

Structural Analysis of High-rise Buildings Under Lateral Loads

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Abstract. With the advanced development of modern society, the structural analysis towards high-rise buildings becomes more and more important to ensure stability for service purposes. Foundations of high-rise buildings provide fundamental support to the structure and transfer lateral loads from the upper portion of the building to soil and deep underground sublayers. While taking multiple factors such as soil-structure interaction, foundation layout configuration, and dampers, into consideration, the foundation must resist seismic energy and prevent excessive soil settlement. Compared to different structure systems, each high-rise building has different design and construction, such as rigid-frame, diagrid frame, and shear wall structure system. Structural analysis about each of the structure systems is conducted in this paper. Structure could dissipate and absorb lateral loads using different mechanics and materials. In addition, the exterior shape would affect the stability of the structure using analysis with fluid mechanics. Finding the most suitable structure system needs collaboration between engineers to achieve the best design with highest safety factor and stability.

Keywords: Structure System, Foundation, Materials, Seismic Load, Lateral Loads, High-rise buildings.

1. Introduction

The rapid pace of urbanization, poor land use planning and development, insufficient material facilities and services, and environmental deterioration have been the key factors in recent years that have raised the danger of seismic risks in cities. When the seismic strength is expressed in 12 degree increments, earthquake protective measures for buildings are typically used in the range of 6 to 10 degree increments, leading to the emergence of super high-rise structures with urbanization. Supertall structures over 100 meters in height that can house a street's worth of people are frequently used for business, residence, office, and educational functions and are regarded as social and economic hubs. High-rise seismic technology emphasizes the fact that once an earthquake damages a very high-rise building, the impact towards the structure stability is unneglectable.

To maintain the stability of the structure, there are several approaches engineers can apply. For example, high-rise buildings' foundation, structure system, and the materials used. These three components of foundation, structure, and material are examined in this paper.

2. Structure Analysis of High-rise Buildings

2.1. Foundation

2.1.1. Role of Foundation

High-rise buildings depend on its foundation design to resist seismic effects. The ability of resisting earthquake loads of foundations depends on several aspects, including the soil on the site, internal reinforcement of the foundation and external installations such as dampers.

2.1.2. Soil-structure Interaction

Foundations support buildings as the transmission of lateral loads caused by seismic loads to soils, transferring loads to soil by side friction and shear force. When the site soil tends to be saturated with moisture, it could result in the sinking of the foundation and cause the collapse of the building.

Applying a foundation into a solid and stable soil layer can better resist the seismic loads. The interaction between foundation and soil is called “Soil-Structure Interaction (SSI)”. In high-rise buildings, the pile foundation is often applied to ensure the stability of the whole structure. One of the examples is the Shanghai Tower, which is a 2,073 ft tall skyscraper with 128 stories. While constructing this exceptional building, engineers took the influence of SSI into consideration making judgements about the collapse resistance capacity of the Shanghai Tower. In IDA analysis, where the intensity of the seismic load increases until the collapse occurs, it is found that the collapse margin ratio of the building increase. Li et al. (2014) made an analysis about the Shanghai Tower’s collapse resistance while considering the influence of SSI [1]. The comparison demonstrates that taking the SSI impact into account boosts the structure's collapse-resistant capacity. The Shanghai Tower's vibrational periods are extended by the SSI effect, which also lowers the structure's seismic demand under the same ground motion data. Thus, if SSI is considered to make resistance against seismic effects, the stability of the high-rise building is improved due to the analysis of the adjacent soil condition.

2.2. Depth of the Foundation

Another feature of foundation of high-rise buildings is the internal reinforcement layout configuration. Foundation needs to provide shear force resistance during earthquakes. In order to provide the structure with more supports, pile foundation can be installed into deep underground soil layers, allowing lateral loads to be transferred into deeper soil to dissipate. The layout configuration of the piled rafts foundation mainly depends on the site soil. Geotechnical engineers provide the subsurface soil profile for foundation design. Notable factors include ground water table, layer thickness and saturation ratio. Deep foundation can reduce the story drift caused by seismic effects. Moreover, it can prevent the settlement caused by lateral loads and other service loads. One of the famous high-rise building examples is the Burj Khalifa Tower located in Dubai, which is 2,722 ft tall [2]. Its foundation design maximizes the settlement that could be made by multiple combination of loads. The tower is founded on a 3.7m thick raft, which rests on 194 bored piles with a diameter of 1.5 m, which extend 47.45 m below the base of the raft; The podium structures are founded on a 0.65 m thick slab which is increased to 1 meter at support points, which rests on 750 bored piles. It has a diameter of 9 m and extends between 30 and 35 m below the pond bottom.

The site was re-assessed for the actual settlement two years of construction, the measured settlement was only 14 mm. This data demonstrates the successful design and usage of the deep foundations in preventing soil settlement of the structure. Therefore, the application of deep foundation can increase building’s resistance of seismic load.

2.3. Dampers

One other crucial factor in resisting seismic effects is the damper. Instead of being influenced by short-wave and high-frequency earthquakes, high-rise buildings are more likely to be affected by long-term and low-frequency ones. During this specific type of earthquake, the slabs in the upper stories of the structure sway due to inertia force while the foundations remain in their original position during the earthquake, failing the structure such as rupture and buckling. The inertia force creates shear force acting on columns as well, which is known as stiffness force, leading to displacements at both ends of columns. Therefore, the method to maintain stability during damaging earthquakes is the installation of self-centring dampers on high-rise buildings [3]. Many structures are subjected to damage which cannot be reversed after earthquakes. The seismic energy that happens on the structure can be absorbed and dissipated by dampers. There are various types of dampers in modern structure construction, such as viscoelastic damper, friction damper and metal yield dampers.

Viscoelastic Dampers are usually used to decrease the amount of energy inside the steel plates. They are characterized by excellent plastic deformation ability, shear stability, ageing resistance, energy dissipation, and low-cost performance features, etc. The viscoelastic materials can manage to resist the vibration with compressible fluid inside the chamber. However, this type of damper can

only be efficient under a certain range of temperatures since the deformation of the materials can take place, which can largely decrease the efficiency of transmitting and restoring energy. Friction dampers are designed to void the seismic energy to have multiple steel plates' friction. With a combination of steel sub-plates and Pall-type friction damper, which can be applied to the centre of supports, friction dampers can limit the displacement of the slabs, the frequency of swaying and the stiffness of the structure with pre-tensioned springs. Lastly, the traditional Metal Yielding Damper is another example of using yielding strength of materials. However, the out-of-plane instability is induced by excessive lateral distribution, especially for the loads on the neck of the steel plate which can result in membrane stress in the horizontal direction. Additionally, there is another hypothetical damper called a Base Isolator, which can separate the foundation of the building from the ground floor where the structure remains constant. However, this type of damper cannot be applied to high-rise buildings because normally high-rise structures suffer from seismic forces from multiple directions, creating tension acting on the springs of the base isolators. The large amounts of tension caused the toppling of the whole building.

3. Structure Systems

3.1. Structure Stability

During seismic load effects, the structure of the building undergoes lateral loads which are transferred through slabs and beams. If the energy within the structure cannot be withstood by its strength, there is failure and deformation such as yielding and rupture. The stability of high-rise buildings is determined by the overall structure system, the reinforcement of the structure, the materials used in construction and the shape of the building. In the modern construction of high-rise buildings, the interior core and exterior frame structure systems vary considering specific requirements for criteria such as floor height, total stories, and site area.

3.2. Different Structure Systems

The structure system plays a vital role in maintaining structure stability against loads that high-rise buildings need to be aware. When the heights of the buildings increase, the lateral loads have greater effects on the structure. Nowadays, structure engineers use rigid-frame structure systems in constructing high-rise buildings. In this type of structure system, beams and columns are connected with joints to prevent deformation under excessive loads. To resist the bending moments that could happen to the structure during the earthquake, rigid-frame systems allow moments to be transferred to connected joints. The joints are allowed to rotate and release the moment. The stiffness and the rigidity of the steel frames to be constructed rigid-frame system is the ability of the structure system to withstand lateral loads and seismic effects. In AISC Steel Specification, the connection stiffness is defined as:

$$K_s = M_s / \theta_s \quad (1)$$

Where stiffness is equal to the moment at service loads divided by the rotation of joints at service loads. Lateral loads are transferred from the top of the building through columns and beams, normally distributed through slabs within each story of the structure. One example of a high-rise building using the rigid-frame system is the Burj Khalifa Tower, from this design, the high-rise building can combine aesthetic aspects of architecture with stability of the exterior structure features to create more possibilities for engineers to design.

Different from rigid-frame systems, although the diagonal grid frame structure system can be also applied to the construction of high-rise buildings, it needs less installation of steel frame to achieve reinforcement purposes and has less blocking of the lights and more aesthetic design consideration. However, this may stimulate the need for bigger column support for the structure. This type of structure system utilized geometry design to arrange the steel members in different angles in order to better distribute the seismic loads due to the stability of triangular arrangements. Jania and Patel (2013)

modeled a 36-story diagrid frame structure to test its stability of it under certain wind and seismic loads, comparing to the story-drift caused by seismic loads, the story drift caused by wind loads is larger [4]. Moreover, they also found out that lateral loads are resisted by exterior frame structure while the combination of interior columns and diagonal frame are distributed with self-weight of the structure. As the story of the building become higher, the lateral loads effects on story-drift increase. In high-rise buildings, the common design language is to let the interior column to resist the overall vertical load. The total structure system becomes more effective in resisting lateral loads by distributing loads in axial direction only within diagonal steel members on the periphery of the structure. The CCTV Headquarters located in Beijing, China is one of the examples using diagrid structure system, it created irregular shape of grid made by steel members, crossing with each other to form the exterior frame of the structure. This design allows less usage of steel members and makes the buildings more iconic to become the landmark in their location cities. However, it is more complicated for engineers to make the complex diagrid system feasible because of the geometry limitation.

Additionally, the interior structure of the higher-rise building is also important. For example, the shear wall structure system and the tube structure can both provide excellent transmission for the lateral loads and are very common in modern high-rise buildings [5]. When the building height is not suitable for designing column and beams within the structure, vertical shear walls with different shape are placed in order to resist and transfer the loads. Shear wall is usually made of reinforced concrete, it is a vertical wall which can distribute seismic loads and prevent excessive lateral loads that can cause displacement of slabs and beams. Shear wall can provide stiffness and strength to the structure. These factors are determined by the thickness of the wall, materials reinforcement and location of the shear wall applied. For high-rise buildings, during long-term earthquake, the shear force exerted on the structure also increases, this requires shear wall to transfer the loads from the upper portion of the building to the lower portion. Shear walls are able to transfer the lateral loads from the upper section of the high-rise building to the lower section by redistribute the loads to each stories' slabs and frames. Therefore, the structure is stable under certain type of seismic activities. Different location of where the shear wall is placed can greatly influence the overall design of the structure because it requires to combine the design of exterior reinforcement layout configuration. Moreover, tube structure system uses vertical structural members such as columns and shear walls to carry and connect horizontal structural members such as exterior continuous frames to create resistance to wind and seismic effects. Tube structure systems often has four large columns at each corner of the building with X bracing on each of the two columns on the same side. The four gigantic corner columns offer a 100-story skyscraper with an aspect ratio of around 7 approximately 25% more lateral rigidity. Although this type of arrangements of structural members can be effective in lateral loading resistance because of the hollow tube arrangements. But the existence of columns may be obscuring the viewing from the interior of the building in corner spaces.

3.3. Application of Fluid Mechanics

As the heights of the skyscraper increase, the wind speed increases as well. Therefore, vortices are created through process of vortices shedding. If the Reynolds number is large to certain number, the flow is dominated by inertial effects. Meanwhile, the viscous effects become only nonnegligible in the thin wake region behind the interface of the wind load. The suction force created by vortex behind the building under wind load also applies lateral load on the structure to cause swaying. By conducting wind-tunnel test, engineers can find the approach to address the vortices. That is, the boundary shape of the skyscrapers plays a vital role in the way the wind flow acting on the building (Fig. 1). The more streamlined design the skyscraper is, the less incompressible turbulent drag force it encounters. This is because the streamlined boundary has less surface area than those are not streamlined. Therefore, with smaller coefficient of drag force, the drag force is smaller as well. Below is an image that shows wake region of vortex in streamlined boundary shape and sharp boundary shape.

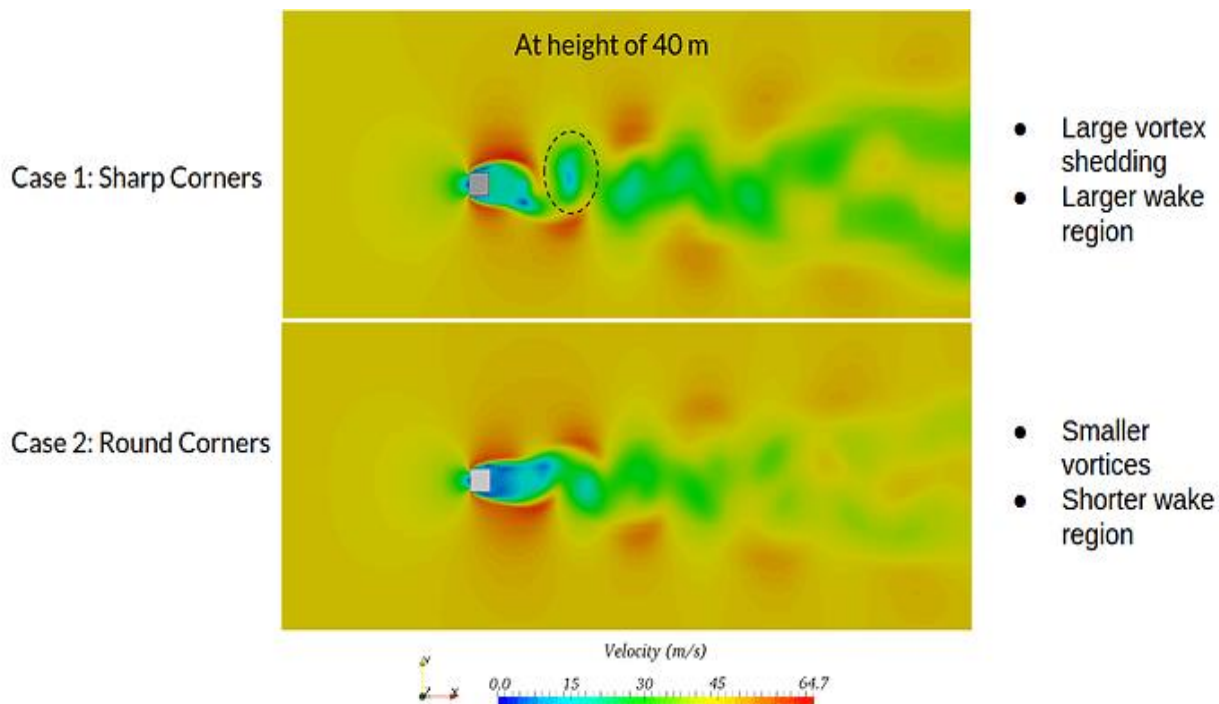


Fig 1. The wind flow performance with different boundary shapes of the skyscrapers [6].

It is clearly to see the streamlined boundary has smaller wake region than the sharp one, this is because by making the surface boundary streamlined, the surface area decreases and results in smaller drag force it creates as well as vortices. In high-rise buildings design, engineers often utilized round corners, tapering, corner cutouts and setbacks as the height of the building increases to reduce the influence and strength of vortex shedding. Therefore, to prevent the formation of the large vortices of wake region, it is crucial to design streamlined building boundaries [7, 8].

4. Conclusion

In conclusion, the structure analysis of high-rise buildings is important because it determines the stability of the structure. There are multiple aspects need to be considered such as the soil-structure interaction between foundation and soil to withstand the shear force and friction to increase the capability of distributing lateral loads. The deep foundation group which can prevent excessive settlement of the structure to prolong the service age of the buildings. In addition, the installation of dampers allows high-rise buildings to dissipate the lateral energy from seismic effects and wind loads. Different structure system has different design language with different design difficulties. By managing to combine different features of exterior frames and interior columns reinforcement, rigid-frame and diagonal frame system can release the moment at connections. The widely usage of shear wall system can transfer lateral loads from the upper portion of the buildings to lower parts. Lastly, the application of fluid mechanics to design the exterior shape of the high-rise buildings can reduce the effects of vortex which can cause swaying of the buildings and damage the stability of the structure. From my perspective, with the development of technology and artificial intelligence, the structural analysis in the future is more specific and easier to be conducted. The evolvement of approaches to increase stability of the structure helps civil engineers to better design, construct, and create more spectacular high-rise buildings for our society.

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