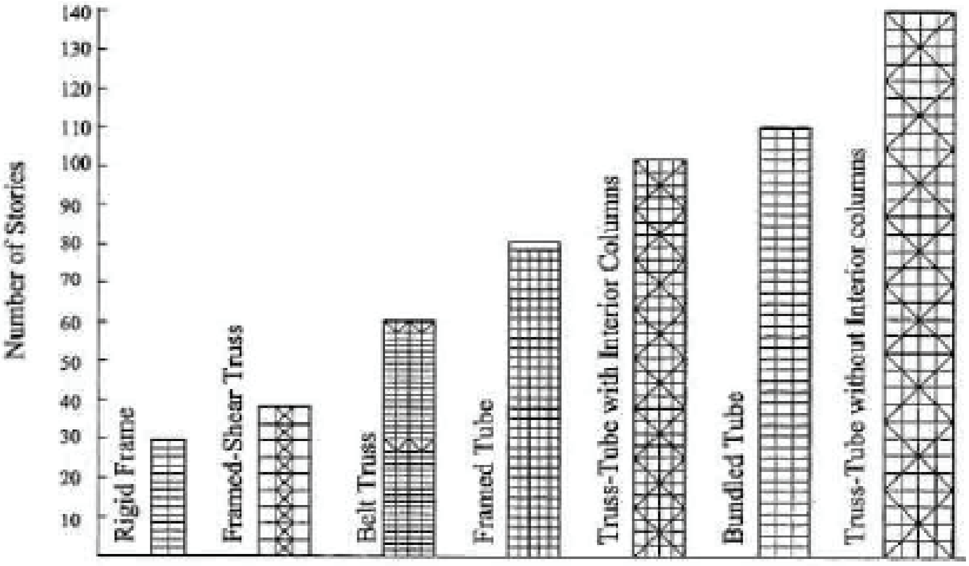


Figure 4 *Classification of tall building structural systems by Fazlur Khan(steel).*

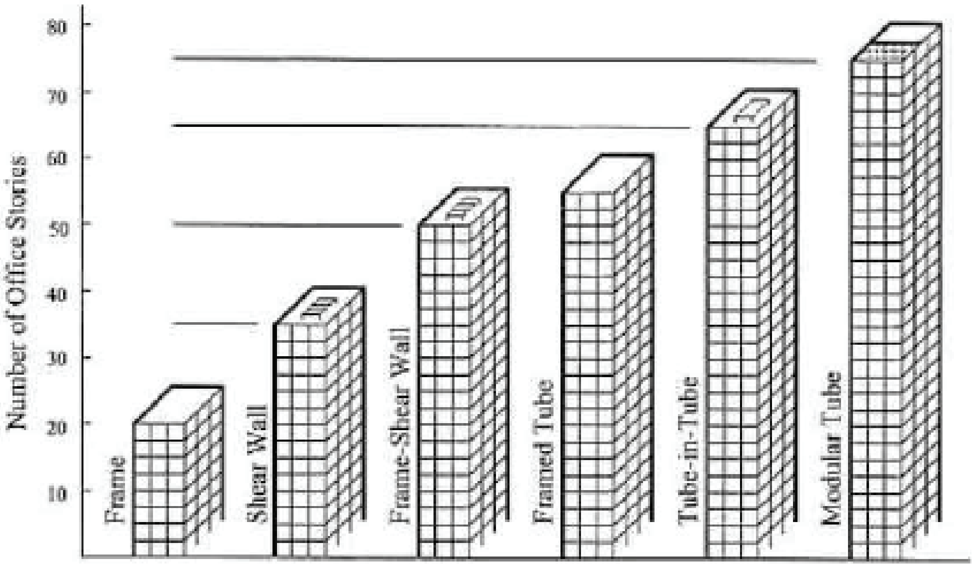


Figure 5 *Classification of tall building structural systems by Fazlur Khan (concrete).*

Because of a better understanding of the mechanics of material and member behavior, he reasoned that the structure could be treated in a holistic manner, that is, the building could be analyzed in three dimensions, supported by computer simulations, rather than as a series of planar systems in each principal direction. Feasible structural systems, according to him, are rigid frames, shear walls, interactive frame-shear wall combinations, belt trusses, and the various other tubular systems [22].

Lu (1974)[24] has presented a classification using the same basic approach, namely, a listing of vertical load resisting members, horizontal load resisting subsystems, and energy dissipation systems. This arrangements is shown in **Table 4**. A more detailed listing of lateral load resisting subsystems is included, which clearly indicates the myriad of combinations of lateral load resisting subsystems employed in the design of tall buildings.

Gravity Load Resistant Systems	**Lateral Load Resistant Systems**
1. Horizontal (floor) Framing	1. Moment Resistant Frame
2. Vertical Framing	2. Shear Wall or Truss
a). bearing walls	3. Combined Frame and Shear Wall or Truss
b). hangers	4. Moment Resistant Frame with Stiffening Features
c). load transfer girders	5. Core Structure
	6. Framed Tube
	7. Combined Framed Tube and Core Structure
	8. Framed Tube with Stiffening Features
	9. Other Tube Structure

Table 4 *Structural Systems (Lu, 1974)*

Drosdov and Lishak (1978)[13] developed a classification that categorizes the variety of existing structural systems into four primary load bearing systems and six secondary (combination) load bearing structures as seen in **Table 5**.

Primary Structural Systems	**Secondary (Combination) Structural Systems**
1. Framed systems (Frame)	1. Frame-Braced System (Frame & Wall)
2. System with Flat Walls (Wall)	2. Frame System (Frame & Core)
3. Core-Trunk System (Core)	3. Frame-Envelop System (Tube & Frame)
4. Envelop-Type System (Tube)	4. Trunk-Wall System (Core & Wall)
	5. Cellular System (Tube & Wall)

Table 5 *STRUCTURAL SCHEMES* (Drosdov, Lishak, 1978)

The six secondary systems are, in fact, combinations of the four primary structures as shown in **Figure 6**. This classification is part of a study of the dynamic response of different tall building structures.

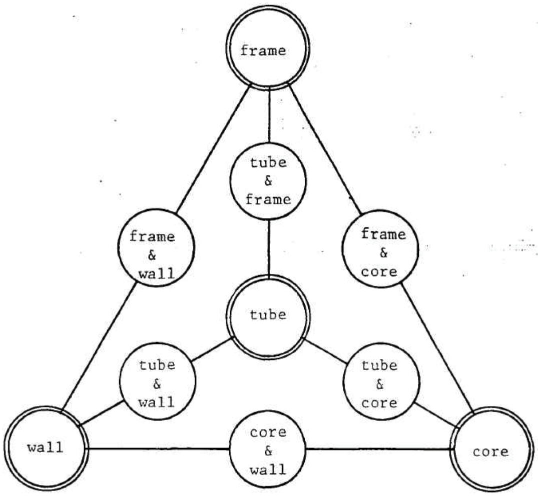


Figure 6 *Classification of Structural Systems of Multi-Story Buildings (Drosdov, Lishak, 1978)*

In Schueller's (1977)[28] classification, primary emphasis is given to visual and descriptive analysis of the structural systems (see **Table 6**). He lists 14 separate tall building structural systems in an attempt to adequately represent the spectrum of tall building structures.

1. Bearing Walls	2. Cores and Bearing Walls	3. Self Supporting Boxes
4. Cantilevered Slab	5. Flat Slab	6. Interspatial
7. Suspended	8. Staggered Truss	9. Rigid Frame
10. Core and Rigid Frame	11. Trussed Frame	12. Belt-Trussed Frame and Framed Core
13. Tube-in-Tube	Bundled Tube .14	

Table 6 *Common high rise structures (Schueller, 1975)*

Structural systems of tall buildings can be divided into two broad categories: ***interior structures*** and ***exterior structures***. This classification is based on the distribution of the components of the primary lateral load-resisting system over the building. A system is categorized as an interior structure when the major part of the lateral load resisting system is located within the interior of the building. Likewise, if the major part of the lateral load-resisting system is located at the building perimeter, a system is categorized as an exterior structure. It should be noted, however, that any interior structure is likely to have some minor components of the lateral load-resisting system at the building perimeter, and any exterior structure may have some minor components within the interior of the building.

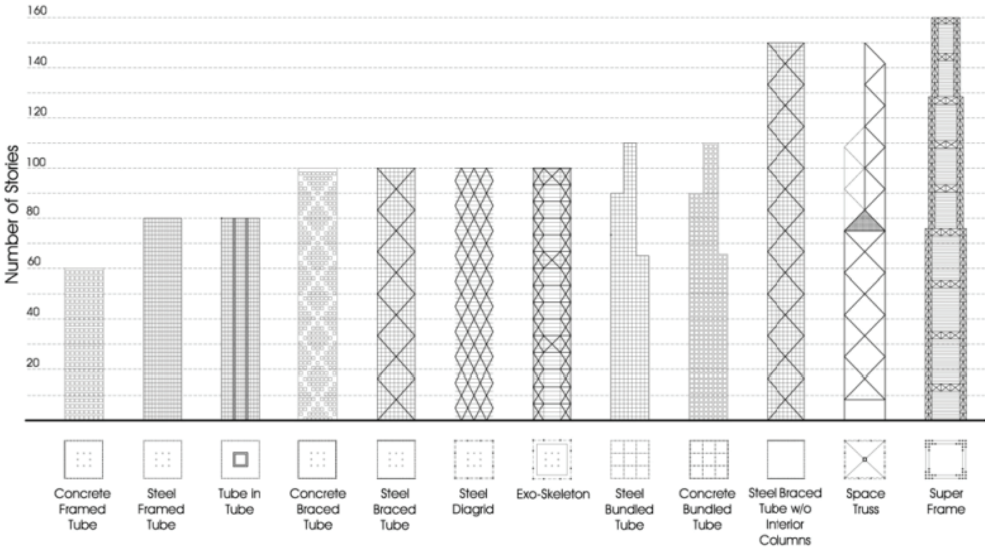


Figure 4 *Interior Structures: single / dual component planar assemblies in 2 principal directions[16]*

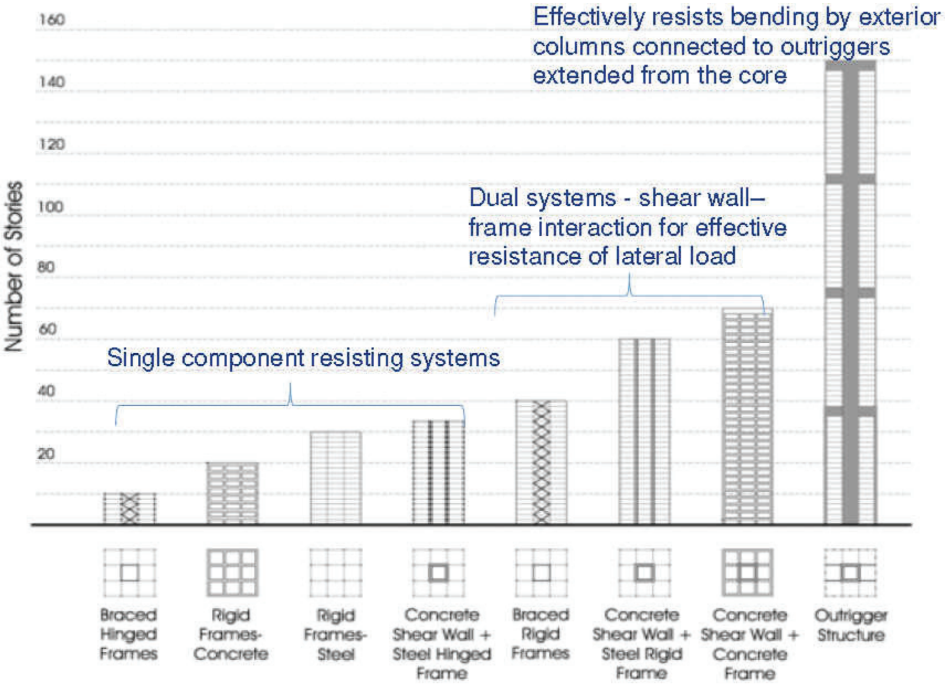


Figure 5 *Exterior Structures: effectively resist lateral loads by systems at building perimeter*

Category	Sub-category	Material/ Configuration	Efficient Height Limit	Advantage	Disadvantages	Building Examples
Rigid Frames	-	Steel	30	Provide flexibility in floor planning. .Fast construction	Expensive moment connections. Expensive fire .proofing	Lake Shore 880 & 860 Drive Apartments (Chicago, USA, 26 stories, 82 m), Business Men›s Assurance Tower (Kansas City, USA, 19 stories), Seagram Building, 30th to the top floor (New York, USA, 38 (stories, 157 m
		Concrete	20	Provide flexibility in floor planning. Easily moldable	Expensive formwork. Slow construc-.tion	Ingalls Building (Cincinnati, USA, 16 stories, (65 m
Braced Hinged Frames	-	Steel Shear Trusses + Steel Hinged Frames	10	Efficiently resist lateral loads by axial forces in the shear truss members. Allows shallower beams compared with the rigid frames without diagonals	Interior planning limitations due to diagonals in the shear trusses. Expensive diagonal connections	Low-rise buildings

Shear Wall (or Shear Truss) - Frame Interaction System	Braced Rigid Frames	Steel Shear Trusses + Steel Rigid Frames	40	Effectively resists lateral loads by producing shear truss - frame .interacting system	Interior planning limitations due to shear trusses	Empire State Building (New York, USA, 102 stories, 381 m), Seagram Building, 17th to 29th floor (New York, USA, (38 stories, 157 m
	Shear Wall / Rigid Frames	Concrete Shear Wall + Steel Rigid Frame	60	Effectively resists lateral loads by producing shear wall - frame inter.acting system	Interior planning limitations due to shear .walls	Seagram Building, up to the 17th floor (New York, USA, 38 stories, (157 m
		Concrete Shear Wall + Concrete Frame	70	=	=	South Wacker Drive 311 (Chicago, USA, 75 stories, 284 m), Cook County Administration Building, former Brunswick Building (Chicago, USA, 38 stories, 145 m
Outrigger Structures	-	Shear Cores (Steel Trusses or Concrete Shear Walls) + Outriggers (Steel Trusses or Concrete Walls) + (Belt Trusses) + Steel or Concrete Composite (Super) Columns	150	Effectively resists bending by exterior columns connected to outriggers extended .from the core	Outrigger structure does not add shear resistant	Taipei 101 (Taipei, Taiwan, 101 stories, 509 m), Jin Mao Building (Shanghai, China, 88 (stories, 421 m

Table 7 *Interior Structure*

Tables 7 and **8** summarize the details of the systems in each category. In addition, **Figure 4** and **5** show the concept of each system diagrammatically. This classification of structural systems is presented more as a guideline and should be treated as such. It is imperative that each system has a wide range of height applications depending upon other design and service criteria related to building shape, aspect ratio, architectural functions, load conditions, building stability and site constraints. For each condition, however, there is always an optimum structural system, although it may not necessarily match one of those in the system's tables due to the predominant influence of other factors on the building form. An exterior structure may be combined with an interior one, such as when a tubular frame is also braced or provided with core-supported outriggers and belt trusses, to enhance the building's stiffness[10, 12].

Interior Structures

The two basic types of lateral load-resisting systems in the category of interior structures are ***the moment-resisting frames*** and ***shear trusses/shear walls***. These systems are usually arranged as planar assemblies in two principal orthogonal directions and may be employed together as a combined system in which they interact. Another very important system in this category is the core-supported outrigger structure, which is very widely used for supertall buildings.

The ***moment-resisting frame*** **(MRF)** consists of horizontal (girder) and vertical (column) members rigidly connected together in a planar grid form. Such frames resist load primarily through the flexural stiffness of the members (Kowalczyk, Sinn, & Kilmister, 1995)[23]. The size of the columns is mainly controlled by the gravity loads that accumulate towards the base of the building giving rise to progressively larger column sizes towards the base from the roof. The size of the girders, on the other hand, is controlled by stiffness of the frame in order to ensure acceptable lateral sway of the building. Although gravity load is more or less the same in all typical floors of a tall building, the girder sizes need to be increased to increase the frame stiffness. Likewise, columns already sized for gravity loads need to be slightly increased to increase the frame stiffness as well. MRFs can be located in or around the core, on the exterior, and throughout the interior of the building along grid lines.

Braced frames are laterally supported by vertical steel trusses, also called shear trusses, which resist lateral loads primarily through axial stiffness of the members. These act as vertical cantilever trusses where the columns act as chord members and the concentric K, V, or X braces act as web members. Such systems are called **c**oncentric **b**raced **f**rames (CBF). **E**ccentric **b**raced **f**rames (EBF) have, on the other hand, braces which are connected to the floor girders that form horizontal elements of the truss, with axial offsets to introduce flexure and shear into the frame [26]. This lowers stiffness-to-weight ratio but increases ductility and therefore EBFs are used for seismic zones where ductility is an essential requirement of structural design. Braced frames are generally located in the service and elevator core areas of tall buildings. The frame diagonals are enclosed within the walls[15].

Reinforced concrete planar solid or coupled ***shear walls*** have been one of the most popular systems used for high-rise construction to resist lateral forces caused by wind and earthquakes. They are treated as vertical cantilevers fixed at the base. When two or more shear walls in the same plane are interconnected by beams or slabs, as is the case with shear walls with door or window openings, the total stiffness of the system exceeds the sum of the individual wall stiffnesses. This is so because the connecting beam forces the walls to act as a single unit by restraining their individual cantilever actions. These are known as coupled shear walls. Shear walls used in tall office buildings are generally located around service and elevator cores, and stairwells. In fact, in many tall buildings, the vertical solid core walls that enclose the building services can be used to stabilize and stiffen the building against lateral loads

Rigid frames may be combined with vertical steel trusses or reinforced concrete shear walls to create ***shear wall (or shear truss)-frame interaction systems***. Rigid frame systems are not efficient for buildings over 30 stories in height because the shear racking component of deflection caused by the bending of columns and girders causes the building to sway excessively. On the other hand, vertical steel shear trusses or concrete shear walls alone may provide resistance for buildings up to about 10 or 35 stories, respectively, depending on the height-to-width ratio of the system (see **Table 4**).

Outrigger systems have been historically used by sailing ships to help resist the wind forces in their sails, making the tall and slender masts stable and strong. The core in a tall building is analogous to the mast of the ship, with outriggers acting as the spreaders and the exterior columns like the stays. As for the sailing ships, outriggers serve to reduce the overturning moment in the core that would otherwise act as pure cantilever, and to transfer the reduced moment to the outer columns through the outriggers connecting the core to these columns (**Figure 6**).

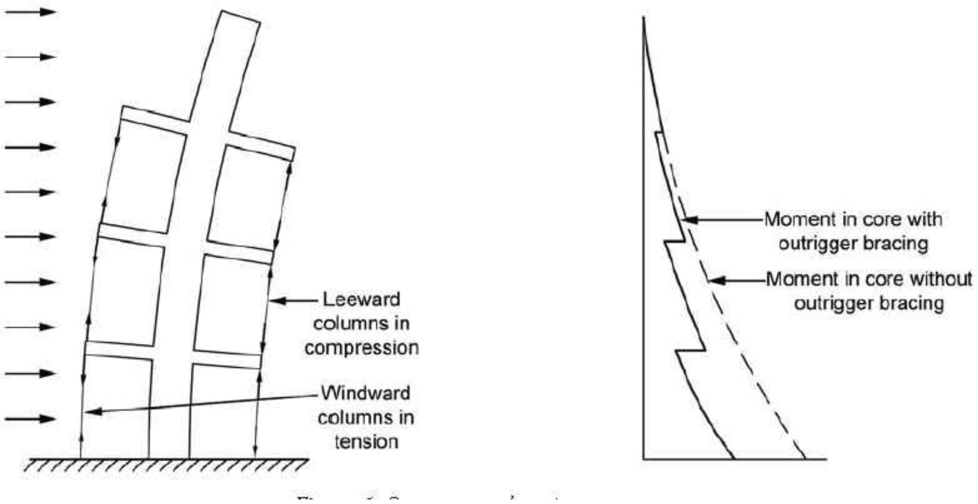


Figure 6 *Core-supported outrigger structures.*

The core may be centrally located with outriggers extending on both sides or in some cases it may be located on one side of the building with outriggers extending to the building columns on the other side (Taranath, 1998)[29].

The outriggers are generally in the form of trusses in steel structures, or walls in concrete structures, that effectively act as stiff headers inducing a tension-compression couple in the outer columns. Belt trusses are often provided to distribute these tensile and compressive forces to a large number of exterior frame columns. The belt trusses also help in minimizing differential elongation and shortening of columns. Outriggers can also be supported on megacolumns in the perimeter of the building. Although this structure is primarily an interior system, the belt trusses or megacolumns offer a wider perimeter, thus resisting the lateral push of the building’s ‘feet’ spread.

For buildings between about 30 to 70 stories, steel braced cores or reinforced concrete core walls are generally effective for resisting lateral loads. However, for greater heights, the resistance of the core systems to bending caused by overturning becomes progressively inefficient. Moreover, a core system with its highly slender attribute can generate excessive uplift forces in the core columns and high overturning forces on the foundation system. In reinforced concrete cores, excessive wall elements where large net tensile forces develop can easily cancel the inherent efficiency of concrete in compression. Likewise, in steel cores, excessive welded or bolted tensile splices could greatly reduce the ease of erection and fabrication. The core-outrigger system alleviates this problem. Some other advantages of the core-and-outrigger system are that the exterior column spacing can easily meet aesthetic and functional requirements, and the building’s perimeter framing system may consist of simple beam-column framing without the need for rigid-frame-type connections.

For supertall buildings, connecting the outriggers with exterior megacolumns opens up the façade system for flexible aesthetic and architectural articulation thereby overcoming a principal drawback of closed-form tubular systems. In addition, outrigger systems have a great height potential up to 150 stories and possibly more. The principal disadvantages are that the outriggers interfere with the rentable space and the lack of repetitive nature of the structural framing results in a negative impact on the erection process. However, these drawbacks can be overcome by careful architectural and structural planning such as placing outriggers in mechanical floors and development of clear erection guidelines. The outrigger systems may be formed in any combination of steel, concrete and composite construction. Because of the many functional benefits of outrigger systems and the advantages outlined above, this system has lately been very popular for supertall buildings all over the world.

Category	Sub-Category	Material / Configuration	Efficient Height Limit	Advantages	Disadvantages	Building Examples
Tube	Framed Tube	Steel	80	Efficiently resists lateral loads by locating lateral systems at the .building perimeter	Shear lag hinders true tubular behavior. Narrow column spacing .obstructs the view	Aon Center (Chicago, USA, (83 stories, 346 m
		Concrete	60	=	=	Water Tower Place (Chicago, (USA, 74 stories, 262 m
	Braced Tube	Steel	100 With) Interior Columns) – 150 (Without Interior (Columns	Efficiently resists lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes. .Reduced shear lag	Bracings obstruct the .view	John Hancock Center (Chicago, USA, 100 stories 344 m
		Concrete	100	=	=	Onterie Center (Chicago, 58 stories, 174 m), 780 Third Avenue (New York, USA, 50 (stories, 174 m
	Bundled Tube	Steel	110	.Reduced shear lag	Interior planning limitations due to the bundled .tube configuration	Sears Tower (Chicago, USA, (108 stories, 442 m
		Concrete	110	=	=	Carnegie Hall Tower (New York, USA, 62 stories, 230.7 (m

	Tube Tube in Tube	Ext. Framed Tube (Steel or Concrete) + Int. Core Tube (Steel or Concrete	80	Effectively resists lateral loads by producing interior shear core - exterior framed tube .interacting system	Interior planning limitations due to shear core	West Madison Street 181 (Chicago, USA, 50 stories, 207 m) Steel 100 Efficiently resists lateral shear by axial forces in the diagonal members. Complicated joints. Hearst
Diagrid	-	Steel	100	Efficiently resists lateral shear by axial forces in the diagonal members	Complicated joints	Hearst Building (New York, USA, 42 stories, 182 m), 30 St Mary Axe, also known as Swiss Re Building (London, (UK, 41 stories, 181 m
		Concrete	60	=	Expensive formwork. .Slow construction	(O-14 Building (Dubai
Space Truss Structures	-	Steel	150	Efficiently resists lateral shear by axial forces in the space .truss members	Obstruct the view. May .obstruct the view	Bank of China (Hong Kong, (China, 72 stories, 367 m
Super frames	-	Steel	160	Could produce super tall buildings	Building form depends to a great degree on the structural system	Chicago World Trade Center (Chicago, USA, 168 stories, Unbuilt
		Concrete	100	=	=	Parque Central Tower (Caracas, Venezuela, 56 stories, (221 m
Exo-skeleton	-	Steel	100	Interior floor is never obstructed by perimeter columns	Thermal expansion / contraction. Systemic .thermal bridges	Hotel de las Artes (Barcelona, (Spain, 43 stories, 137 m

Table 8 *Exterior Structure*

Exterior Structures

The nature of building perimeters has more structural significance in tall buildings than in any other building type due to their very tallness, which means greater vulnerability to lateral forces, especially wind loads. Thus, it is quite desirable to concentrate as much lateral load-resisting system components as possible on the perimeter of tall buildings to increase their structural depth, and, in turn, their resistance to lateral loads.

The **tube** is one of the most typical exterior structures, which can be defined as a three-dimensional structural system utilizing the entire building perimeter to resist lateral loads. The earliest application of the tubular notion is attributed to Fazlur Khan, who thought of this concept in 1961 (Ali, 2001)[7] and designed the 43-story DeWitt-Chestnut Apartment Building in Chicago, completed in 1965, the first known building designed as a framed tube. The introduction of tube systems has been revolutionary since for the first time the three-dimensional response of buildings was directly exploited to advantage departing from the conventional rigid frame system consisting of rigidly connected planar beam-column grids. Tubular forms have several types depending upon the structural efficiency that they can provide for different heights. In a ***framed tube*** system, which is the basic tubular form, the building has closely spaced columns and deep spandrel beams rigidly connected together throughout the exterior frames. Depending upon the structural geometry and proportions, exterior column spacing should be from 1.5 to 4.5m on centers. Practical spandrel beam depths should vary from 0.6 to 1.2m. As shown in **Figure 7**, for a framed tube subjected to lateral loads, the axial forces in the corner columns are the greatest and the distribution is non-linear for both the web frame (i.e., frame parallel to wind), and the flange frame (i.e., frame perpendicular to wind). This is because the axial forces in the columns toward the middle of the flange frames lag behind those near the corner due to the nature of a framed tube which is different from a solid-wall tube. This phenomenon is known as *shear lag*. The purpose of optimal design of a framed tube is to limit the shear lag effect and aim for more cantilever-type behavior of the structure within reasonable and practical limits (i.e., by achieving a cantilever deflection of 50 to 80 percent of the total lateral sway of the building).

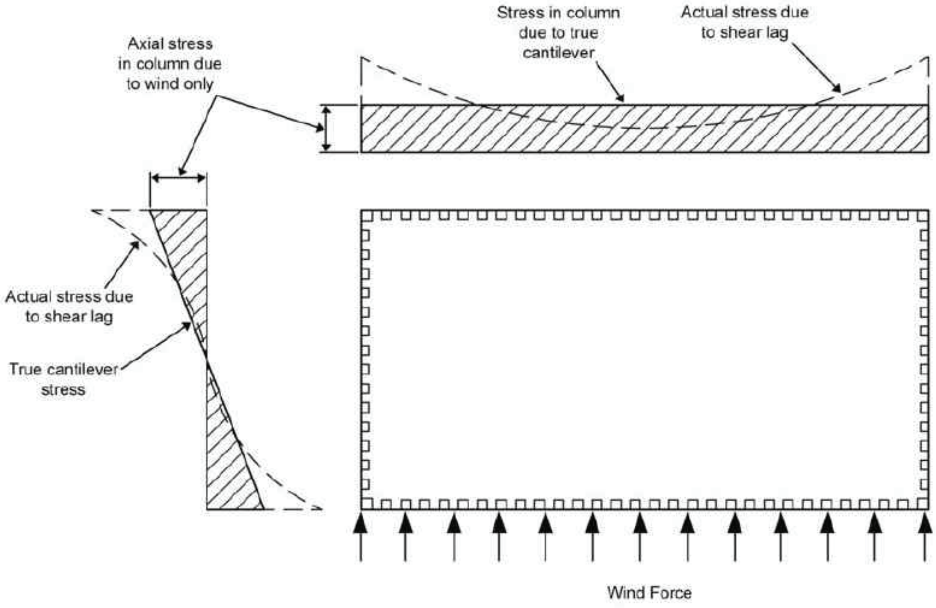


Figure 7 *Shear lag*

A ***braced tube*** is a variation of the framed tube and was first applied on the 100-story John Hancock Center of 1970 in Chicago (Ali, 2001)[5, 7]. This concept stems from the fact that instead of using closely spaced perimeter columns, it is possible to stiffen the widely spaced columns by diagonal braces to create wall-like characteristics. The framed tube becomes progressively inefficient over 60 stories since the web frames begin to behave as conventional rigid frames. Consequently, beam and column designs are controlled by bending action, resulting in large size. In addition, the cantilever behavior of the structure is thus undermined and the shear lag effect is aggravated. A braced tube overcomes this problem by stiffening the perimeter frames in their own planes. The braces also collect gravity loads from floors and act as inclined columns. The diagonals of a trussed tube connected to columns at each joint effectively eliminate the effects of shear lag throughout the tubular framework. Therefore, the columns can be more widely spaced and the sizes of spandrels and columns can be smaller than those needed for framed tubes, allowing for larger window openings than in the framed tubes (Khan, 1967)[18].

A ***bundled tube*** is a cluster of individual tubes connected together to act as a single unit. For very tall structures, a single framed tube is not adequate, since the width of the building at its base should be large to maintain a reasonable slenderness (i.e., height-to-width) ratio such that the building is not excessively flexible and does not sway too much. The system efficiency is considerably diminished in a single framed tube of enormous height due to shear lag effect. For such a structure, the three-dimensional response of the structure could be improved for strength and stiffness by providing cross walls or cross frames in the building.

The 110-story Sears Tower completed in 1974 was the first bundled tube structure in which nine steel framed tubes are bundled at the base, some of which are terminated at various levels along the building's height with two tubes continuing between the 90th floor and the roof. Such flexibility of organizing the floor areas, from very large at the base to much smaller at the top, gave the bundled tube system an added advantage. The bundled tube concept also allowed for wider column spacing in the tubular walls, which made it possible to place interior frame lines without seriously compromising interior space planning of the building. The bundled tube system thus offers great freedom in the architectural planning by creating a powerful vocabulary for a variety of existing building forms. **Figure** 8 shows the bundled tube concept as it was applied to the Sears Tower (Ali, 2001)[1, 4, 7]. A bundled tube building in concrete is One Magnificent Mile of 1983 in Chicago. In this multi-use building, it was possible to assemble the individual tubes in any configuration and terminated at different heights without loss of structural integrity. By carrying the idea of bundled framed tubes further, it is possible to add diagonals to them to increase the efficient height limit. In addition, it is worth noting that to behave as a bundled tube the individual tubes could be of different shapes, such as rectangular, triangular or hexagonal as is demonstrated by this building.

The stiffness of a framed tube can also be enhanced by using the core to resist part of the lateral load resulting in a ***tube-in-tube*** system. The floor diaphragm connecting the core and the outer tube transfer the lateral loads to both systems. The core itself could be made up of a solid tube, a braced tube, or a framed tube. Such a system is called a tube-in-tube, an example of which is the 52-story One Shell Plaza of 1971 in Houston, Texas. It is also possible to introduce more than one tube inside the perimeter tube. The inner tube in a tube-in-tube structure can act as a second line of defense against a malevolent attack with airplanes or missiles.

A **diagrid** system is another type of exterior structure. With their structural efficiency as a varied version of the tubular systems, diagrid structures have been emerging as a new aesthetic trend for tall buildings in this era of pluralistic styles. Early designs of tall buildings recognized the effectiveness of diagonal bracing members in resisting lateral forces. However, while the structural importance of diagonals was well recognized, the aesthetic potential of them was not appreciated since they were considered obstructive for viewing the outdoors. Thus, diagonals were generally embedded within the building cores which were usually located in the interior of the building.

A major departure from this design approach occurred when braced tubular structures were introduced in the late 1960s. For the 100-story tall John Hancock Center in Chicago, the diagonals were located along the entire exterior perimeter surfaces of the building in order to maximize their structural effectiveness and capitalize on the aesthetic innovation. This strategy is much more effective than confining diagonals to narrower building cores. Despite the clear symbiosis between structural action and aesthetic intent of the Hancock Tower, this overall design approach has not emerged as the sole aesthetic preference of architects. However, recently the use of perimeter diagonals – thus the term “diagrid” – for structural effectiveness and lattice-like aesthetics has generated renewed interest in architectural and structural designers of tall buildings.

The difference between conventional exterior-braced frame structures and current diagrid structures is that, for diagrid structures, almost all the conventional vertical columns are eliminated. This is possible because the diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration in a distributive and uniform manner. Compared with conventional framed tubular structures without diagonals, diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional tubular structures carry shear by the bending of the vertical columns and horizontal spandrels (Moon, 2005)[25].

The diagrid can be compared with another prevalent structural system, the outrigger structures. Properly designed, an outrigger structure is effective in reducing the overturning moment and drift of the building. However, the addition of the outrigger trusses between the shear core and exterior columns does not add lateral shear rigidity to the core. Thus, tall buildings that employ outrigger systems still require cores having significant shear rigidity. The diagrid structure provides both bending and shear rigidity. Thus, unlike outrigger structures, diagrid structures do not need high shear rigidity cores because shear can be carried by the diagrids located on the perimeter, even though supertall buildings with a diagrid system can be further strengthened and stiffened by engaging the core, generating a system similar to a tube-in-tube.

Other types of lateral load-resisting systems in the category of exterior structures include ***space trusses, super frames and exoskeleton***. These have been occasionally used for tall buildings.

Space truss structures are modified braced tubes with diagonals connecting the exterior to interior. In a typical braced tube structure, all the diagonals, which connect the chord members – vertical corner columns in general, are located on the plane parallel to the facades. However, in space trusses, some diagonals penetrate the interior of the building. Examples include the Bank of China Tower of 1990 by I. M. Pei in Hong Kong.

A ***superfram*e** is composed of megacolumns comprising braced frames of large dimensions at building corners, linked by multistory trusses at about every 15 to 20 stories. The concept of superframe can be used in various ways for tall buildings, such as the 56-story tall Parque Central Complex Towers of 1979 in Caracas, Venezuela and the 168-story tall Chicago World Trade

Center.

In ***exoskeleton*** structures, lateral load-resisting systems are placed outside the building lines away from their facades. Examples include Hotel de las Artes in Barcelona. Due to the system's compositional characteristics, it acts as a primary building identifier – one of the major roles of building facades in general cases. Fire proofing of the system is not a serious issue due to its location outside the building line. However, thermal expansion/ contraction of the system, exposed to the ever-changing outdoor weather, and the systemic thermal bridges should be carefully considered during design[10].

4. Models of structural systems

Reinforced concrete (RC) high-rise buildings designed to resist vertical loads in general, and checked on the seismic loads, in particular, adopted structural systems in the design to resist the forces of earthquakes consist of [**Figure** 8.] :

1. Shear Walls System.
2. Moment - Resisting Frame System.
3. Dual System is the system that contains together frames and shear walls.

In couple system, shear walls were presented as central reinforced concrete core of the stairs and lifts, which were favorite to resist the shear forces in general in the regular structures and private due to its symmetry and placed in the centre of the structure, and if the shear walls were insufficient to resist the shear forces caused by earthquakes, the additional shear walls are added to give structural system appropriate stiffness to resist the horizontal forces in both directions [2, 8].

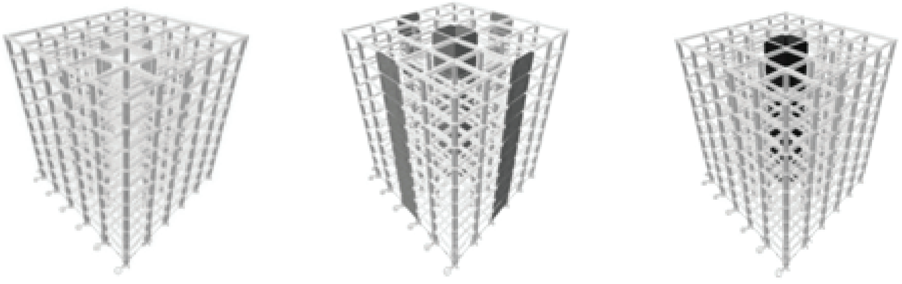
There are many types of structural systems, resistance to the forces of earthquakes, and structural systems which previous referred to it considered more systems used in the design of public and private structures, but in the design of RC high-rise buildings, can we adopt certain structural system without the other and generalization use in the design of RC high-rise buildings whatever the number of stories, type of foundation soil and regardless of whether this system achieve the economic cost of the building required designing it, and what if one of these systems achieve economic cost of the multi-storey building without the other, whether those buildings are similar to or different from each other in the number of storeys, type of foundation soil. To answer these questions and study the problem at hand the following models of RC high-rise buildings was imposed, as shown in **Figure 9**:

- Structural models for RC high-rise building consisting of 10-storey, structural systems in it are:

Frames system (F).
Shear Walls system (SW).
Couple system (C)(Dual System).

5. Characterization of the Problem

Two architectural plans of the structure of RC high-rise buildings are supposed for D. The first dose not contain shear walls, as shown in **Figure 9**, for F , SW and C system and for 10 storey. Analysis was done by STAAD-pro.



Frames system (F) Shear Walls system (SW) Couple system (C)

Figure 8: *some of supposed structural models for three structural systems (F,SW, C)*

Geometric characteristic of the Problem

- Structure regular RC high-rise building is supposed
  (the architectural plan is symmetrical for axes x and y).
- The structure floor area is 30x30m2 for 10storey.

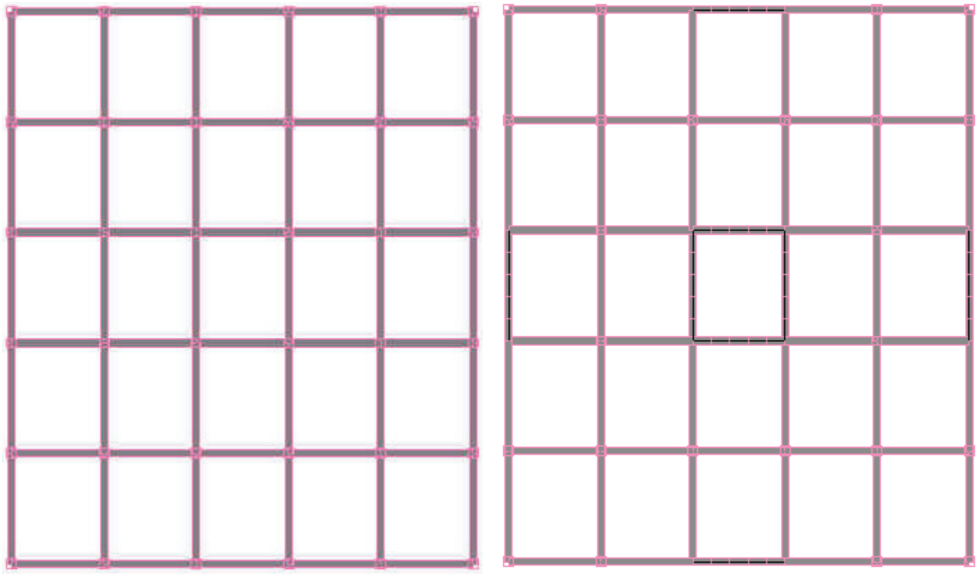


Figure 9. *architectural plan of related models to F-SW-C systems and for 10 storey.*

- Height of storey is 3.5m.
- The thickness of floor slab is 15cm.
- The structural systems are: F-SW-C.
- Seismic zone 2C and therefore the seismic zone factor is Z=0.25.
- The importance factor of construction is I =1.
- Overstrength Factor R, so we have: frames system, R=8 and shear walls system, R=4.5 and In couple system, R is determined according to the frames contribution percentage in bearing base shear forces.
- Yield strength of steel for longitudinal reinforcement =.
- Yield strength of steel for cross-sectional reinforcement for shear walls and = for stirrups in beams and columns.
- Characteristic compressive strength of concrete =21MPa(the amount of cement is 350kgf/m3 in control concrete case and 400kgf/m3 in non-control concrete case).
- To simplify the problem, it is assumed that all columns have square cross-section with initial dimensions begin from 50x50cm and 50x60cm for beams.

- Dead load on all slabs is assumed and live load

6. The results, Conclusion and Summary

We take in consideration internal forces and the result was inserted in **table 9**

System		**Frame(F)**		**Shear Wall (SW)**		**Dual System (c)**	
		LC		LC		LC	
Axial Force [kN]	Max Fx	5 DEAD LOAD	4124.59	1 EQ+X	5520.64	5 DEAD LOAD	3839.19
	Min Fx	2 EQ-X	1453.15	1 EQ+X	5520.64	1 EQ+X	-593.89
Torsion moment [kNm]	Max Mx	5 DEAD LOAD	5.656	2 EQ-X	32.01	5 DEAD LOAD	74.04
	Min Mx	5 DEAD LOAD	-5.66	1 EQ+X	-32.01	5 DEAD LOAD	-74.63
Bending moment [kNm]	Max Mz	1 EQ+X	655.75	2 EQ-X	627.41	1 EQ+X	348.77
	Min Mz	2 EQ-X	-655.75	1 EQ+X	-627.41	2 EQ-X	-348.77

Table 9 *Maximum and Minimum forces in Systems F-SW-C*

- The axial load in frame system increase about 10% than in system C (Dead load).
- Torsion moments in all systems is so small, where bending moment is dominated by component of earthquake in direction X.
- The value of moment in frame system increase about 53% than Dual System. At the end this table explain that system (c) is the best system to carry lateral load.
- Tall buildings present special challenges to design & construction.
- The challenges from seismic loads can be addressed through innovative design concepts.
- Moving forward, more complex & taller buildings will be conceived & constructed.
- Structural engineers have the biggest contribution to make in making buildings safe & economical.

References

[1]**Ali, M.M. (1990*). Integration of structural form and esthetics in tall building design: the future challenge***. In L.S. Beedle & D. Rice (Eds.), *Proceedings of the 4th World Congress of the Council on Tall Buildings and Urban Habitat: Tall Buildings-2000 and Beyond.* Chicago, IL: Council on Tall Buildings and Urban Habitat, 3-12.

[2] Abalos, I., & Herreros, J. (2003*). Tower and Office: From Modernist Theory to Contemporary Practice. Cambridge, MA: MIT Press.*

[3] Ali, M.M., & Armstrong, P.J. (Eds). (1995). *Architecture of Tall Buildings*. Council on Tall Buildings and Urban Habitat Monograph. New York: McGraw-Hill.

[4] Ali, M.M. (2005). ***The skyscraper: epitome of human aspirations.*** In *Proceedings of the 7th World Congress of the Council on Tall Buildings and Urban Habitat: Renewing the Urban Landscape* [CD-ROM]. Chicago, IL: Council on Tall Buildings and Urban Habitat.

[5] Ali, M.M., & Armstrong, P.J. (2007). *Strategies for integrating sustainable tall buildings.* In *Proceedings of the AIA Convention 2007: Growing Beyond Green.* Washington, DC: American Institute of Architects.

[6] **Alberti, Leon Battista (1992): On the Art of Building in Ten Books**. MIT Press, Cambridge/ London.

[7] Ali, M.M. (2001). ***Art of the Skyscraper: The Genius of Fazlur Khan.*** New York: Rizzoli.

[8] ASCE/Sei7-16 Ł *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*

[9] **Beedle, L. s., Ed**.:- ***TALL BUILDING SYSTEMS IDENTIFIED***, The Times, Vol. 11, No. 2, p. 2, 1980

[10] Billington, D.P. (1983). **The Tower and the Bridge: The New Art of Structural Engineering. Princeton**, NJ: Princeton University Press.

[11] Connor, J.J. (2003). ***Introduction to Structural Motion Control***. New York: Prentice Hall.

[12] Corrin, M.E., & Swensson, K.D. (1992). ***Eccentrically braced frames: Not just for seismic design. Modern Steel Construction,*** 33-37.

[13] Drosdov, P. F. and Lishak, v. I.:-***SPATIAL RIGIDITY & STABILITY OF TALL BUILDINGS OF DIFFERENT STRUCTURAL SCHEMES***, Prefabricated Multi-Storey Buildings, proceedings of Conference held in Moscow, October 1976, Central Research and Design Institute for Dwellings, Moscow, pp. 27-35, 1978.

[14] **Huxtable, A.L. (1984).** ***The Tall Buildings Artistically Reconsidered****: The Search for a Skyscraper Style.* New York: Pantheon Books

[15] Iyengar, H. (1986). ***Structural and steel systems. Techniques and Aesthetics in the Design of Tall Buildings,*** Bethlehem, PA: Institute for the Study of High-Rise and Habitat, Lehigh University, 57-69.

[16] Juneid Qureshi ***Design of slender Tall Buildings for Wind & Earthquake***. Regency Steel Asia Symp. On Latest Design & Construction Technologies for Steel and Composite Steel-Concrete Structures 2015

[17] **Khan, F. R**.:***CURRENT TRENDS IN CONCRETE HIGH-RISE BUILDINGS***, Tall Buildings, A. Coull and B. S. Smith, Eds., Pergamon Press, London, pp. 571-590, 1967

[18] Khan, F.R. (1967*). The John Hancock Center*. *Civil Engineering*, *37*(10), 38-42.

[19] Khan, F.R. (1969). ***Recent structural systems in steel for high-rise buildings***. In *Proceedings of the British Constructional Steelwork Association Conference on Steel in Architecture.* London: British Constructional Steelwork Association.

[20] Khan, F.R. (1972). ***Influence of design criteria on selection of structural systems for tall buildings***, In *Proceedings of the Canadian Structural Engineering Conference.* Toronto: Canadian Steel Industries Construction Council, 1-15.

[21] **Khan, F.R. (1973).** ***Evolution of structural systems for high-rise buildings in steel and concrete***. In J. Kozak (Ed.), *Tall Buildings in the Middle and East Europe: Proceedings of the 10th Regional Conference on Tall Buildings-Planning, Design and Construction.* Bratislava: Czechoslovak Scientific and Technical Association.

[22] **Khan, F.R., & Sbarounis, J. (1964).** ***Interaction of shear walls and frames in concrete structures under lateral loads***. *Structural Journal of the American Society of Civil Engineers, 90*(ST3), 285-335.

[23] **Kowalczyk, R., Sinn, R., & Kilmister, M.B. (Eds) (1995).** ***Structural Systems for Tall Buildings (Council on Tall Buildings and Urban Habitat Monograph).*** New York: McGraw-Hill.

[24] **Lu, L. W**. ***STRUCTURAL SYSTEMS***, Modern Engineering and Technology Seminar 1974, Vol. IX, Building and Architecture Session, Modern Engineering and Technology Seminar Committee, Taipei, Taiwan, pp. 15-46, 1974.

[25] **Moon, K. (2005).** ***Dynamic Interrelationship between Technology and Architecture in Tall Buildings*. Unpublished PhD Dissertation, Massachusetts Institute of Technology.**

[26] **Popov, E.P. (1982).** ***Seismic framing systems for tall buildings***. *Engineering Journal/American Institute of Steel Construction, 19*(Third Quarter), 141-149.

[27] **Schueller, W. (1986).** ***High-Rise Building Structure*** (2nd ed). Malabar, Florida: Krieger.

[28] **Schueller, W.** ***HIGH-RISE BUILDING STRUCTURES***, Wiley Interscience, New York, 1977.

[29] **Taranath, B. (1998**). ***Steel, Concrete, & Composite Design of Tall Buildings***. New York: McGraw-Hill.