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*(Review)*

# Natural Frequency of Buildings and Resonance Phenomenon: Impacts on Structural Design

Ghada G. Salem[1, *]

[1] *Construction Engineering Department, Faculty of Engineering, Egyptian Russian University, Badr City, Cairo 11829, Egypt.*

*Corresponding author(s): Ghada G. Salem, E-mail: ghada-gamal@eru.edu.eg , Tel: +201007307927

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**ABSTRACT**

This article examines the natural frequency of buildings and the resonance phenomenon, highlighting their significant impacts on structural design. Understanding the natural frequency is crucial for predicting how buildings respond to dynamic loads such as earthquakes and wind. The study emphasizes the importance of considering the height and mass of buildings, as these factors influence their natural frequency and, consequently, their behavior during seismic events. Through theoretical discussions and practical examples—including the Tacoma Narrows Bridge collapse and the Mexico City earthquake of 1985—the paper demonstrates the risks posed by resonance when the natural frequency of a structure aligns with external excitation frequencies. A case study of the Burj Khalifa is presented to showcase advanced structural and aerodynamic design strategies for mitigating seismic and wind-induced resonance. This research aims to serve as a reference for engineers and architects in understanding and addressing resonance-related challenges to enhance the safety and resilience of tall structures.

*Keywords: Natural Frequency; Resonance Effects; Seismic and Wind Response; Structural Dynamics; Structural Failure Analysis.*

## 1-Introduction

In recent years, tall buildings, or high-rise structures, have become increasingly important in urban environments, as they allow for greater population density in limited space. However, the design of these buildings must consider the effects of earthquake and wind loads. A building is classified as tall or high-rise if its aspect ratio (height divided by the smallest overall lateral dimension) exceeds 5:1 [1]. Skyscrapers serve multiple purposes, including office spaces, hotels, residential units, and retail areas [2]. The following points illustrates the advantages and the disadvantages of tall buildings [3]:

- **Advantages of tall buildings:**
  1. They save space and accommodate more residents as compared to shorter buildings, However, their compact footprint also increases their vulnerability to resonance during seismic or wind events.
  2. The higher floors are relatively airier and receive more sunlight. This advantage might be affected under extreme lateral movements caused by natural phenomena.
  3. Taller buildings are a better option for the idea of a green building since they are more lit, airy and provide more surface area to install solar panels. However, these benefits come with the challenge of ensuring structural stability, requiring advanced engineering efforts to mitigate the impacts of seismic and wind forces.
  4. They are much more economical as buying a small land and constructing a tall building is more affordable than purchasing a widespread land. Despite this, higher construction costs arise from the need for advanced materials and structural designs to counter natural forces.

- **Disadvantages of tall buildings:**
  1. The construction of very tall buildings requires highly skilled engineers and architects to design the building, thus increasing the total cost. This is particularly true when addressing seismic and wind resistance.
  2. Very tall buildings bear wind forces and seismic forces apart from dead and live loads, this complicates their design and necessitates specialized damping systems.

3. Buildings above 100 story heights face the problem of oscillation, sometimes resulting in crashing of windowpanes (e.g. the case of 200 Clarendon). These oscillations are often amplified during earthquakes or strong winds due to resonance phenomena.
4. The foundations of very tall buildings with smaller construction land are under tremendous load, and soil failure due to seismic activity can lead to the collapse of the building.
5. Constant oscillations may give a nauseating feeling to the residents of the building. This highlights the importance of vibration control in their design.

It is noteworthy that the ten tallest buildings in the world are illustrated in Table 1.

**Table 1**. The 10 Tallest Buildings in the World [4].

| No. | Name | Height (m) | City | Country | Year of Completion |
|---|---|---|---|---|---|
| 1 | Burj Khalifa | 828 | Dubai | UAE | 2010 |
| 2 | Merdeka 118 | 678.9 | Kuala Lumpur | Malaysia | 2023 |
| 3 | Shanghai Tower | 632 | Shanghai | China | 2015 |
| 4 | Abraj Al-Bait Clock Tower | 601 | Mecca | Saudi Arabia | 2012 |
| 5 | Ping an International Finance Centre | 599.1 | Shenzhen | China | 2017 |
| 6 | Lotte World Tower | 554.5 | Seoul | South Korea | 2017 |
| 7 | One World Trade Center | 541.3 | New York City | United States | 2014 |
| 8 | Guangzhou CTF Finance Center | 530 | Guangzhou | China | 2016 |
| 9 | Tianjin Chow Tai Fook Finance Center | 530 | Tianjin | China | 2019 |
| 10 | China Zun | 527.7 | Beijing | China | 2018 |

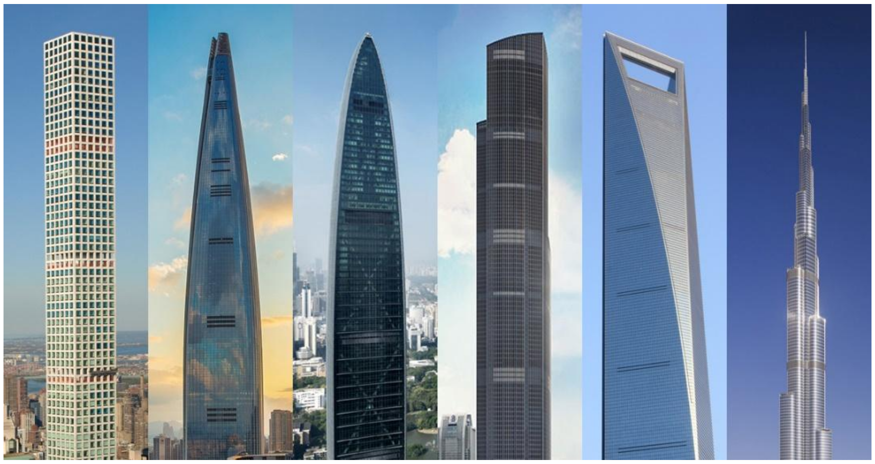


**Figure 1.** The Tallest Buildings in the World

One critical factor in the design of tall buildings is the natural frequency, which indicates the structure's flexibility or rigidity. The natural frequency refers to the complete back-and-forth motion of a structure in the absence of external forces, influenced by its height, mass, and inertia [5]. It is typically expressed in hertz (Hz) or cycles per second (cps). The natural frequency can be calculated using theoretical equations or through software that employs the Finite Element Method. Two manual calculation methods exist for determining the natural frequency: the Single Degree of Freedom (SDOF) method [6] and the Multi Degree of Freedom (MDOF) method [7].

A related phenomenon is resonance, which occurs when an object or system is subjected to vibrations matching its natural frequency. This results in the object absorbing energy and vibrating with greater amplitude, potentially leading to excessive vibrations or structural failure [8]. To mitigate resonance, engineers must analyze the natural frequencies of their designs carefully, ensuring they are not exposed to oscillating forces at these frequencies. This can involve using various materials, altering the structure's shape, or adding dampers to absorb energy and reduce vibrations [9].

Understanding natural frequency and the phenomenon of resonance is very important for improving the design of buildings to withstand earthquakes. This research is especially crucial in areas prone to earthquakes, as poor design can lead to significant failures. Cities like San Francisco and Tokyo have experienced the effects of earthquakes on tall buildings, highlighting the need for careful analysis and innovative design methods to reduce these risks.

## 2. Objective

This review article aims to provide a comprehensive explanation of the natural frequency as one of the dynamic characteristics of the structure and its relationship to structural resonance. The study will discuss the impact of resonance on buildings, highlighting the failures of historical structures due to resonance effects, such as the collapse of the Tacoma Narrows Bridge. Additionally, the article will focus on a case study of the Burj Khalifa, illustrating how modern engineering practices, including seismic and wind resistance, address the challenges posed by resonance in tall structures. This research aims to deepen the understanding of the natural frequency and resonance phenomena and their importance in the design of high-rise buildings, offering valuable insights for future research in this field.

## 3. Theoretical Background

In this section, various methods for calculating the natural frequency of buildings are discussed, including manual analysis methods like the Single Degree of Freedom (SDOF) and Multi Degree of Freedom (MDOF) approaches, as well as the Dynamic Analysis using Finite Element Method (FEM) and Experimental Modal Analysis.

### 3.1 The single degree of freedom (SDOF) method:

This method addresses structures with a single degree of freedom. In general, continuous structures have an infinite number of degrees of freedom, but a single degree of freedom model can be used for simple buildings that primarily move as a single unit [6]. Figure (2) illustrates examples of structures that may be represented as one-degree-of-freedom systems for dynamic analysis.

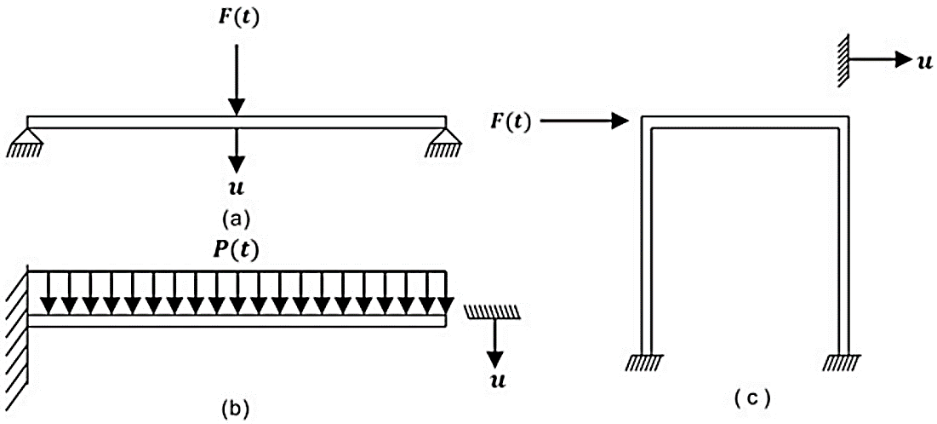
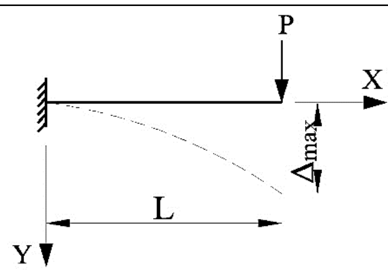


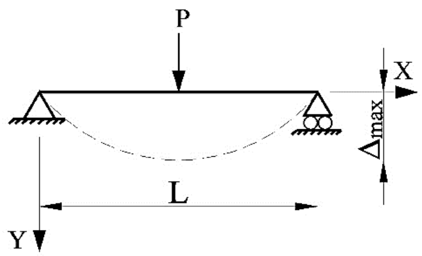
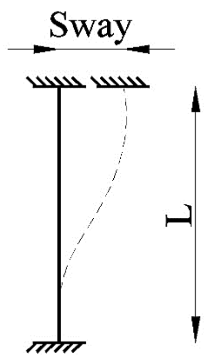
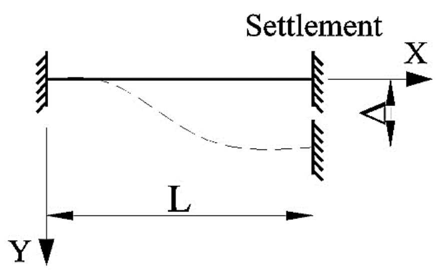

**Figure 2.** Examples of Structures Modelled as One Degree of Freedom System [6]

The natural frequency in SDOF method is calculated using equation (1) [6] that incorporate the building's mass and stiffness, where the stiffness influences the natural frequency based on boundary conditions (type of supports at each end) and applied loads (uniform load, concentrated load, etc.). Table (2) provides examples for calculating stiffness in various scenarios.

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \quad Hz \tag{1}$$

**Table 2**. Examples for Calculating Stiffness

| Boundary Condition and Loading | Stiffness (K) |
|---|---|
|  | $K = \dfrac{3EI}{L^3}$ |

| | |
|---|---|
|   | $K = \frac{48\, EI}{L^3}$ |
|     | $K = \frac{12\, EI}{L^3}$ |

Where;

E is the modulus of elasticity [Pa]

I is the moment of inertia [m4]

m is the mass of the whole building [kg]

L is the height of the building [m]

**3.2 The multi degree of freedom (MDOF) method:**

The MDOF method [7] is suitable for multi-storey structures, such as the frame shown in Figure (3). This approach simplifies the Multi-Degree of Freedom (MDOF) method by approximating it using the Single Degree of Freedom (SDOF) system. The MDOF method typically requires matrix analysis, but in this case, to facilitate the calculation of the natural frequency, we approximate the structure as a simplified system with a total mass ($m_{tot}$) and an equivalent stiffness ($K_{eq}$), which allows for a similar approach to SDOF.

In this method, the total mass ($m_{tot}$) is calculated as the sum of the masses for each floor, as shown in equation (2). The equivalent stiffness ($K_{eq}$) for the entire structure is determined using equation (3), while the stiffness for each column can be individually calculated by equation (4). The natural frequency is then obtained through equation (5) [7].

$$m_{tot} = m_1 + m_2 + m_3 \tag{2}$$

$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} \tag{3}$$

$$K = \frac{12\,EI}{L^3} \tag{4}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{K_{eq}}{m_{tot}}} \quad Hz \tag{5}$$

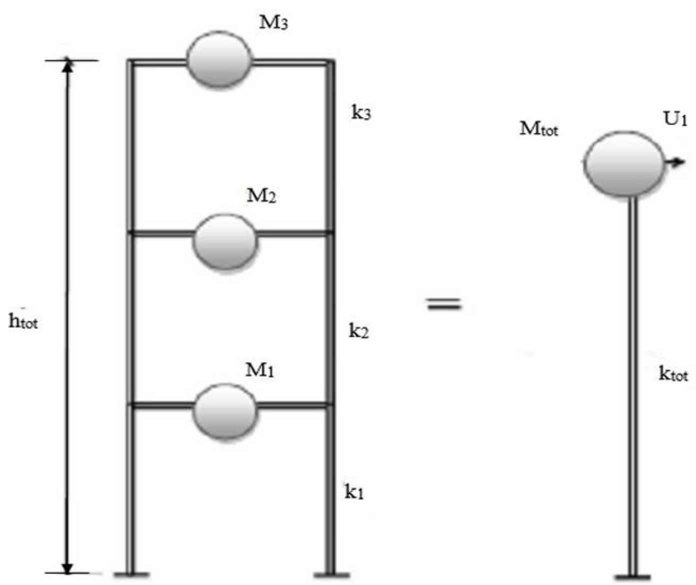



**Figure 3.** Multi-storey Frame and Its Equivalent Single Degree of Freedom System [7]

### 3.3 Dynamic Analysis Using Finite Element Method (FEM):

The Finite Element Method (FEM) is a numerical analytical method used in software like ANSYS to calculate the natural frequency of structures. This approach divides the structure into small elements and solves dynamic equations for each element to determine the natural frequencies. FEM is highly accurate and enables the analysis of complex effects, such as material variations and dynamic loads, making it suitable for complicated structures that cannot be easily represented by SDOF or MDOF methods.

### 3.4 Experimental Modal Analysis:

Experimental Modal Analysis is a practical approach used to measure the natural frequencies of actual structures by applying vibrations to the structure and recording its response. Measuring tools, like accelerometers, are used to capture these vibrations, providing precise data on the building's true natural frequencies. This method is often employed to validate numerical and theoretical results, especially in cases where computational models may not accurately represent real-world behavior.

### 3.5 Choosing the Appropriate Analytical Method:

The selection of an appropriate method for calculating natural frequency depends on the structure's complexity and the desired level of accuracy. Designers should select the calculation method based on structural characteristics and project requirements:

1. **Use the SDOF method:**

   Suitable for small, simple structures with a clear single degree of freedom, where mass and stiffness can be easily defined. This method is efficient and provides a quick approximation. The following conditions must be met for the application of this method on a structure:

   a) Structure must behave like a single mass-spring system.
   b) The mass of the structure should be concentrated at a single point.
   c) Suitable for simple structures with a dominant mode of vibration.

2. **Use the MDOF method:**

   Best for multi-story buildings where each floor has distinct mass and stiffness. This method is necessary for structures with multiple degrees of freedom to achieve accurate results for each floor's response. For this method to be applicable, the structure must satisfy the following criteria:

   a) Structure should have multiple masses and stiffnesses.
   b) Suitable for more complex structures with multiple degrees of freedom.
   c) Necessary when the interaction between masses and degrees of freedom is significant.

3. **Dynamic analysis using FEM:**

   Essential for irregular or tall structures, complex geometries, or buildings with critical performance requirements. Although time-intensive, FEM provides the highest accuracy and is valuable in final design stages or when experimental validation is required. To effectively apply this method, the structure should meet the following requirements:

   a) Structure must be discretized into finite elements.
   b) Suitable for structures with complex geometries and material properties.
   c) Necessary when detailed stress, strain, and deformation results are required.

By carefully considering these options, designers can select a method aligned with structural complexity, height, and project stage, ensuring a balanced approach between accuracy and efficiency.

The natural frequency of a building is significantly influenced by its height; as height increases, the natural frequency tends to decrease. This variation creates different natural frequencies for tall, medium, and short buildings. When a building is subjected to dynamic forces, such as wind or earthquake loads, it oscillates at a specific frequency. If this oscillation frequency aligns closely with the building's natural frequency, resonance can occur, potentially leading to severe structural damage. The following section will discuss the phenomenon of resonance in detail.

## 4. Resonance of buildings:

Resonance is a phenomenon that occurs when the frequency of ground motion or wind matches the natural frequency of a building, leading to the largest possible oscillations and, consequently, significant structural damage. The BOSS model (Building Oscillation Seismic Simulation) effectively demonstrates this resonance phenomenon.

Dr. Robert Butler [8] conducted an experiment using the BOSS model to illustrate how buildings of varying heights respond differently during an earthquake. The experiment setup includes three wooden blocks (1x4 inches in cross-section and 8 inches in length), three wooden dowels (14, 18, and 22 inches in length), and a 2x4 inch wooden base, 24 inches long.

- **Procedure:**

1. Three holes were drilled vertically into the 2x4 base board, one at the center and two about 3 inches from each end of the board – Figure 4.a.
2. Felt pads were added to the bottom of the 2x4 base board to stabilize it.
3. A 1/4-inch hole was drilled into one end of each 1x4 wood block, parallel to its length, about one inch deep.
4. Each dowel was inserted into the 1/4-inch hole in the block and then into the base, representing buildings of different heights: the tallest dowel represents a tall building, the medium dowel an intermediate building, and the shortest dowel a short building – Figure 4.b.
5. The 2x4 board was then shaken to simulate ground motion, using three different frequencies: low, medium, and high.

- **Observations:**

1. The tall building responded primarily to low-frequency oscillations.
2. The medium building responded to medium-frequency oscillations (note: during these frequencies, the tallest and shortest buildings may not be significantly affected).
3. The short building responded to high-frequency oscillations.

- **Conclusions:**

Thus, a high-frequency earthquake predominantly affects short buildings, while low-frequency ground motion impacts taller buildings more. As stated, when the frequency of ground motion aligns with a building's natural frequency, the building will experience maximum oscillations, a phenomenon known as resonance. The following real-life examples provide further illustration of this effect.

**Figure 4.a** – Three holes in 2x4 board

**Figure 4.b** – BOSS

**Figure 4.** Procedure for Constructing BOSS Model

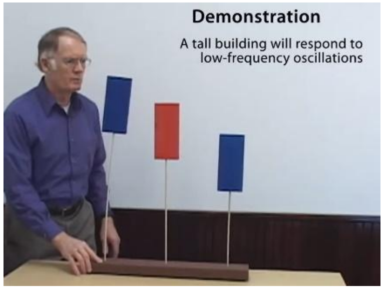



**Figure 5.a** – Tall building responses to low-frequency

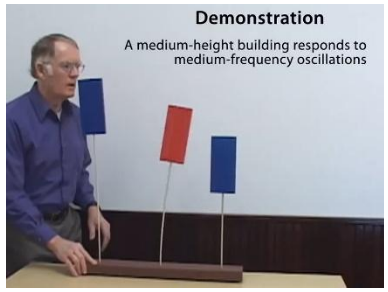



**Figure 5.b** – medium building responses to medium-frequency

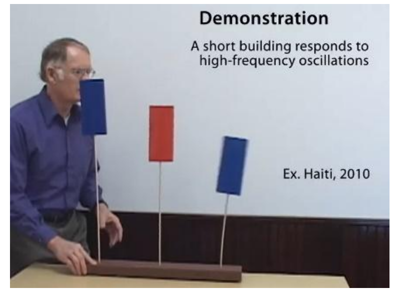



**Figure 5.c** – short building responses to high-frequency

**Figure 5.** Each Building Has Different Response to The Ground Motion According to Its Height

## 5. Examples From Real Life Collapsed Due to Resonance Phenomenon:

### 5.1 The Collapse of The Tacoma Narrows Bridge:

The Tacoma Narrows Bridge, a suspension bridge constructed over the Tacoma River in Washington, USA, was built with a length of 853 meters, making it the third longest suspension bridge in the world at the time. It opened in July 1940, but only four months after its inauguration, it collapsed due to ***mechanical resonance*** [9]

On November 7, 1940, the bridge dramatically oscillated up and down under strong winds, resulting in ***resonance*** (where the bridge’s natural frequency aligned with the wind’s oscillation frequency). This caused intense vibrations that ultimately led to the bridge's collapse, earning it the nickname “Galloping Gertie” [10,11]

Ten years after the Tacoma Narrows Bridge collapsed, a new bridge was constructed on the original foundations and opened on October 14, 1950. This new design incorporated wind-resistant features, including reinforced main columns to account for aerodynamic effects [11]

**Figure 6.** The Tacoma Narrows Bridge 1940 [11]

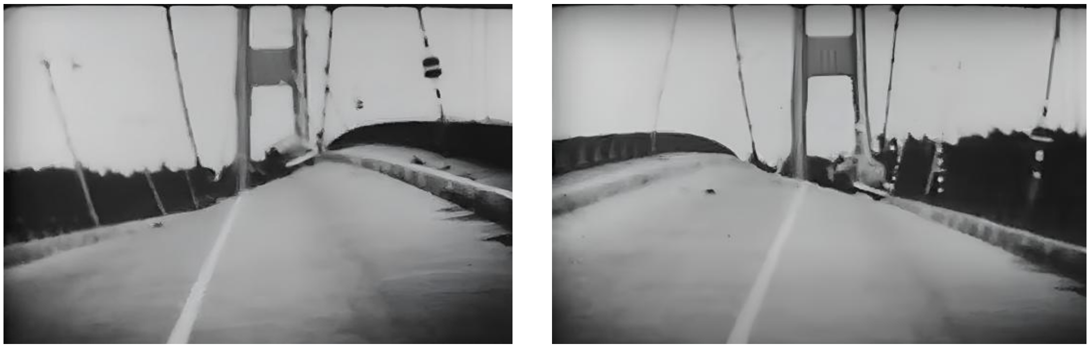


**Figure 7.a** – The bridge's movement up and down

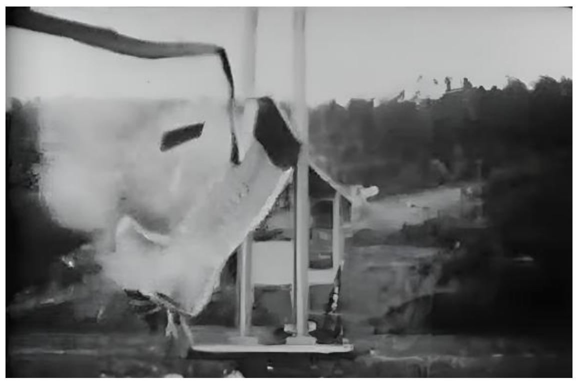


**Figure 7.b** – Collapse of the bridge due to ***resonance***

**Figure 7.** The Tacoma Narrows Bridge's Movement Up and Down During High Winds Causing the ***Resonance Phenomenon*** Until Collapse [10]

### 5.2 1985 Mexico City earthquake:

On September 19, 1985, a powerful earthquake of magnitude 8.0 struck Mexico City, resulting in significant casualties and structural damage. Buildings between 5 to 15 floors high were the most severely affected. ***The resonance phenomenon*** occurred because the earthquake's frequency closely matched the natural frequencies of these buildings, causing them to sway violently and leading to partial or total collapse in many cases [12, 13].

**Figure 8.** An Eight-Story Structure Collapsed on Sept. 19, 1985, Mexico City Earthquake [12]

**Figure 9.** Relief Workers Outside the Urbana Suarez Apartment Complex, Which Completely Collapsed on Sept. 19, 1985, Mexico City Earthquake [12]

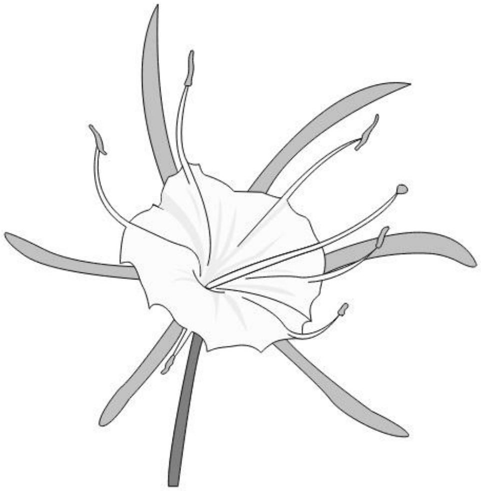
## 6. Case Study: Burj Khalifa – Structural Design for Seismic and Wind Resistance:

The Burj Khalifa, located in Dubai, stands as the tallest building in the world, with a height of 828 meters. Due to its immense height and unique location, it was essential for the building to be designed to withstand not only wind forces but also seismic forces, given the region's vulnerability to potential earthquakes.

**Figure 10.** Burj Khalifa

### 6.1 Architectural Design:

The architectural design draws inspiration for Burj Khalifa from the Hymenocallis flower, with three 'petals' arranged in a modern and innovative Y-shaped plan – See Figure 11. This configuration enhances both the aesthetic appeal and structural balance of the tower.



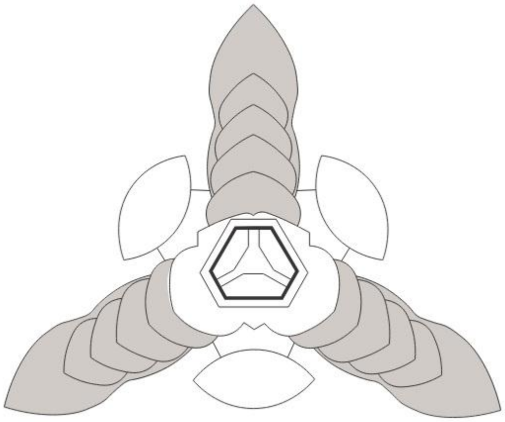


**Figure 11.a** – Hymenocallis Flower **Figure 11.b** – Y Shape of Burj Khalifa

**Figure 11.** Architectural Design of Burj Khalifa [14]

**6.2 Structural Design:**

The Mega Structure System, also known as the Buttressed Core System, plays a pivotal role in the design of the Burj Khalifa. This system relies on three structural wings, or "mot-shapes," that extend outward from a strong central core. These wings not only enhance the architectural appeal but also contribute to the building's structural stability.

The Y-shaped plan of the tower is both aesthetically striking and highly functional. It ensures a balanced distribution of loads onto the foundation, minimizing the impact of lateral forces such as wind and seismic activities. The Buttressed Core System integrates the three wings, which converge at the central core to provide additional resistance against external forces.

Furthermore, the design incorporates gradual setbacks as the tower rises, reducing the floor area progressively to decrease the dynamic effects of wind loads. This tapering design enhances the aerodynamic performance of the structure while maintaining its stability. Figure 12 shows the plan for the floors from 7 to 18 and from 64 to 75 to illustrate the gradual setbacks of the tower.

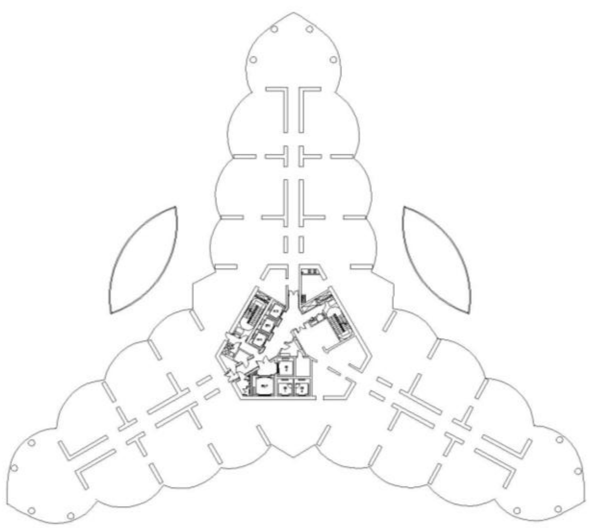


**Figure 12.a** – Levels 7-18 **Figure 12.b** – Levels 64-75

**Figure 12.** Plan of Burj Khalifa for The Gradual Setbacks of The Tower.

The system also ensures load path efficiency, with the structural wings channelling forces directly into the central core. This mechanism significantly improves the tower's capacity to withstand both gravity and lateral forces, ensuring its resilience at extreme heights.

Seismic resonance, which occurs when the natural frequency of a structure aligns with the frequency of seismic waves, is a critical factor in the design of high-rise buildings like Burj Khalifa. The tower's natural frequency is carefully designed to avoid resonance with the typical seismic frequencies in the region. In addition, the building's foundation is supported by deep piles, ensuring stability during seismic shaking and reducing the risk of settlement.

**The seismic and wind resistance techniques for Burj Khalifa can be summarized as follow:**

- **Seismic Resistance:**
  1. Core and Outrigger System: The structural design integrates a central core and outrigger walls, enhancing overall stability and resistance to seismic forces.
  2. High-Performance Concrete: The structure incorporates special concrete mixtures to increase stiffness and energy absorption during earthquakes.
  3. Mass Distribution: Strategic placement of mass helps in balancing forces and reducing the impact of vibrations.
  4. Tuned Damping Systems: Advanced damping techniques were integrated to absorb and dissipate seismic energy.

- **Wind Resistance:**
  1. Y-Shaped Design: The unique shape minimizes wind vortex shedding by breaking up airflow around the structure.
  2. Gradual Setback Design: The tapering design reduces wind force intensity as the height increases.
  3. Aerodynamic Shaping: The building's smooth curves and asymmetrical layout help divert wind forces effectively.
  4. Wind Tunnel Testing: Extensive simulations and testing were conducted to optimize resistance and ensure stability under high wind loads.

In conclusion, the Burj Khalifa exemplifies the integration of advanced engineering principles, including resonance control, damping systems, and innovative structural solutions, to achieve resilience against seismic forces and wind-induced stresses. This study highlights the critical role of vibration and resonance control in ensuring the safety and stability of skyscrapers in earthquake-prone regions.

## 7. Conclusion:

This review highlights key insights about the natural frequency of buildings and the resonance phenomenon. The following points summarize the main findings:

1. Natural Frequency as a Key Factor:

   The natural frequency is a critical indicator of a building's flexibility or rigidity and plays a significant role in the design of tall structures.

2. Definition of Tall Buildings:

   A building is classified as tall or high-rise if its aspect ratio (height to the smallest lateral dimension) exceeds 5:1.

3. Impact of Earthquake Frequency on Building Height:

   According to the BOSS model, high-frequency earthquakes primarily affect low-rise buildings, while low-frequency earthquakes have a greater impact on tall structures.

4. Resonance and Building Response:

   When the natural frequency of a building matches the frequency of ground motion, the building will experience the largest possible displacement and may suffer significant structural damage. This phenomenon is known as resonance.

5. Historical Example of Resonance Effect:

   The collapse of the Tacoma Narrows Bridge in 1940 is a notable example of structural failure due to resonance effects.

6. Mexico City Earthquake (1985):

   During the 1985 Mexico City earthquake, which measured 8.0 on the Richter scale, buildings with 5 to 15 floors suffered the most damage. This was due to harmonic resonance caused by their natural frequencies aligning with the earthquake's shock waves.

7. Burj Khalifa's Seismic and Wind Resistance:

   The case study of the Burj Khalifa provides a real-world example of how advanced engineering design can mitigate the risks posed by both seismic and wind forces.

   - Seismic Resistance: The Burj Khalifa's structural design effectively integrates a Buttressed Core System, enhancing the building's ability to resist seismic forces. This system ensures that seismic forces are distributed efficiently, reducing the potential for resonance with typical seismic frequencies in the region.

- Wind Resistance: The building's Y-shaped design, gradual setbacks, and aerodynamic shaping significantly reduce wind load effects, enhancing the tower's stability even in extreme wind conditions.
- These design strategies ensure that the Burj Khalifa not only stands as the tallest building in the world but also serves as an exemplary model for resilience against both seismic and wind forces in modern high-rise architecture.

## 8. Recommendations for Future Research:

1. <u>Study of Modern Seismic Isolation Technologies:</u>

   Future research could focus on the impact of advanced technologies such as smart materials or active isolation systems in reducing the effects of earthquakes on structures.
2. <u>Expanding Studies to Different Types of Buildings:</u>

   Future research can look into the effect of seismic isolation on different types of structures, such as residential, cultural, or ancient buildings.
3. <u>Impact of Environmental and Climatic Factors:</u>

   Research could examine how environmental changes, such as temperature and humidity, influence the properties and effectiveness of seismic isolation materials.
4. <u>Digital Seismic Simulation Models:</u>

   Researchers could develop advanced simulation techniques to better model seismic events and their impact on various types of buildings.
5. <u>Effects of Earthquakes on Historic Structures:</u>

   Further work can focus on the effects of earthquakes on ancient monuments and the development of preservation methods to protect cultural heritage.
6. <u>Seismic Isolation and Building Sustainability:</u>

   Research could explore how seismic isolation contributes to the long-term sustainability of buildings, reducing maintenance costs and enhancing their longevity.
7. <u>Experimental Validation of Computational Models:</u>

   Practical experiments on different seismic isolation systems could be conducted to validate and improve computational models, providing real-world data for more accurate predictions.

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- **Conflict of Interest**

There is no conflict of interest.

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