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New High-rise Building Systems in the World's Contemporary Construction

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Abstract: Structure and architecture are two inseparable categories. Structure has such a place in architecture that it both gives existence and preserves form. Architects define and separate structures based on their physical form and morphology. Basically, buildings cannot be categorized by height or number of floors. The height itself is relative, and the height of a building depends on the individual's social circumstances and perceptions of the environment. From an engineering point of view, a structure can be called tall when its height causes significant side effects due to wind and earthquake. Construction of tall buildings began with the goal of defense and then took on symbolic and practical aspects. The growth and development of new high-rise buildings began in the 1980s with commercial and residential use. Therefore, the present text intends to introduce and differentiate the structural systems used in tall buildings based on the descriptive characteristics of the structural systems of high-rise buildings, the characteristics and criteria of each in the distribution of forces.

Keywords: *Structural Systems, Skyscrapers, High-rise Network Structures, Trunk Structures, High-rise Structures with Central Core.*

INTRODUCTION

The rapid increase in urban population and space constraints have also affected the architecture of residential structures. Rising land prices, the need to limit the horizontal expansion of cities, and the preservation of agricultural land are factors that have contributed to the development and construction of tall structures. Meanwhile, in some cities, such as Hong Kong and Rio de Janeiro, due to the topographic conditions of the region, the construction of tall structures is the only solution to provide housing. The efficiency and effectiveness of tall structures are directly related to the available materials, manufacturing technology, the degree of progress, and efficiency of the relevant services. With the rapid expansion of tall brick buildings in the late nineteenth century, in 1891, the tallest 16-story brick building was built in Chicago. This building (Monadnock), which is the last tall structure with heavy materials, has walls with a thickness of 2 meters in the lowest floor, which have occupied the main space of this floor.

The growth and development of tall structures are due to two important innovations that were achieved in the mid-nineteenth century, and these two important innovations are elevators and materials with high strength and efficiency, such as iron and steel. The new materials made the skeletons of the structures lighter, their height higher, their interiors more open, and their windows and openings increased. The first high-rise structure with a steel structure was the 114-story Chicago Insurance Building in 1884. Advanced design methods and manufacturing technology led to the gradual increase in the height of steel structures, and in 1913, the 60-story Woolworth building was built in New York.

The process of growth at this stage, known as the Golden Age of Skyscraping, culminated in 1931 with the construction of the 102-story Empire State Building (381 meters high). Although the use of reinforced concrete became common in the late nineteenth and early twentieth centuries, it does not appear to have been used in tall structures before the end of World War I. At that time, the properties of composite materials and their capabilities were still unknown, and the structures were generally steel. During this period, the growth and development of reinforced concrete structures were very slow and temporary, and when the metal structure of Empire State was completed, the tallest concrete structure was a 23-story building located in Seattle, USA.

Figure 1. High brick buildings in Chicago (www.greatarchitecture.com)

After World War II, instead of trying to increase the height of the specialists, they introduced new structural systems, materials with better efficiency and quality, and more advanced design and construction methods. During this process, in 1973, using the structural system of the perimeter frame of the 110-story New York World Trade Towers, it was built at a height of 412 meters.

In 1998, the Petronas Twin Towers were built in Kuala Lumpur, Malaysia, at a height of 452 meters, breaking the record for the tallest building in the world. Finally, the Burj Khalifa was built in the United Arab Emirates, which is currently the tallest building in the world with a height of 828 meters. The tower was commissioned in 2010 (Murphy, 2014).

Figure 2. World Trade Tower in New York and Burj Khalifa in Dubai (www.greatarchitecture.com)

Design Criteria in High-rise Buildings

High-rise buildings are usually designed for residential, commercial, or sometimes a combination of both. In most cases, the primary criterion is its architectural design, and only in the case of exceptional, tall buildings, the structure of the building and the conditions and limitations of engineering is replaced by architecture as the primary criterion. The main structural criteria are adequate resistance to destruction, lateral stiffness, and proper efficiency during the life of the building. Many structural criteria are common to tall and short buildings, so special cases are mentioned that need to be considered in the design of tall buildings (Murphy, 2014).

- **Resistance and Stability**

The primary goal of design in the final level of resistance is that the structure is sufficiently resistant and stable due to the most critical loading mode possible in its useful life and the executive loads of the construction period. For this purpose, it is necessary to analyze the forces and stresses created in the structural components as a result of the most critical combination of loads, including additional anchors caused by the relocation of the second-class locations. Additional stresses due to relative precipitation, creep, waterlogging, or heat must also be included in the analysis. In addition to the above, the basic conditions of equilibrium must also be controlled. By anchoring around the edge of the foundation, the resistant anchor due to the dead load of the building weight must be larger than the inverted anchor by applying safety factors.

Figure 3. View of high-rise buildings in Chicago (www.greatarchitecture.com)

- **Hardness and Displacement Constraints**

Supply of suitable hardness, and especially lateral hardness of the structure, is one of the main reasons for the design of tall buildings for very important reasons. To the extreme of resistance, lateral deformation must be limited in such a way that the secondary effects of vertical loading do not cause the structure to fail. In terms of operation, first of all, deformations should be limited to the extent that non-structural members such as doors and elevators work well. Second, to prevent cracking and hardening, it is necessary to prevent the increase and intensification of stress in the structures and to prevent the distribution of load on non-structural members such as between frames or facades. Third, the stiffness of the structure should be such that its dynamic movements are limited and do not cause safety and comfort to users and cause problems in building facilities (Murphy, 2014).

- **Comfort Criteria**

In a high-rise structure, due to the lateral displacements caused by the wind, the periodic motion created will cause discomfort to the users of the building. Acceleration is usually considered to be the main and determining factor in human response to vibration. Human behavioral limit curves are available in terms of acceleration and frequency. Therefore, a dynamic analysis is needed to compare the structure's response with the behavioral limit curves.

- **Creep, Waterlogging, and Heat Effects**

In tall concrete buildings, the total displacement due to creep and waterlogging, especially in the upper parts of the building, may create stresses in non-structural members and exert significant forces on horizontal structural members. To determine these long-term deformations, the effects of several important factors such as concrete properties, loading history, and concrete life in the loading stage, volume to concrete ratio, and the amount of steel required in the calculations must be included in the calculations. We can then estimate the forces created in the horizontal members due to the relative vertical deformation of the supports. By uniformly distributing the stresses in the vertical members, the relative vertical displacements caused by the creep can be greatly reduced (Murphy, 2014).

- **Fire Protection Considerations**

In high-rise buildings, fire is one of the most important considerations for two main reasons. First, because most floors of buildings are not accessible by fire truck ladders, firefighting and rescue operations are only possible from inside the building. Second, complete emergency evacuation is not practical in the short term.

Structural Systems of High-rise Buildings

The best structural form is the choice in which the main members of the various combinations of vertical and horizontal loads are optimally tolerated. But in practice, non-structural considerations usually have very important effects on the choice of structural form and may be decisive. Important factors that should be involved in deciding the form of the structure are architectural design, interior plan, materials, method of execution, external shape of the building, location and route of installation systems, type and amount of side load, and height of the building. The taller and thinner the building, the more important the structural factors are, and the greater the need to choose the structural form. Among the types of structural systems for tall buildings, the following can be mentioned (Powley, 2009).

- **Braced Frame Structures System**

In the braced frames, the lateral strength of the structure is provided by the diameter members, which together with the beams form the life of a vertical truss system. In this system, the columns are the edges of the truss.

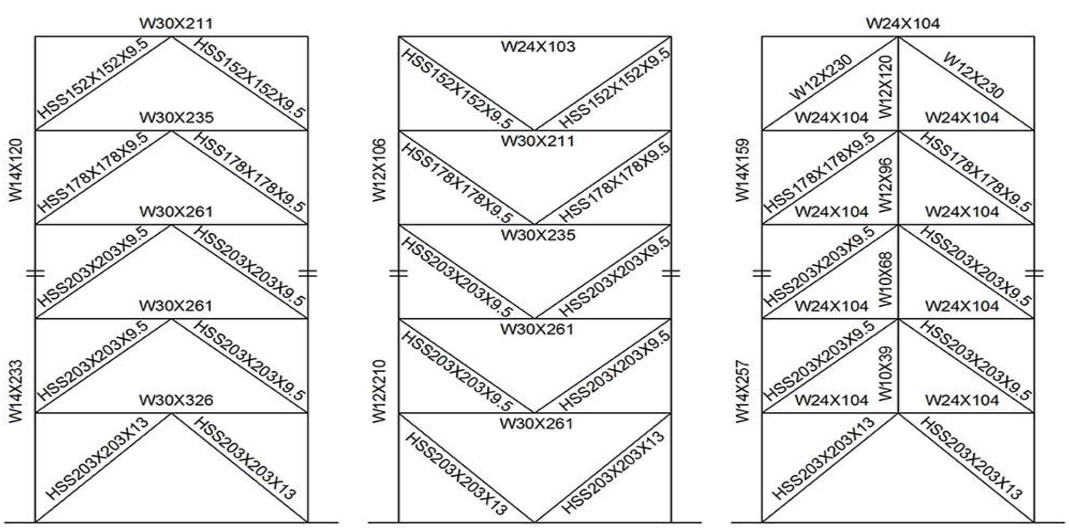

Figure 4. An example of a braced frame system (www.structuremag.org)

- **Rigid Frame Structures System**

The rigid frame structure consists of columns and beams that are connected by bending connections. The lateral stiffness of a rigid frame depends on the bending strength of the columns, beams, and joints on the plate. The main advantage of the rigid frame is its open composition and freedom of action in interior design and optimal replacement of doors and windows. If we use a rigid frame as the only resistance factor of the building against lateral loads, this type of structural structure with common spans of 6 to 9 meters will be economical only for buildings up to 25 floors. In buildings with more than 25 floors, due to the relatively high flexibility of the frames, members and large non-economic sections will be required to control the movement (Powley, 2009).

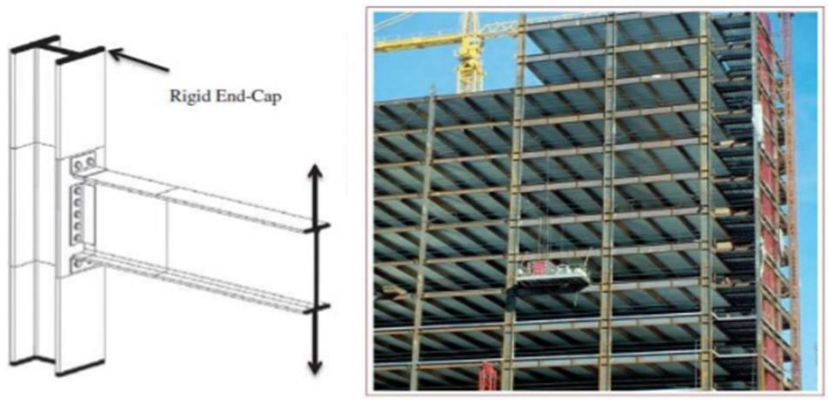

Figure 5. An example of a Rigid Frame Structures System (www.theconstructor.org)

- **Infilled Frame Structures System**

In many countries, frame beams are the most common structural form for buildings up to 30 stories high. In this type of structure, reinforced concrete and sometimes steel frames are filled with building materials such as bricks or concrete blocks or concrete in place. When a mid-full frame is affected by lateral loads, the fillers act effectively as the compressive members of the diameter braces. Since the fillers also work on external walls or internal blades, they are an economical system for strengthening and hardening the structure (Qala-e-Novi, et al., 2012).

Figure 6. An example of an Infilled Frame Structures System (www.sabzsaze.com)

- **Shear Walls Structures System**

Concrete continuous vertical walls or building materials can be used in architecture as a separator and in terms of the structural bearing of vertical and lateral loads in the building. Because shear walls have great strength and durability, they are very suitable for restraining tall buildings. In structures with shear walls, shear walls withstand lateral loads. The walls act as separate vertical layouts on the screen or with a non-plate combination around the elevator, stairs, and service passages. Because the walls are harder horizontally than rigid frames, these types of structures will be up to 35 floors (Engel, 1998).

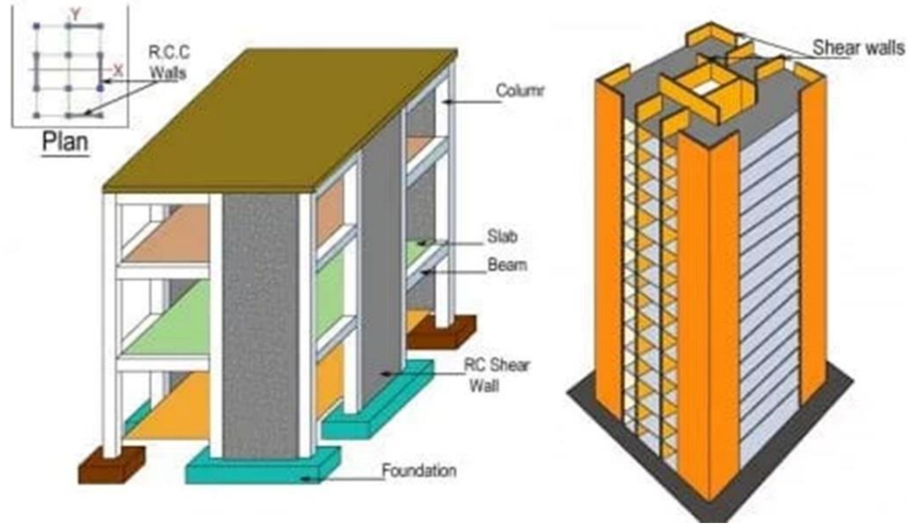

Figure 7. An example of a Shear Walls Structures System (https://dailycivil.com)

- **Wall-Frame Structures System**

When the shear walls are combined with rigid frames, the walls will be forced to have the same deformation when the bends are deformed and the frames will be bound by the beams and ledges during the shear deformation. As a result, the frames and walls work together horizontally, especially on top of the building, to form a more durable and rigid structure. The combined structure of the wall frame is suitable for buildings of 40 to 60 floors. This number of floors is much higher than the number of floors of buildings with solid frames or single shear walls (Powley, 2009).

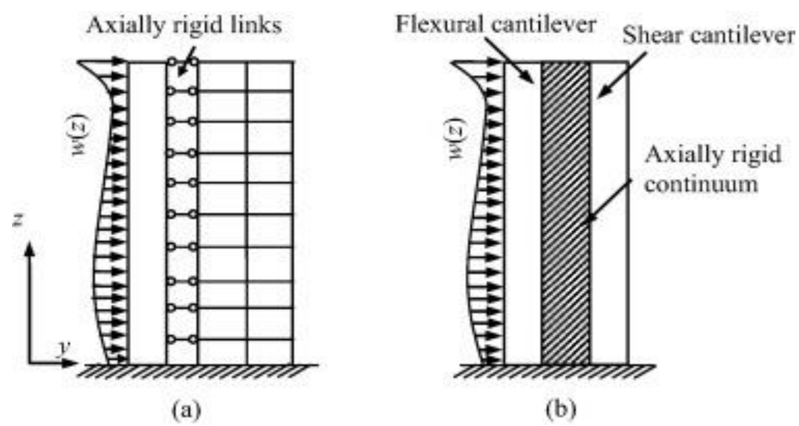

Figure 8. An example of a Wall-Frame Structures System (https://ars.els-cdn.com)

- **Tubular Structures System**
  - ✓ **Framed-Tube Structures System**

The lateral resistance of structures with perimeter frames is provided by the very hard frames that are placed in the building environment and form a closed wall. Environmental frames include columns 2 to 4 meters apart that are connected by deep beams. Although perimeter frames support all lateral loads, vertical loads are also divided between peripheral columns and internal columns. When the structure is subjected to lateral loads, the perimeter frames will act as loads for the loads and the perpendicular frames for the load will act as the wings of the bulk of the perimeter. An environmental frame structure is one of the most advanced structural systems of tall buildings, which, in addition to good relative efficiency and easy execution, is also suitable for any high height (Qala-e-Novi et al., 2012).

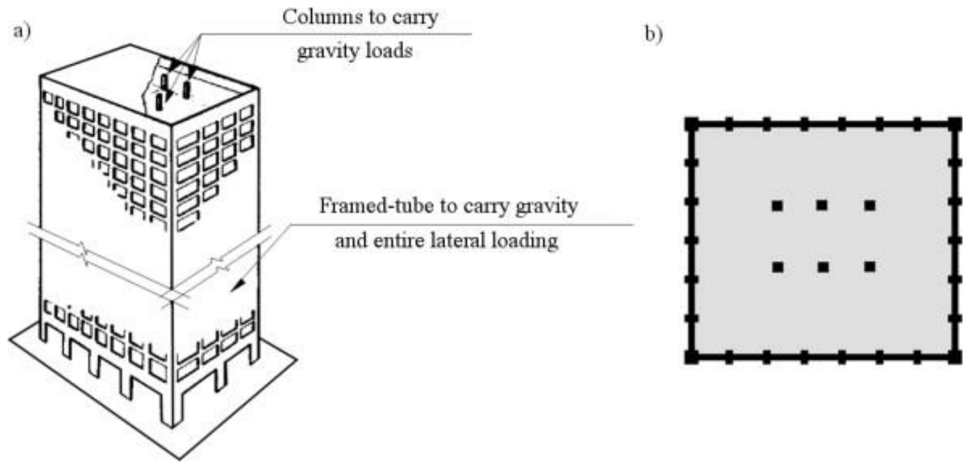

Figure 9. An example of a Framed-Tube Structures System (https://ars.els-cdn.com)

✓ **Tube-in-Tube Structures System**

This structural form includes an external perimeter frame or shell and a core related to the elevator or service passage. The core and shell work together to withstand vertical and lateral loads. In steel structures, the core may consist of restrained frames, while in concrete structures it is a combination of shear walls (Powley, 2009).

✓ **Braced-Tube Structures System**

Another way to increase the efficiency of environmental frames is to increase the distance between the columns and increase its potential for proper use in taller buildings by adding diagonal braces around the structure. This type of structure was first used in 1969 in the John Hancock metal building in Chicago and then in 1985 in the concrete building number 780 in New York. In metal perimeter frames, the braces are placed diagonally on the rigid frames of the building facades. However, in concrete structures, braces include concrete panels with the dimensions of openings, which are poured in place with frames and run diagonally on the facades of the building (Golabchi & Mazaherian, 2010).

Figure 10. An example of a Braced-Tube Structures System (https://ars.els-cdn.com)

- **Outrigger-Braced Structures System**

This structural form has a central core consisting of shear walls or braced frames. The central core is connected to the outer columns by trusses or arm-like beams. To participate in the environmental columns that are not directly connected to the arms, all the environmental columns can be connected by one or more belts consisting of trusses or beams at the level of the arms. Arm-restrained structures have been used for 40- to 70-story buildings (Qala-e-Novi et al., 2012).

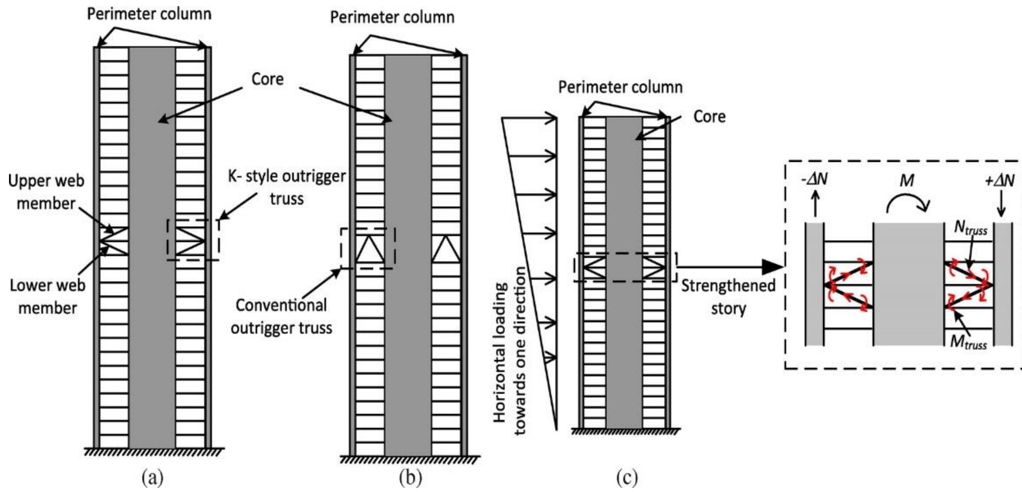

Figure 11. An example of an Outrigger-Braced Structures System (https://ascelibrary.org)

- **Suspended Structures System**

Suspended structures include one or more central cores and horizontal planks at roof level to which the hanging members consisting of cables, rods or steel plates are attached, in other words, they are suspended (Asefi and Imani, 2012).

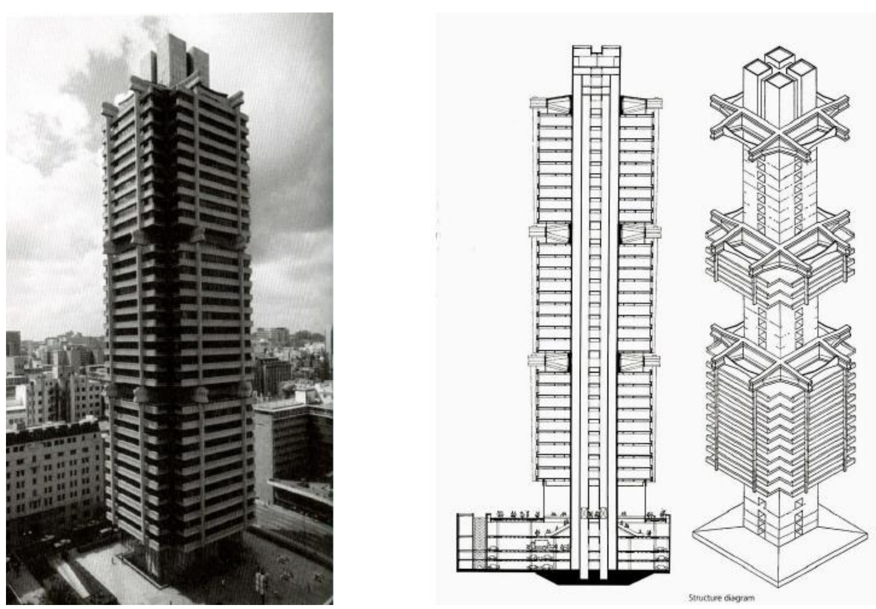

Figure 12. An example of a Suspended Structures System (https://ascelibrary.org)

- **Core Structures System**

In this type of structure, a single core can withstand vertical and horizontal loads. In some varieties, the tubes are carried at each level by coils attached to the core. The main purpose of this type of structure is to create an open space without columns on the ground floor and the floors below the planks. This structural form, of course, has many structural disadvantages, the most important of which are: the effective depth of the low-core structure and thus the inefficiency in bearing the lateral loads as well as the bearing load of the floors by the planks, which are structural members with high efficiency. They are few (Sandoghianzadeh, 1996).

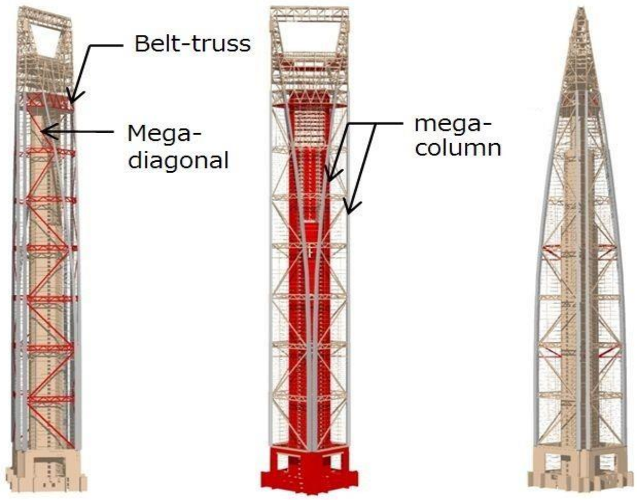

Figure 13. An example of a Core Structures System (https://i.pinimg.com)

- **Space-Frame Structures System**

The Space-Frame structure system consists of a three-dimensional truss whose members bear vertical and horizontal loads. This system has very high efficiency and low relative weight and can be used up to any height. The 76-story Hong Kong Bank building is a classic example of this structural form (Schuler, 1992).

Figure 14. An example of a Space-Frame Structures System (https://adsteelstructure.com)

Conclusion

In general, in high-rise structures, the importance of lateral force increases with increasing building height at high speed. At a certain height, the lateral displacement of the building increases so much that the hardness of the controller is taken into account. The degree of hardness basically depends on the type of structural system. In addition, the efficiency of any particular system is directly related to the amount of materials consumed. Therefore, the maximum hardness must be obtained by optimizing the structure for certain space conditions with minimum weight. This leads to the invention and design of structural systems suitable for certain heights. These structural systems have a variety of structural design based on the ability to run and also create beautiful architectural structures. Depending on the type of use and design form and the number of floors, the appropriate system mentioned in this article can be used correctly and logically.

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