2. High-rise buildings

2.1. INTRODUCTION

How high is a high-rise building? It is different from country to country. In Hungary we call the buildings high-rise above 10-15 stories. In some countries the limit is 200m. From a structural point of view, high-rise buildings are those which require extra care to handle the consequences coming from its height.

Main problems:

- Large gravitational loads.
- Large horizontal loads.
- The foundation must carry large loads.
- Special architectural requirements.
- Dynamic effects.
- Other special effects.

The main problem of high-rise buildings is to handle the *dynamic effects*. Such dynamic effect is caused by **earthquake** and the **wind load**. In case of buildings with a height less than 200m, the dynamic effect of wind load is negligible.

2.2. GRAVITATIONAL LOADS

Vertical loads are carried by vertical elements (columns, walls). They depend on the function of the building and the self-weight of the structure. To reduce the self-weight, we can use voided structures. However, reduced self-weight results in bad acoustic properties and low fire resistance.

Slabs

Too light or too heavy slabs should be avoided because of the above mentioned factors. It is beneficial to reduce the number of columns and use larger cross-sections to support the slabs (leading to larger spans).

One traditional solution is to **support the RC slabs with steel beams or steel trusses**. This results in low self-weight and can cover 15-20 m. However, it is sensitive to fire loads, therefore the steel elements should be protected with fire protection coating. Unfortunately, this solution can resist fire for only a short period of time (this was the problem of the WTC building in 2001).

Nowadays, the combination of concrete and steel beams is still widespread, but now we combine them to create a **composite structure**. In this way, they can bear the load together. If the concrete covers the steel beams, the structure can resist fire loads. Furthermore, the steel structure can bear the concrete slab, so scaffolding is unnecessary.

Post-tensioned concrete is also a solution, which leads to small thickness and small self-weight. Moreover, it is resistant to fire loading.

The idealized model of composite slabs and steel supported RC slabs are usually **statically determinate (**simply supported or simply supported with cantilever end). Since foundation settlements and geometric changes common in case of high-rise buildings would cause indirect stresses in statically indeterminate structures, they are preferred to be statically determinate. Foundation settlements are expected under the columns above 5-10 floor buildings.

Monolith reinforced concrete results in two-way slabs leading to a statically indeterminate multi-span structure which is sensitive to movements.

Columns

Steel replaced wood after the industrialization in the XIX. century, and it was the structural material of the first high-rise buildings. Back then, steel was considered to have better fire resistance performance, than wood. Today, it is well-known, that steel is also sensitive to fire because it loses its strength at high temperature (above 300-400 °C). High strength of the material leads to small cross-sectional areas. Until the 1970s, steel was the main structural component of high-rise buildings.

The **steel columns** were hot rolled L, U profiles or the combination of I and flat steel profiles with riveted joints. Later riveted joints were replaced by bolted joints and welded joints.

The main disadvantage of steel is its sensitivity to fire. The first steel columns were covered by heavy stone envelopes which protected the structure from fire. However, the spreading of light envelopes and curtain walls that provide no protection led to the need of fire protective coverages and paints on steel structures. These fire-related issues led to the rise of RC structures. **RC columns** have larger cross-sectional areas which is often undesirable.

- If the strength of the concrete is 10-15 N/mm^2 standard 30x30cm RC columns are suitable for 3-4 floors, but above 20-30 floors the diameter of the column is over 1m.
- Nowadays high strength concrete is available (60-80 N/mm^2, 100 N/mm^2) which can lead to smaller cross-sections, but they are very expensive.

The construction of a dorm in Vancouver, Canada started in 2015, which has 18 floors and it is composed of a **wood frame structure** (combined with RC bracing core).

Walls

The load-bearing elements around the façade are usually columns (resulting in freedom of the design of the façade). However, the core of the building including the stairway and the elevator shaft is created by walls which are parts of the stiffening system. Nowadays, all **stiffening and load-bearing walls** in high-rise buildings are made of **RC**.

20 cm thickness of an RC wall is enough to carry 20-30 floors. The thickness of the wall is limited by factors such as acoustics, building thermotechnics, fire protection and construction. The reinforcement bars are located on both sides of the walls (2 layers) which are covered by a concrete layer. As a result of the construction technique (casting, vibration etc) the minimal thickness is 18-20 cm.

Besides the RC frame system, it is possible to build high-rise buildings with steel frame system.

2.3. HORIZONTAL LOADS

Horizontal loads are usually live loads and act for a short period of time. Their effect can be neglected only in case of compact, small buildings. The higher a building is, the more significant the effect of horizontal loads on the structure.

The most important horizontal loads: wind load, earthquake load, earth pressure, water pressure, impact, explosion etc. Most of the horizontal loads are dynamic loads which results in an increased complexity in the structural design and analysis.

Wind load

It depends on the velocity of the wind and the shape of the building. Near the earth's surface it's amplitude is smaller because of friction. It is also smaller in an urban environment, where many objects block the wind and contrarily wind load is large in open spaces (water surface, desert etc.). Because of building aerodynamics, vortex shedding occurs at the edges and corners leading to dynamics effects. In the calculations we consider wind loads as static or quasistatic loading. However, in case of high-rise buildings, the dynamic effects cannot be neglected! Above 200m the large amplitude of the wind load leads to non-negligible dynamic effects coming from vortex shedding. There are two consequences of dynamic loads: 1. they amplify the loads and the movements of the building, 2. reduces serviceability.

- Serviceability: Dynamic loading leads to vibrations. The natural frequency of the structure is almost the same as the vortex-shedding frequency leading to vortex-induced vibration. This vibration does not lead to the failure of the structure, but it leads to large movements (30-40 cm). These movements can destroy the joints and envelopes of the building structures. From the physiological point of view, the maximal acceleration of the building should be limited. The allowed acceleration for residential buildings: 15-18 mg (milligravity), for office blocks: 20-25 mg. If the slenderness of the building less than 1/8 (the ratio of the diameter of the bracing system and the height of the building) enforcement of the bracing system is ineffective in reducing the acceleration and further techniques should be used to damp the system and to comply the serviceability requirements.

Eurocode provides data for wind loads up to 200 m height. In case of buildings higher than 200 m individual studies are necessary e.g. using wind tunnel experiments. There might also be local regulations.

Earthquake load

It depends strongly on the geographical location. In moderate earthquake hazard zones (e.g. New York, Chicago, Budapest) the earthquake load should be incorporated in the horizontal loads, but the shape of the bracing system and the necessary damping should be determined by considering the dynamic effects of wind loads. In major seismic zones (e.g. California, Japan, New-Zealand) the effect of the earthquake is the most significant of all other loads and determine the whole designing process. In areas where the probability of damaging earthquake effects is very low (e.g. London), the most significant dynamic horizontal load is the wind load (for both serviceability and the load-bearing capacity).

What are the main differences between wind load and earthquake load? In case of wind load, we must reduce the amplitude of the movements ⇒ the stiffness of the structure has to be increased. In contrary, buildings with lower stiffness have better resistance to earthquake loads. In summary, wind load and earthquake load require contrasting strategies. This contradiction was resolved by developing the **capacity design** technique. Capacity design ensures that the building undergoes ductile behavior under a design-level earthquake load leading to a lower overall stiffness. Plastic deformations lead to energy dissipations and controlled damage prevents the structure from collapse. Structures in Japan and Chile designed using this technique resisted 6-9 magnitude earthquakes which illustrated the efficiency of this technique.

Besides horizontal acceleration, the **horizontal movements = interstorey drifts** should also be limited. The joints of the building are protected by reducing the relative displacements of the stories. The displacement/height limit in case of wind load is 1/400 – 1/500, and 1/50 – 1/100 for earthquake load. This allowed displacement should be considered in the design of the joint gaps, envelope systems, gaskets.

Bracing systems

Two common type of bracing elements:

- **Shear wall system**: the bracing behaves like a cantilever beam. The displacements at the lower stories are small, but the upper stories go through large rotations.
- **Frame system**: the shear deformations are dominant. There are large displacements at the first few stories but only small rotations at the top stories.

These two elements can be combined to utilize their advantages. However, girders connected to bracing cores are sensitive to dynamic loads ⇒ it is not recommended to combine these systems if there is a high risk of seismic activity. What about the dynamic effect of wind loads? Taking the fact, that the frequency of the wind load is smaller, than the frequency of the earthquake load, dynamic effects of wind load affects only serviceability.

Most common bracing layouts:

- **Braced core**: The core is at the center of the floor plan. Horizontal loads cause bending moment in the core. This solution is effective for 20-40 story-high buildings.
- **Frame system**: moment-resisting frames leading to lower overall stiffness (compared to buildings with bracing cores). In case of sufficient ductility of the joints, the structure can resist dynamic loading (especially earthquake). This solution is effective for 20-40 story-high buildings. In case of this structure, the vertical columns bear not only the vertical loads but they are also parts of the bracing system! This leads to large bending moments and large cross-sectional areas!
- **Combined bracing**: the braced core and the frame system is combined together. This solution is sensitive to dynamic loading, but they support each other. Maximal number of stories: 30-50.
- **Tube bracing**: it is possible to place the bracing elements on the façade (leading to a larger moment of inertia of the elements). However, it provides less freedom in the façade design and the amount of openings is also limited. Maximal number of stories: 60-80. Possible constructions of the tube:
    - **trussed tube**: the bracing planes are composed of plane trusses (with diagonal or cross bracing).
    - **framed tube**: numerous columns and beams with large cross-sectional areas constitute the bracing frame. Note: while the distance between the columns in case of a frame system is 6-8 m (up to 15-20 m), in case of framed tubes the distance should not exceed 3-4 m!
- **Tube-in-tube structure**: tube structure and a braced core combined together. It improves the shear stiffness in resisting lateral forces. Maximal number of stories: 60-80.
- **Bundled tubes**: it behaves like a multicellular box girder. In theory it can be constructed by adding an inner wall-system into the tube-in-tube structure. It can slightly increase the possible number of stories up to 80-100.
- **Joined bracing**: The main problem with tube bracing is the restrictions regarding the location and size of the openings. Braced core is a better choice regarding the architectural freedom, but how can we increase the maximal number of stories and while providing freedom in the design of the façade at the same time? If the vertical load-bearing elements around the façade are pillars, the openings are not limited. They can be connected to the bracing system by story-high cantilever beams, clamped in the braced core. As a result, the moment of inertia of the bracing system increases and the maximal number of stories also increases up to 80-100. This structural combination provides freedom in the design of both the façade and the floor plans.
- **Custom bracing systems**: Above 80-100 stories, the classical systems are insufficient. It is possible to create a “bone-like” bracing structure, which follows the shape of the building. Such technique was used in the design of the Eiffel-tower and Burj-Khalifa (consisting of a structural steel spire utilizing a diagonally braced lateral system).

2.4. FOUNDATION

In case of the foundation, the horizontal and vertical loads cannot be considered separately. Large vertical loads result in large stresses in the soil. Moreover, classical foundation structures can bear no tension $\Rightarrow$ the bending moment coming from horizontal load should be handled with care!

Vertical effects

The load-bearing capacity of the soil is usually around 200-400 kN/m^2. In case of the classical flat foundation this leads to a maximal number of 20-30 stories. Although there is usually a stronger layer of soil deep under the upper layer, it might be located hundreds of meters deep. By increasing the depth of the foundation (30-40 m up to 80-100 m), the load-bearing capacity can also be increased. Up to 10-20 m depth it is enough to design a multi-story underground car-park with 3-4m thick slab foundation. In case of larger necessary depth, *deep foundation* is required.

Pile foundation or *diaphragm wall* are the most common options. It is not necessary but beneficial if they are supported by the bearing stratum. For example, in Budapest the bearing stratum is located so deep, that it is not worth reaching it. In contrary, the granite blocks forming the bearing stratum in New York is close to the surface and easy to reach. In such areas (another example is Toronto) it might be enough to use shallow foundation for high-rise buildings.

Horizontal effects

Bending moment coming from horizontal loads lead to the eccentricity of the vertical loads. If the eccentricity is small, the acting point is inside the cross-section and it is enough to use shallow foundation.

If the building can bear the vertical loads but it must be stabilized against overturning, a solution is to increase the area of the foundation (e.g. with an underground car park). The car park must be constructed as a cellular structure to provide the consistent settlement.

If the shallow foundation is not enough to carry the bending moment, anchorages or pile foundation should be designed to provide the necessary load-bearing capacity. They utilize the weight of the soil and the friction between the pile and the soil to bear tension.

2.5. SPECIAL REQUIREMENTS

Lower stories

From the structural point of view, it is required to choose a structural system that connects all stories with the foundation. However, the architectural aspects often require open spaces on the ground floor of the buildings which violates the bracing system. The fulfillment of these contradictory requirements is a complex task and it not only increases the risks but also the overall cost of the structure. Lintel structures:

- **Frame structure**: the height of the horizontal elements and the width of the vertical elements is 1-2 stories.
- **Truss-like rod structure**: pillars combined with trusses leads to lower cross-sectional areas. However in this solution, the horizontal forces arising in the diagonal elements is problematic.
- **Lintel slab**: a slab collects the pillars on above the ground floor and behaves as a lintel. This slab must be 2-3 m thick which is a complex task to construct.

Asymmetric geometry

There is no need of extra measures if the geometry of the load-bearing structure is regular and symmetric and only the façade is asymmetric. However, if the whole concept is asymmetric, additional shear stresses arise as a result of torsion leading to the need of larger cross-sectional areas.

If the center of torsion and the centroid of the building are far from each other, torsion emerges under earthquake load. Moreover, wind load can also induce torsion. Unfortunately, a high level of symmetry is required to reduce the torsional effects. It also worth to mention, that vertical loads can also cause torsion if vertical load-bearing elements are not vertical (and therefore they have horizontal support force components).

It is possible to bear torsion, but it is uneconomical hence the asymmetric architectural concepts should be avoided in the absence of other important benefits.

Damping

If the natural frequency of the structure is close to the frequency of the load, it leads to resonance. If the structure is very stiff, the dynamic loading is transformed to forces, otherwise it is transferred to movements.

High-rise buildings have low overall stiffness, their natural frequency is low and their period is high resulting in large movements. This low stiffness has great advantages: it reduces the effects of the excitation. However, it leads to the increase of the frequency of vortex shedding and loads coming from wind load. Moreover, large movements can destroy the joints in the building and reduce serviceability. As a result, these movements must be damped. Damping dissipates kinetic energy and leads to reduced movements.

Types of damping solutions:

- **Designing ductile structural joints**, utilizing plasticity at critical points such as the corners of frames. These joints must be able to bear the periodic loads. Appropriate materials: steel, synthetic resin. Concrete or brick is inappropriate because their deformation limit is small and they cannot bear periodic loading. **Steel frames** are ductile and therefore appropriate to dissipate the energy of seismic activity. However it must be emphasized, that the joints should not be brittle (e.g. bolted joints). In case of **RC structures**, the ductility can be increased by designing an appropriate layout of the reinforcement bars. In the critical joints synthetic resin often replaces concrete providing ductility. However, ductility dissipates energy only in the ultimate limit, but it does not help in the serviceability limit!
- **Damping system** can help to reduce movements coming from wind loads: e.g. tuned mass dampers
- In-built **dissipative elements** with small load-bearing capacity but large damping.
- Allowing the movements of the building.

Illustration of the damping system: https://m.youtube.com/watch?v=kApmX-OqWNY

Resonance: https://m.youtube.com/watch?v=uFIIbujTuIY

2.6. ANALYSIS

High-rise buildings require a complex analysis because the combination of the effects require special solutions. The usual hierarchical approach in the design of the load-bearing structure cannot be applied especially in case of dynamic loads. Furthermore, the plastic deformations play an important role in the calculations, but the material properties especially in the plastic stress state are hard to measure. Moreover, the consolidation of the soil is also an important factor. There exists software to calculate high-rise buildings, but they must be used with extra care.