Review Article

Examination of The Core as A Rigidity Center in High-Rise Buildings

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Abstract

The visibility and number of high-rise buildings, which have a direct impact on shaping the texture and identity of the city in which they are located, are increasing day by day. While developing technology, new construction techniques and high-strength building materials make it possible to increase the height of the building, each increase in height occurs difficulties and requires more engineering problems to be solved. When the distribution of loads acting on high-rise buildings and their effects on the structure are examined, it is seen that the core is designed as a center of rigidity in the structure to provide inertia against horizontal loads.

In order to make the core design of the building effective and efficient, it will be a proper and correct approach to understand the center of rigidity function of the core to design and implement it from this point of view.

This study aims to examine the core, which plays a primary role in providing inertia against horizontal loads acting on high-rise buildings, as a center of rigidity.

First of all, the loads that are effective in the design were explained. It has been stated that the horizontal loads acting on the structure cause bending, shear and torsion. The interaction of wind load, which is a more critical load especially in high-rise buildings, with the building is emphasized. In order to facilitate the understanding of the core as the center of rigidity in high-rise buildings, its place in the structural system hierarchy was defined.

It has been seen that core designing is a necessity in order to provide inertia against horizontal loads in high-rise buildings that becomes independent from its surroundings as the height and the loads acting on the structure increase. It has been seen that besides the core is designed as a service core within the building, the building shell is designed as a core also.

Keywords: High-Rise Building, Core, Rigidity

1. Introduction

High-rise buildings emerge in the city silhouette as prestige structures where states, countries, cities, big companies show their power and reputation with advanced technology. The increase of steel structures, technological developments, the use of new and high-strength building materials and new construction techniques, especially rapid urbanization experienced after the Industrial Revolution, made it possible to increase the height of the buildings. As the height of the building increases, the loads acting on the building become more critical in the design. Especially horizontal loads are more critical than vertical loads for high-rise buildings. Considering the high-rise building rises from the ground like a cantilever, is shown in Figure 1, wind and earthquake loads which are acting horizontally on the building, cause bending and shear forces in the structure [1]. It is very important to control the vibration caused by horizontal loads on the building. An effective structural system should be designed for provides inertia against the horizontal loads acting on the structure.

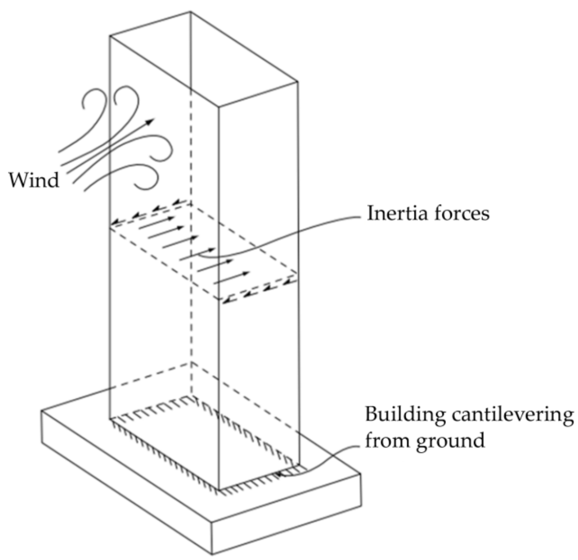


Figure 1 High-rise building cantilevering from ground [1]

2. The Loads Effecting High-Rise Buildings

Loads acting on the building are various physical effects that must be considered and calculated in the design of the building, which can effect the building throughout its lifetime. These physical effects can effect the building horizontally or vertically [2].

2.1. Vertical Loads

2.1.1. Dead (Permanent) Loads

Dead (permanent) loads refer to the self-weight of the building. The weights of all load-bearing and non-bearing elements such as columns, beams, walls, floors, roofs, stairs, and exterior cladding systems constitute the dead (permanent) loads of the building [2,3].

2.1.2. Live Loads

Live loads are the loads that will not remain on the structure continuously throughout its life [3]. Human, furniture, rain and snow loads constitute the live loads of the building.

2.2. Horizontal Loads

2.2.1. Earthquake Loads

The layers of the earth's crusts create a tectonic effect during their movements and create energy waves suddenly called earthquakes at various periods during fault ruptures [4]. As a result of the vibration created by the earthquake force, the building becomes damaged, is shown in Figure 2, as a result of the inertia force that emerges as an internal force in the structure.

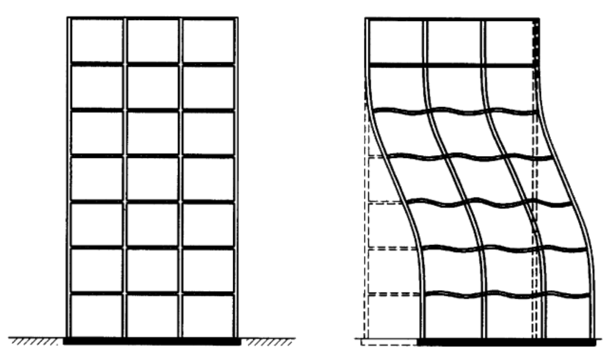


Figure 2 Damage of the structure due to dynamic effect [5]

Every building has a natural period of vibration. However, when horizontal loads such as wind or earthquake act on the building, the top of the building starts to move under this effect. After the top of the building moves a certain distance, it returns to the starting position and makes same bending to the other direction. And returns to the starting position again. This duration, during which the building makes a full vibration, is shown in Figure 3, is called the period of the building [6]. As the height of the building increases, the period increases.

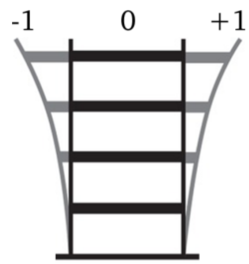


Figure 3 Vibration of high-rise building [6]

The floor, on which the building located, has a period value also depending on its class and quality. Resonance occurs in the building when the period of the ground on which the building located (Tground) and the vibration period of the building (Tbuilding) overlap (Tbuilding = Tground). Resonance causes collapse of the building. The period of stiff soils is small and the period of soft soils is large. For this reason, high-rise buildings should be built on stiff soil.

The period of the earthquake is usually around 1 second. Because of the period of high-rise buildings is large, the period of the earthquake and the period of the high-rise building usually do not overlap, so the resonance risk that may occur in high-rise buildings is reduced. For this reason, it can be said that the earthquake load is less critical for high-rise buildings when compared to wind load.

2.2.2. Wind Loads

Temperature differences create different pressure zones in the atmosphere. Due to these differences in temperature and pressure, air streams occur called wind between regions [7]. Contrary to the dead load of the structure or the live loads, whose effect can be predicted, the wind effects the building suddenly and its intensity is variable. These sudden changes and wind characteristic have an important effect on the building [8].

Between surface and the fluids which is flowing on the surface, shear force occurs in the opposite direction to the movement due to the viscosity of the fluid. This situation also exists between the air, whose viscosity is 16 times less than water, and the earth. As wind flows from the surface on the layers near the ground, tends to stop and return to the opposite of its movement direction [8].

Therefore, the speed of the wind approaches almost 0 at the point close to the ground where the friction effect is high. These inner layers slow down the outer layers respectively [5].

The region where the wind speed is effected by the environment is called the atmospheric boundary layer [8].

As the height increases, friction effect disappears and eventually becomes negligible. In this case, the speed of the wind takes a form that is not effected by friction. Therefore, a curvilinear increasing graph, is shown in Figure 4, can be drawn [6].

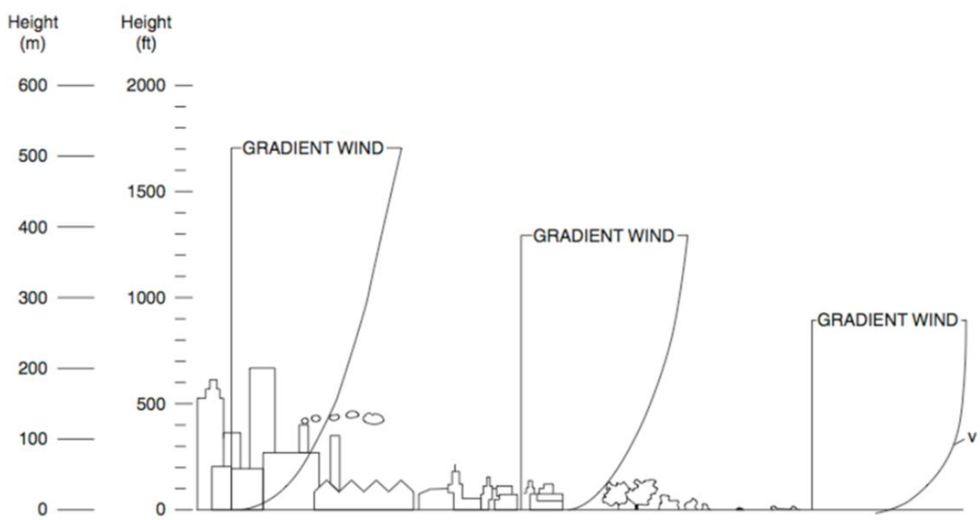


Figure 4 Wind profile developments for different terrains [9]

The wind speed profile in open and rural areas with low surface roughness and the wind speed profile in the region where high-rise building typology is seen are not the same. As the height of the building increases, the amount of surface area that the wind will encounter increases. Thus the pressure of the wind increases. Parallel to this, the average wind speed profile increases in such areas. The height at which the speed increase is interrupted is called the gradient height, and the speed reached by the wind at this height is called the gradient speed [7]. For this reason, wind load becomes a very critical load on high-rise buildings, as the wind takes a form that is not effected by friction with the increase in height. There are 4 basic types of air streams, is shown in Figure 5, laminar, split, turbulance and vortex [10].

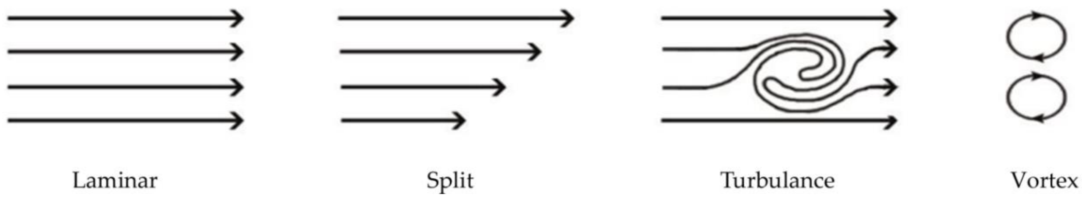


Figure 5 Air streams [10]

The building acts as a barrier against the wind. When the laminar stream hits the facade of the building, it becomes a split stream and the split stream continues to flow from the side facades of the building. The split stream combines with the laminar stream flowing in the free zone on the side facades of the building and creates a turbulance on the building. The vortex is the circular form of the wind flow under the effect of turbulance. Wind load can creates 3 different types of motion on the building, is shown in Figure 6, vibration along wind, vibration transverse wind and torsion [4].

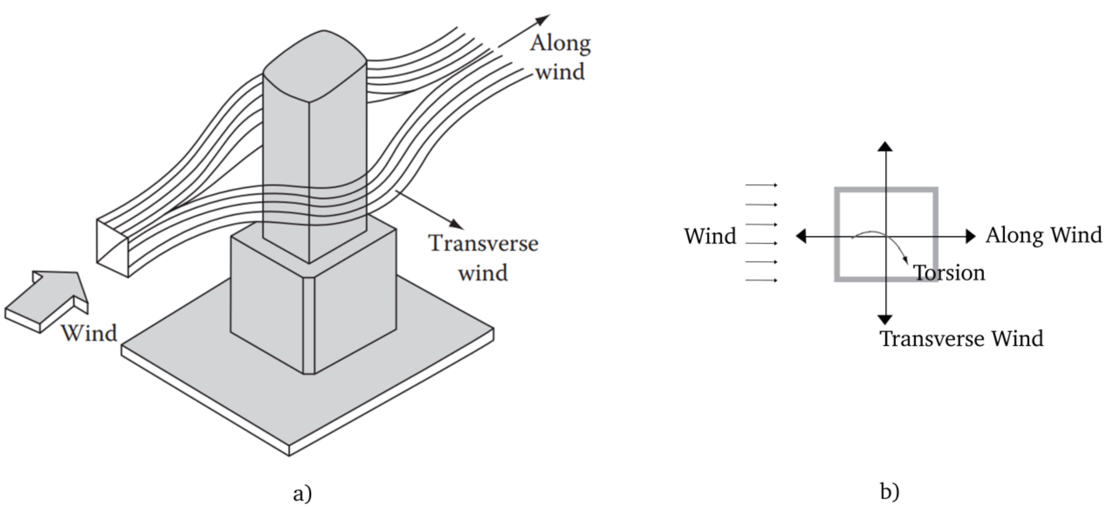


Figure 6 a) Wind flow around the building [10] b) Wind effect on cross section of the building

Building vibration parallel to the direction of the wind is termed “along-wind motion”. It creates a drift effect on the building. Building vibration perpendicular to the direction of the wind is termed “transverse-wind motion”. Torsion, on the other hand, is the moment when the building gains momentum around its vertical axis due to the fact that the geometric center of the building and the center of rigidity do not overlap.
At high wind speeds, turbulent winds and vortexs that form on the side facades of the building can not occur simultaneously and equally due to the nature of the wind that changes direction and intensity suddenly. Therefore, in addition to the drift effect of the

wind, which is the along wind direction, vortex shedding occurs, which is a vibration transverse the wind and the resonance occurs on building [7].

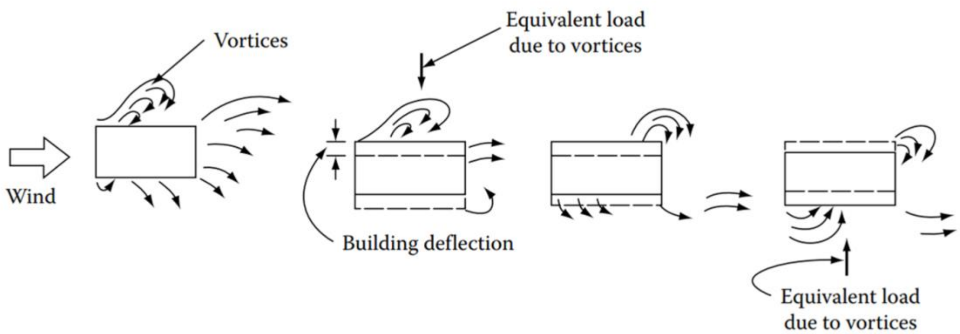


Figure 7 Vortex shedding generates building vibrations in the transverse direction [7]

Because of that transverse-wind motion and the torsion are more critical than along-wind motion because of the risk of resonance they create [4].

3. Core

While designing the structural system for high-rise buildings, it is important that the design can provide inertia to the loads acting on the building. It is necessary to ensure the stability of the structure, especially against the horizontal loads like earthquake and wind loads [6].

Shear walls and trusses are the most important structural elements for providing rigidity to the building against shear and bending forces and limits the vibration of the building [11].

As seen in Figure 8, shear wall / shear truss is planned as singular element on the floor plan or they can combined as a core by concentrating wall or truss on a specific area on the floor plan. Because of this, the core provides inertia on 2 directions [4].

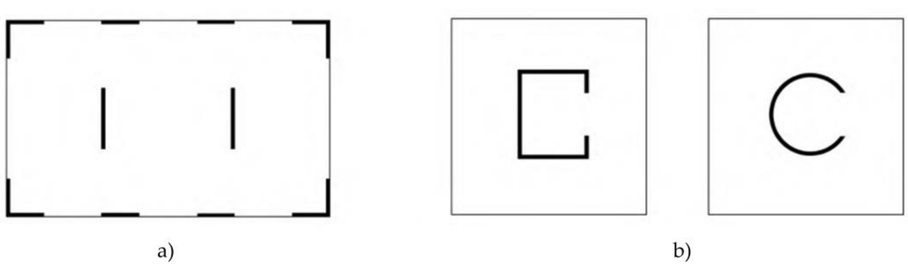


Figure 8 a) Shear truss / Shear wall system b) Cores [4]

4. Core As a Rigidity Center

Rigidity means that the displacements of the building are limited under horizontal loads and these displacements remain in the linear elastic region [12]. In other words, rigidity is the inertia of the building against deformation and rotation under horizontal loads.

The core is the primary element that provides inertia against bending, shearing and torsion in high-rise buildings and provides the rigidity of the building against horizontal loads [4].

The location of the core has great importance for the performance level of structural system of high-rise buildings under the horizontal loads. The geometric center of the building and the center of rigidity, which is the center of the structural system, should be overlap in order to provide better inertia and prevent the structure from rotating around its own vertical axis (Figure 9).

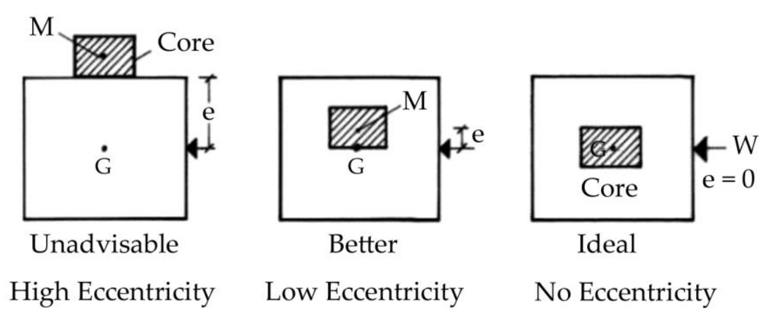


Figure 9 Core placements [1]

Therefore, while making design decisions for high-rise buildings, it is necessary to plan the placements of the core correctly and analyze the effects of different placements of the core on the floor plan.

On the floor plan, the core can be designed in various ways (Figure, 10).

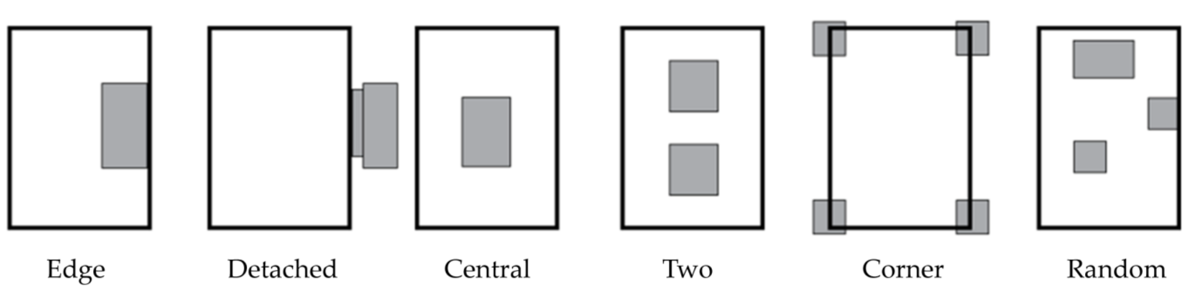


Figure 10 Core designs and building characteristics [13]

The central placement of the core and its similarity to the form of the floor plan prevents occur of eccentricity. In other words, central placement of the core on the floor plan is the optimum solution for the performance of the structural system under the horizontal loads. For this reason, edge and detached cores are not optimum core options in high-rise buildings.

Because of the highest moment occurs at the corner points in the building, the ground on which the building is located must has good load-bearing capacity in order to design a corner core. The random solution of multiple cores on the floor plan also causes eccentricity because of increases the rigidity of certain parts of the building.

5. Structural Systems of High-Rise Buildings

Structural systems used in high-rise building design can be listed to ensure that the core can be understood as the center of rigidity:

1. Frame System
2. Frame + Rigid Floor System
3. Frame + Shear Truss / Shear Wall System
4. Frame + Shear Truss / Shear Wall + Rigid Floor System
5. Frame + Core System
6. Frame + Core + Rigid Floor System
7. Core + Console System and
8. Tube Systems.

5.1.Frame System

The frame system, is shown in Figure 11, is based on the creation of moment-transferring frames with rigid connections in steel or reinforced concrete structures with column-beam arrangement [4]. The moment interaction between the columns and beams provides inertia against the horizontal loads [6].

However, in framed systems, high-rise buildings can be built up to a limited height, because of the vibration caused by wind loads. Various methods are used to control the vibration.

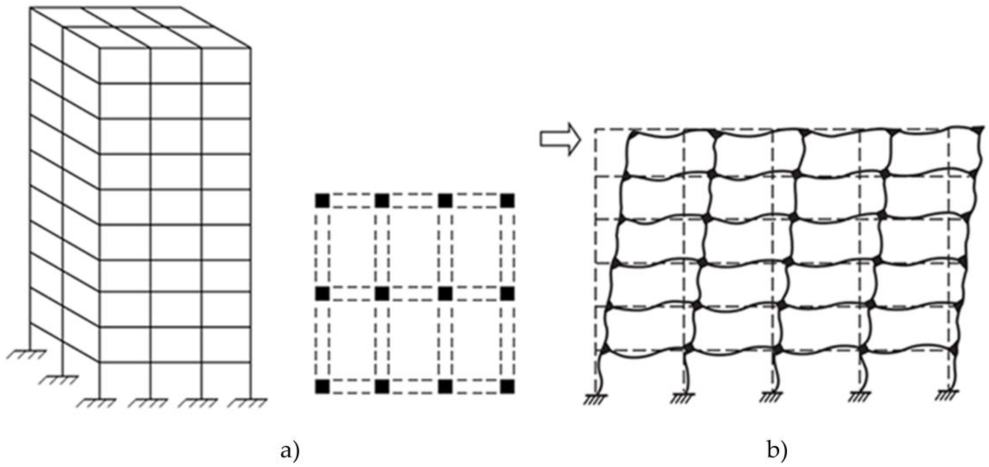


Figure 11 a) Frame system [4] b) Rigid frame behaviour under the horizontal loads [6]

5.2.Frame + Rigid Floor System

In high-rise buildings, designing rigid floors with the frame system is very effective on limiting vibration. Rigid floors can be designed inside or on the facade of the building, one or more floors high. Rigid floors consist outrigger trusses in steel structures or walls in reinforced concrete structures. Outrigger trusses of rigid floor have connection with belt trusses and perimeter columns.

In 156 m high 37 storey Huntington Center (Columbus, 1983), is shown in Figure 12, 4 rigid floors were planned on the facade [14].

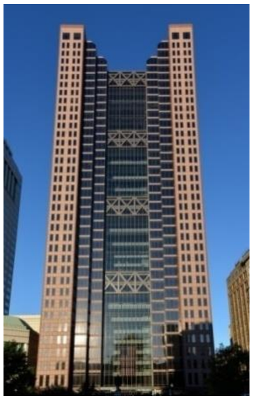


Figure 12 Huntington Center [14]

If a single rigid floor is to be designed for building, its placements should be at 3/5 of the building height. If 2 rigid floors are to be designed, their placements should be at 1/5 and 3/5 of the building height. If the number of rigid floors are more than 2, these floors placements should be designed to divide the building facade equally. This design provides the most effective limiting against vibration.

5.3.Frame + Shear Truss / Shear Wall System

As the building height increases, designing the shear trusses / shear walls with the frame system is efficient option to limit the vibration. As shown in Figure 13, structural system can be designed as shear trusses or shear walls. Shear trusses / shear walls can be designed on the facade of the building, inside of the building or both.

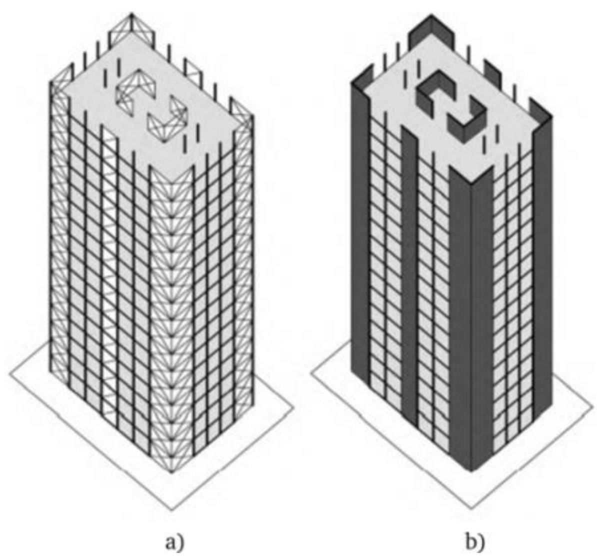
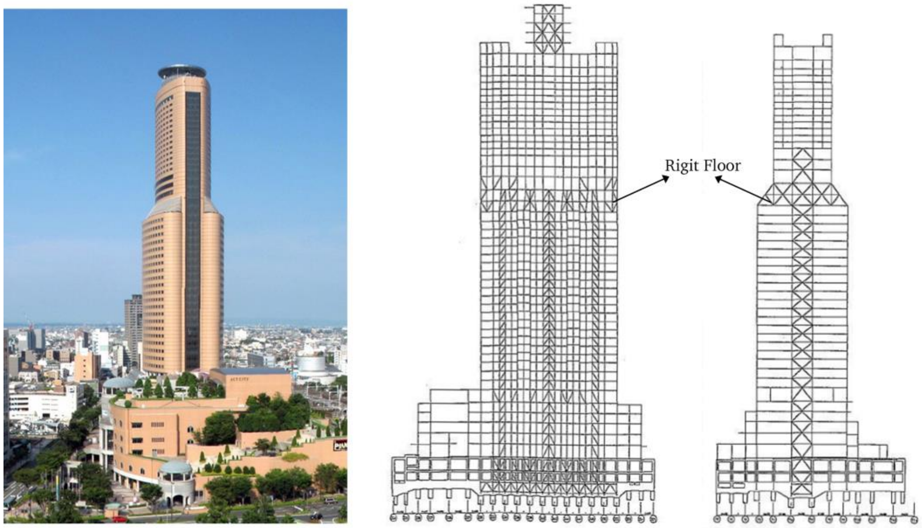


Figure 13 a) Steel truss b) Reinforced concrete shear wall [4]

5.4.Frame + Shear Truss / Shear Wall + Rigid Floor System

Shear trusses and shear walls are used together with rigid floors as a more effective structural system option to control the vibration in the building as the height of the building increases.

In 212 m high 45 storey ACT Tower (Hamamatsu, 1994), is shown in Figure 14, 2 storey high rigid floor was planned with the shear truss system [15]. Load transfer of the floors located above the rigid floor is provided by the rigid floor.



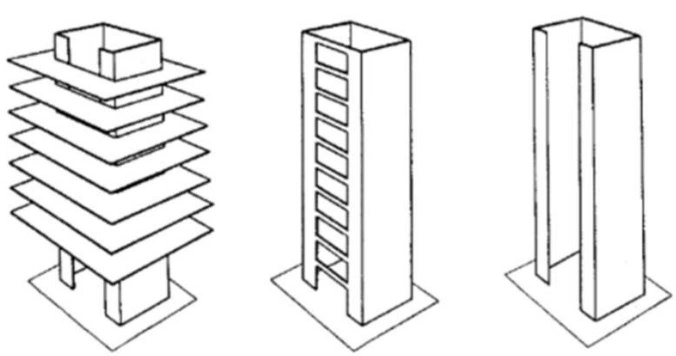
a) b)

Figure 14 a) ACT Tower [15] b) ACT Tower's section [16]

5.5.Frame + Core System

The further structural system for providing inertia of the building is the frame + core system.

The core is the primary element in high-rise buildings, providing the rigidity of the building against vertical and horizontal loads, providing inertia against bending, shear and torsion [17]. Although a fully closed core which is consists of shear walls / shear trusses is the most rigid solution against horizontal loads and torsion, partially closed core design serves as a center of vertical transportation, shaft and shared spaces beside its rigidity function [4]. The core can be partially closed by cantilever slabs or by beams (Figure, 15).



a) b) c)

Figure 15 a) Core partially closed by floor slabs b) Core partially closed by beams c) Open-section core [17]

Because of shear walls act as cantilever, they show bending behavior under horizontal loads and the successive drifts between floors are gradually increasing. In frame systems, the shear is highest at the lowest floors, and the successive drifts between the floors decrease as the height increases (Figure 16). Frame system has high ductility and low elastic behavior. On the other hand, shear wall system has low ductility and high elastic behavior. With the combined use, the increasing bending of the shear wall element towards the upper floors prevents by the frames, and the high sliding of the frames on the lower floors prevents by the shear wall [18].

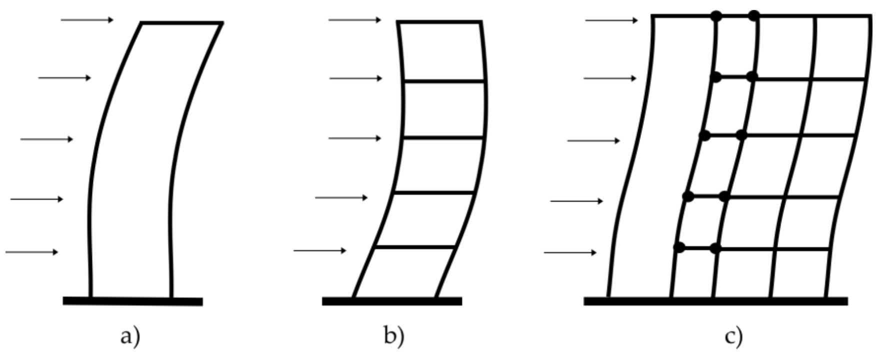


Figure 16 a) Bending of shear wall b) Shear of frame c) Combined use [18]

Systems, take advantages of each other's advantages and limit their disadvantages. Therefore, many structural system options occur, is shown in Figure 17, when they are use in interaction [1].

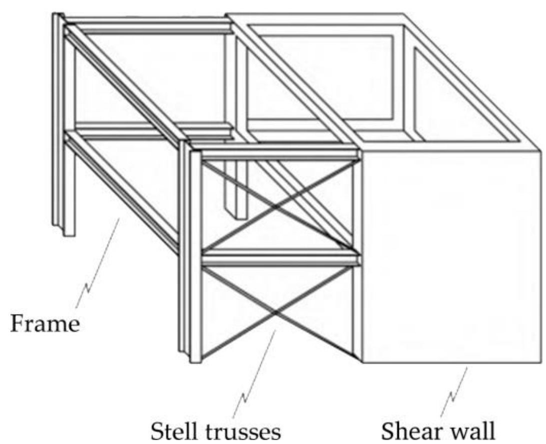


Figure 17 Combined use [4]

https://doi.org/10.56038/ejrnd.v2i2.57

5.6.Frame + Core System + Rigid Floor System

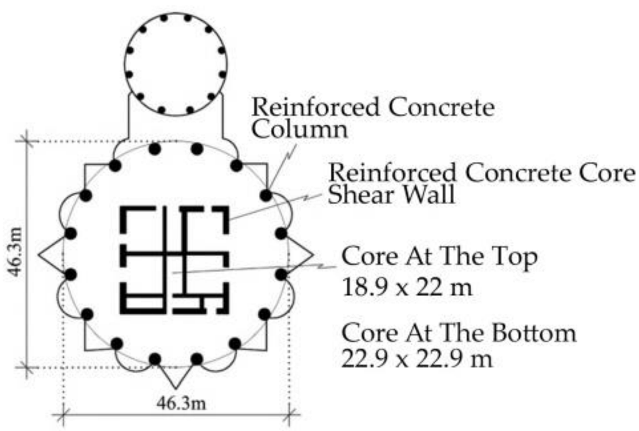
The planning rigid floors with the core + frame system is very effective on limiting vibration.

If the core is termed the mast of the ship, the rigid floors serve as spreaders and the perimeter columns serve as supports in high-rise buildings [7]. Belt trusses are used to limit the displacements of the surrounding columns [19].

The central placement of the core and connection of the trusses / walls to the core symmetrically is optimum design because of the outrigger trusses control the core's bending and torsion.

The structural system of the 452 m high 88 storey Petronas Towers (Kuala Lumpur, 1998), is shown in Figure 18, is frame + core + 2 rigid floors system. The reinforced concrete central core of the building starts as a square section, 22.9 m x 22.9 m on the ground, and ends at 18.9 m x 22 m as the building rises [4]. The core serves as center of rigidity of the structure against the horizontal loads without need to further increase the dimensions of the elements of the frame system.

a)



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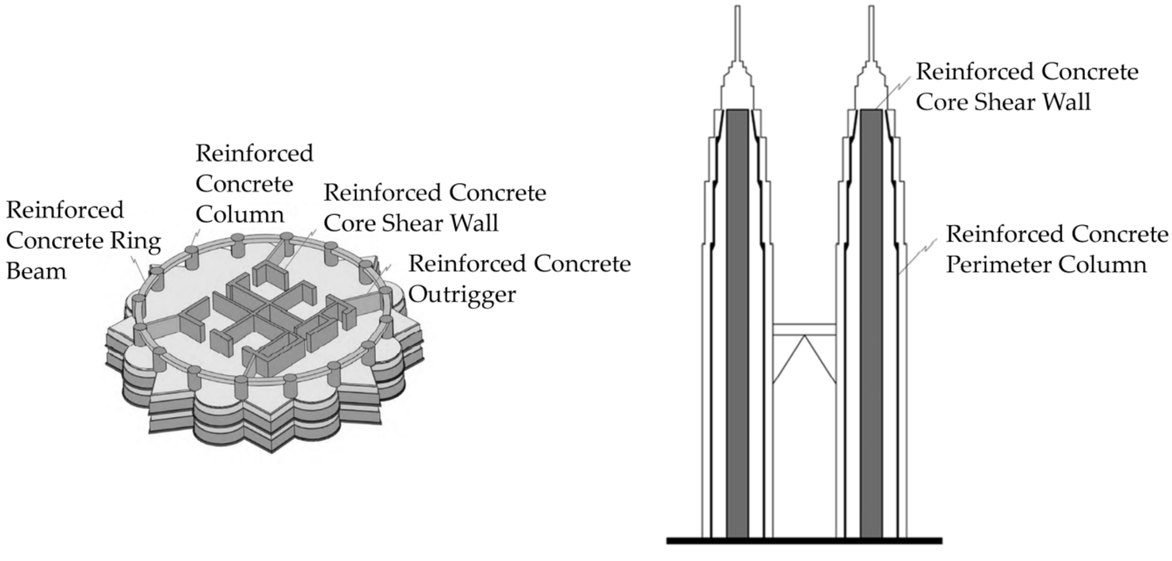


Figure 18 a) Petronas Towers [20] a) Plan [4] b) Structural axonometric [4] c) Schematic section [4]

5.7.Core + Console System

The core + console system, is shown in Figure 19, in which the core is used as the primary structural system alone, consists of a reinforced concrete shear wall core provide inertia to vertical and horizontal loads and cantilever floor slabs rigidly connected to the core [4].

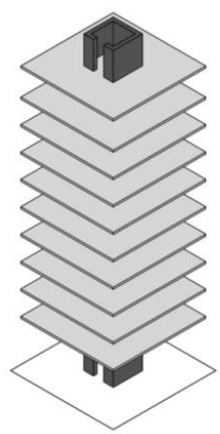


Figure 19 Core + Console system [4]

The floor slabs can be supported by the perimeter columns of the building or the hangers suspended from the core, and suspended systems, is shown in Figure 20, are formed [4]. In the suspended system, the ground floor of the building is free from structural elements, as the floors are hung on the core.

Steel suspension elements do not restrict the relationship of the building with the view due to their small cross-sections. In this system, the production of the floor slabs are made on the ground and stacked on the floor to be lifted to their own level one by one [17]. The structure is completed from top to bottom.

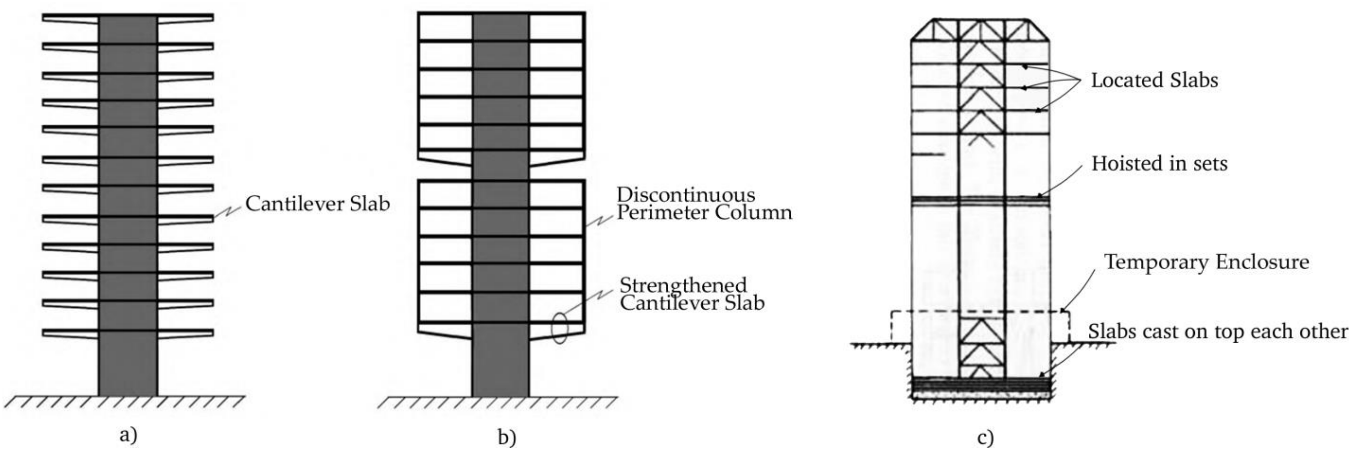


Figure 20 a) Core + Console system [4] b) Suspendend system [4] c) Suspended system construction [17]

In core + console system and suspended system, only the core volume exists on the ground floor. For this reason, the transfer of vertical loads to the ground is provided only by the core. Because of that core + console system and suspended system are not an effective structural system options due to their high vibration under horizontal loads in earthquake zones, in regions with strong winds effecting the structure and in cases where ground conditions are not good. Core + console system and suspended system are mostly used in prestige buildings.

101 m high 21 storey BMW Building (Munich, 1972), is shown in Figure 21, is a suspended structure. Floor slabs were suspended by steel cables to the core. The central core placement of the building has same form with the floor plan [21].

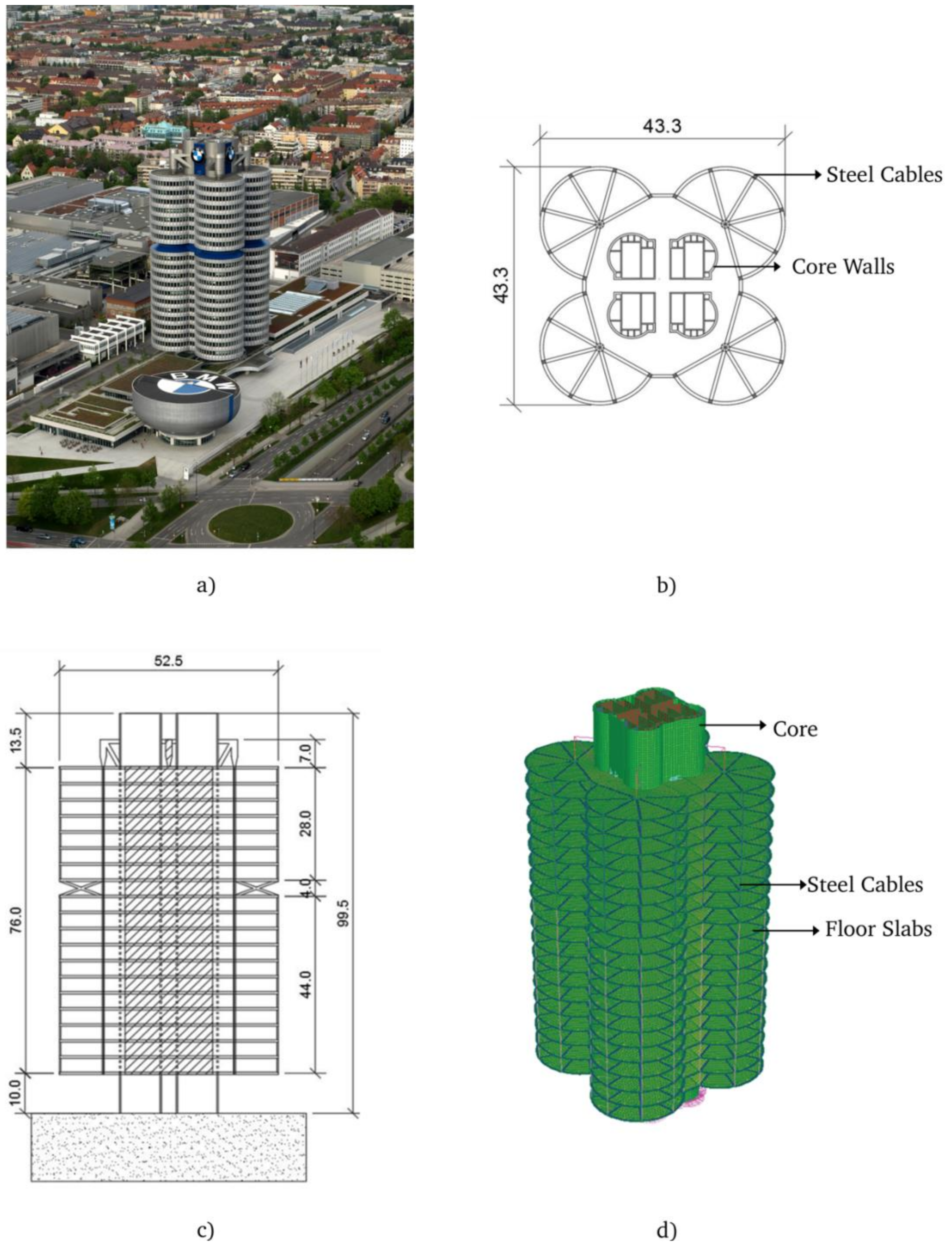


Figure 21 a) BMW building [22] b) Plan [23] c) Elevation [23] d) Modeled structure [23]

5.8.Tube System

In tube systems, columns are connected within the frame of 120 cm axles to each other with high beams. Tube systems can be designed and implemented with various ways as framed tube, tube in tube or bundled tube depending to vertical and horizontal loads.

5.8.1. Framed Tube System

In framed tube system, is shown in Figure 22, the outer tube surrounding the structure provides inertia against the horizontal loads [24]. Vertical loads are shared by the outer shell (outer tube), the inner columns and shear walls / shear trusses. In this system, the outer shell acts as the core.

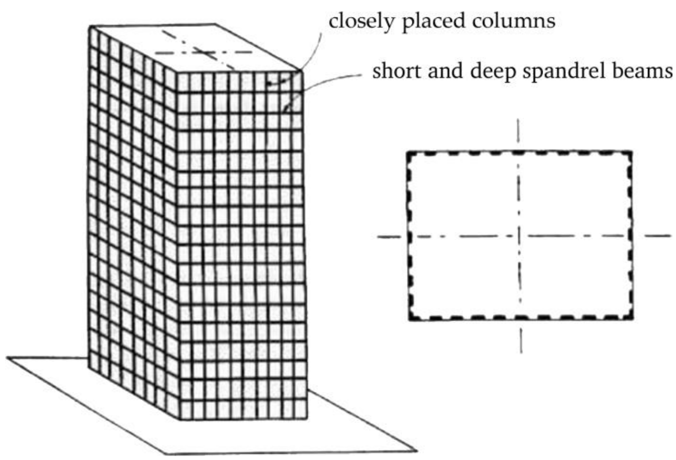
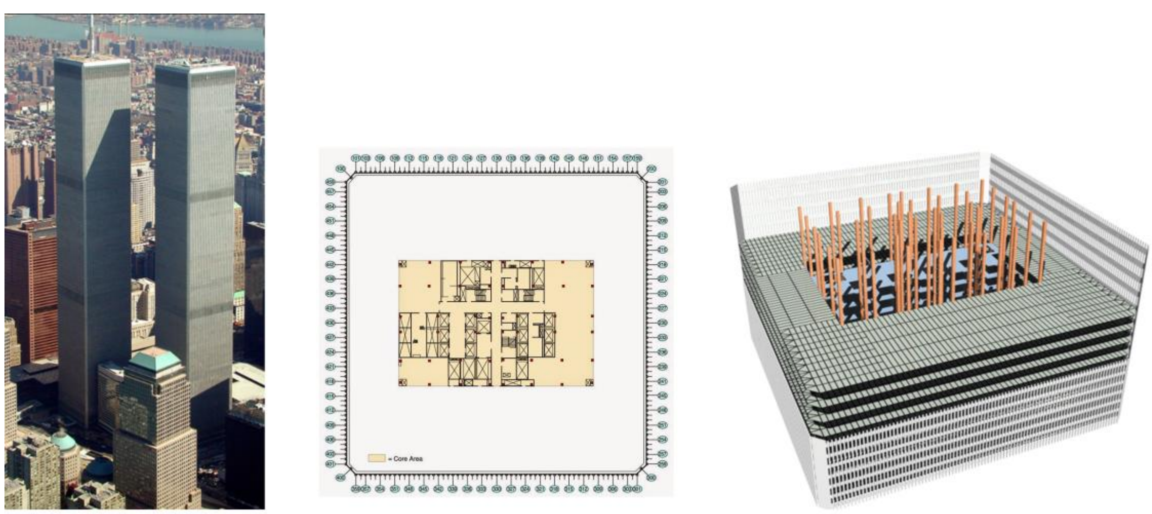


Figure 22 Framed tube system [17]

In 415 m / 417 m high 110 storey World Trade Center Twin Towers (New York, 1972), is shown in Figure 23, steel tubes were planned at spacing of 1.02 m at shell. 46 steel columns were planned in the center of the building [4,25].



a) b) c)

Figure 23 a) World Trade Center Twin Towers [26] b) 94th floor plan [27] c)Modeled structure [27]

5.8.2. Tube in Tube System

Tube in tube system, is shown in Figure 24, is designed as two tubes, with the outer tube as the shell and the inner tube as a tube surrounding the service core of the building [28]. This system can also termed as a "core in core".

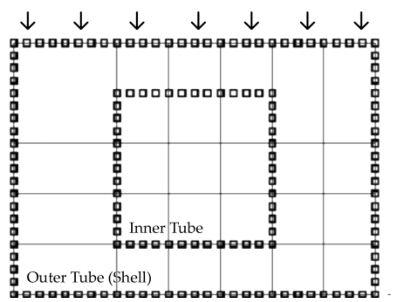


Figure 24 Tube in tube system [28]

In 217 m high 49 storey One Shell Plaza (Houston, 1971), is shown in Figure 25, the outer tubes were spaced 182 cm axles [29,31]. The reinforced concrete shear wall core of the building is the inner tube. The outer tube, which is the shell, provides the inertia of the structure as primary.

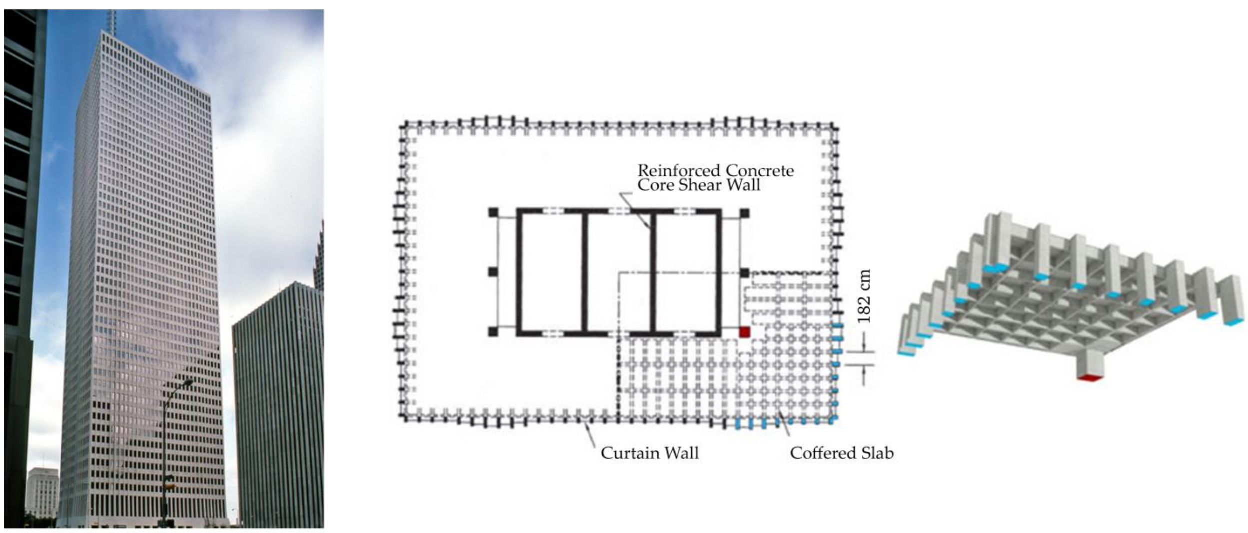


Figure 25 a) One Shell Plaza [30] b) Plan [31] c) Modeled coffered slab [31]

5.8.3. Bundled Tube System

The bundled tube system, is shown in Figure 26, is designed multiple framed tube system that acts like a single tube [4]. Bundled tube system can also termed as "multi-core system".

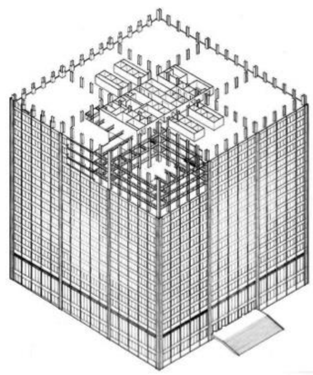
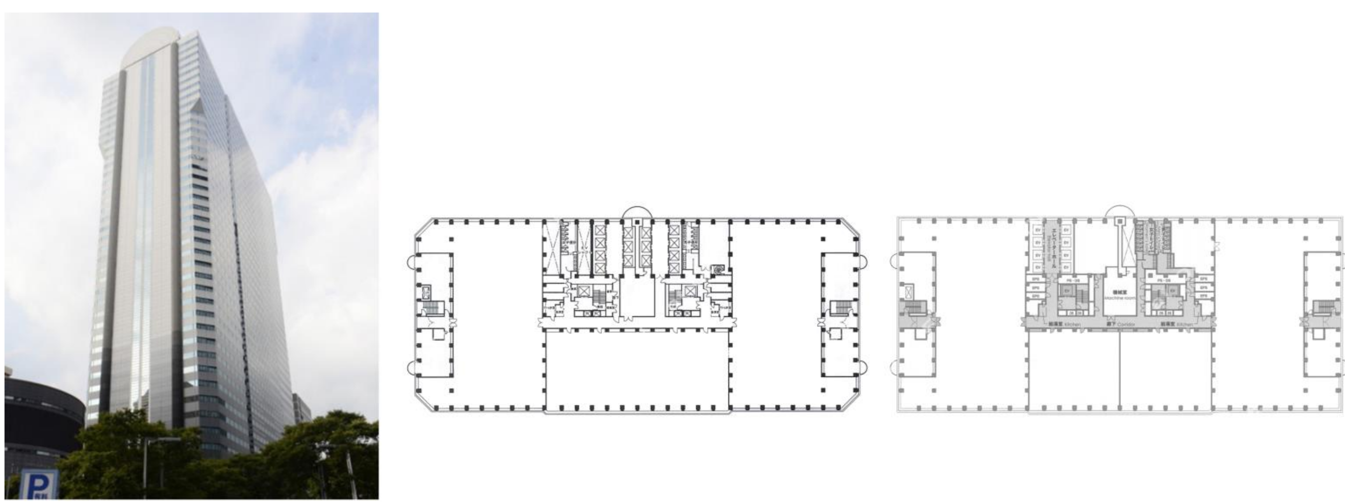


Figure 26 Bundled tube system [32]

In 189 m high 44 storey Shinjuku I-Land Tower (Tokyo, 1995), is shown in Figure 27, the service core was designed eccentrically in the floor plan [33]. For this reason, bundled tube system was chosen as the structural system to provide sufficient inertia.



a) b) c)

Figure 27 a) Shinjuku I-Land Tower [34] b) 25th Floor Plan [35] c) 42th Floor Plan [35]

6. Conclusion

As the height of the building increases, the horizontal and vertical loads acting on the building become more important. In particular, vibration caused by wind effect, which one of the horizontal loads, should be controlled. The structural system used in the building should be able to provide sufficient inertia against horizontal loads. When the structural systems used in high-rise design are examined, it is seen that the core is designed as the primary rigidity element that provides inertia against loads. Therefore, a core design is an obligatory to ensure the stability of the high-rise buildings. In the study, examining the core as the center of rigidity and evaluating its place in the structural system hierarchy in order to make easier the examination is main focus. When the structural systems used in high-rise buildings are evaluated within the hierarchy, it is seen that frame systems allow the height of the building to increase up to a certain point. Various methods are used in the structural system to control the vibration, especially to control caused by wind loads. The study provided information on this topic.

The structural system option is frame + core system for increase the inertia of the building. The core system, which is formed by designing the shear walls / shear trusses in various ways, is the basic rigidity center of the high–rise building. The shear walls / shear trusses of the core prevent bending and torsion of structure under the horizontal loads, thus ensuring the inertia of the structure.

Tube systems are examined under 3 headings. In framed tube systems, building shell is acts as the core. As the height of the building and horizontal, vertical loads increase tube in tube system is used. Tube in tube systems are designed as two tubes. The outer tube (shell) acts as the core and provides primary inertia, while the service core is located inside the structure and supports the inertia of the system. Therefore, the system can be defined as "core in core". The next choice in increasing inertia of building is bundled tube system. The bundled tube system includes multiple cores designed side by side in a relationship. Therefore, the system can be defined as multi-core system.

As a result, it is obligatory to design a core as a rigidity center in order to provide inertia against horizontal loads in a high-rise building that becomes independent from its surroundings as its height increases. The core can be a service core in the building or shell of the building can acts as a core.

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