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# Modal analysis and harmonic response analysis of the Petronas Twin Towers

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**Abstract.** The Petronas Twin was once the tallest building in the world and the tallest twin tower nowadays. We are interested in the twin tower's structural performance. In this regard, a simplified geometric model of the Petronas Twin Towers has been developed, and the structural performance has been simulated using the finite element analysis software, Ansys. The analysis primarily focuses on investigating the behavior of the towers when subjected to wind loads, and other external factors that may affect the structural integrity of the buildings. We were especially interested in building's performance when a damper is not existed or when it is small. The modal and harmonic response analyses are used to observe the response of the Twin Towers at different frequencies. The mesh independence study is also conducted for the accuracy of the results.

**Keywords:** harmonic response analysis, modal analysis, ANSYS model, mesh independence study.

## 1. Introduction

The Petronas Twin Towers in Kuala Lumpur, Malaysia, are the world's tallest twin buildings. They were designed by Argentine-American architect César Pelli and completed in 1996 after a seven-year project. The two towers have 88 floors and a height of 451.9 meters [1]. The towers are built with high-strength concrete with varying strengths up to 80 mPa [2]. The strength of concrete used to build the towers decreases as the tower goes up. One outstanding feature of the Petronas Twin Towers is the skybridge. The skybridge spans 58.4 meters and connects the two towers on the 41st and 42nd floors. Rotational pins are situated on the top of the arch crown, which helps the crown rise and fall when the towers fluctuate. In addition, each tower has a 74 m steel spire [1]. Because of the soil conditions, the foundation of this building is a 4.42 m thick grade 60 concrete pad, and each building's concrete pad is supported by 85 concrete friction piles, some of which are 121.8 m deep [3].

Previous studies on the Petronas Twin Towers focus mainly on the analysis of the structural parts of the tower and the materials used to construct the tower and its foundation. However, the response of the towers to loads at different frequencies is rarely studied. This paper studies the modal and harmonic responses of the Petronas Twin Towers at different frequencies, which provide an insight into the tower's response to various environmental situations it is exposed to in Malaysia.

## *2.* Method

### *2.1. Settings*

The average annual wind speed in the Kuala Lumpur area is 1.8 m/s, and the optimistic design wind speed is 35 m/s [4]. Steel's material characteristics cannot meet the comfort and safety requirements in the area. In the end, the engineers selected reinforced concrete as the main material of the tower, which met the comfort design requirements with its large mass and high rigidity. It can also dampen the tower's sway in strong wind weather and minimize its vibration. Another reason is that importing steel will increase costs because Malaysia does not produce structural steel. Therefore, the reinforced concrete structure for the Twin Towers is the most suitable for the existing conditions.

On the other hand, Malaysia is not in an earthquake zone, so the tower is mainly designed for wind resistance. Therefore, it is wider at the bottom and narrower at the top. The top of the tower is the damper of the twin towers, which can control the counterweight object to move in the opposite direction through spring and hydraulic device in strong wind weather or earthquake, thereby reducing the vibration of the building. The formula for the damping ratio is

$$\xi : \frac{C}{Ccr} \tag{1}$$

Where $Ccr$ is the critical damping coefficient, and c is the damping coefficient. The system is critically damped when $C = Ccr$, over-critically damped when, $C > Ccr$ and under-critically damped when $C < Ccr$ [5].

Generally, buildings use about 0.15 for shock absorption and 0.15 to 0.3 for seismic isolation. In the Petronas Twin Towers, the damping ratio varies according to wind speed or earthquake frequency but is between 0.01 and 0.02. This research will analyze the tower's conditions when the damping ratio is 0, 0.01, and 0.02.

In the study of the Twin Towers, we used modal analysis and harmonic response analysis.

First, we need to understand the principles of kinetic analysis. Dynamic behavior can be used to analyze the vibration and natural frequencies of the structure when designing the building structure. The principal equation of kinetics is

$$F(t) = Mx^{''} + Cx^{'} + Kx \tag{2}$$

where $F$ is the force vector, $M$ the mass matrix, $C$ the damping matrix, $K$ the stiffness matrix, $x''$ the acceleration vector, and $x'$ the velocity vector [6]. Since our dynamic model needs to account for the structure's inertia, the building material's parameters are critical. The model must refer to the architectural drawings and define indispensable parameters such as the exact density, Young's modulus, and Poisson's ratio of the material.

### *2.2. Boundary conditions*

In the analysis of the Petronas twin towers, since the towers were in contact with the ground, the tower was subjected to the boundary conditions at the bottom of the model.

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### *2.3. Mesh independence study*

To ensure the accuracy of our result, the study also conducted a mesh independence study to test the results' dependence on mesh density. By changing the mesh size, the relationship between the number of nodes and the fundamental frequency is as Figure 1 shown:

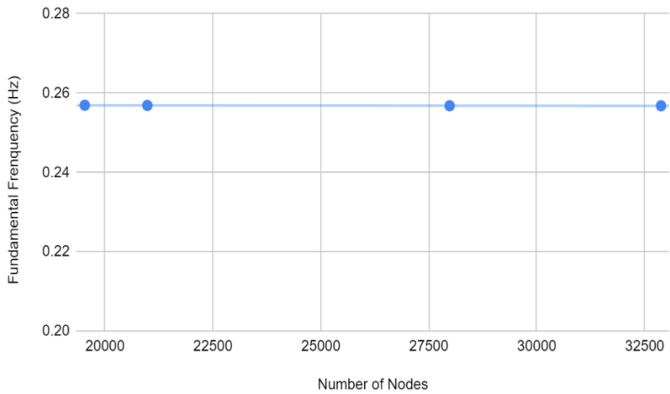


**Figure 1.** Mesh independence study.

Since there is no major discrepancy in the result, the mesh independence study shows that the result is independent of mesh density.

### *2.4. Modal analysis*

Modal analysis is a major way to analyze structures that vibrate and resonate at natural frequencies. Engineers can thus recognize how the structure responds to different types of situations. The topics we study include the response of the twin towers with and without dampers, so we will use the equation of motion:

$$Mx'' + Kx = 0 \tag{3}$$

The free vibration of the structure is the simple harmonic vibration, which is the sine function [7]

$$x = x\sin * (\omega t) \tag{4}$$

In our model, we adopted three types of reinforced concrete as our main material for the tower and the foundation and construction steel at the top of the tower as the damper. The tower uses stronger concrete material at the bottom and less dense concrete at the top. According to our research [8, 9], the material properties are as Table 1 shown:

**Table 1.** Material properties.

| | Grade 40 Concrete | Grade 60 Concrete | Grade 80 Concrete | Structural Steel |
|---|---|---|---|---|
| Density (kg/m$^3$) | 2300 | 2804.2 | 2957.2 | 7850 |
| Young's Modulus (MPa) | 35200 | 39100 | 42244 | 200000 |
| Poisson Ratio | 0.18 | 0.13 | 0.1 | 0.3 |

### *2.5. Harmonic responses*

This study also performed a harmonic response analysis of the model to confirm the steady-state effects of the structure under sinusoidal loads of known frequency and magnitude. Harmonic response analysis is a time domain analysis, so it only calculates the steady-state forced vibration of the structure and does not consider the transient vibration at the onset of excitation [10].

In our experimental model, we use swept frequency analysis to analyze the structure's response to harmonic loads of different frequencies and amplitudes to analyze at what frequencies the structure will resonate.

The load for the harmonic response is a sinusoidal equation that varies with time. Considering the most frequent natural conditions in Malaysia, typhoons. The area of with load factor is shown in Figure

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2 and Table 2. The following equation converted the wind speed to the pressure used on the side of the building.

$$P = \frac{F}{A} \tag{5}$$

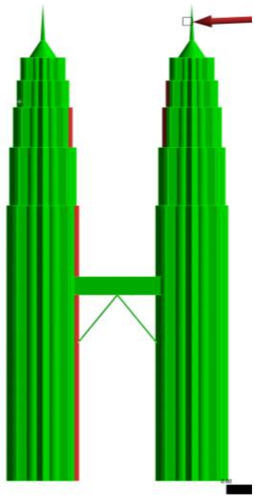


**Figure 2.** Visual image of surface area of towers.

**Table 2.** Surface area of towers façade.

| Entity | Surface Area ($m^2$) | Centroid X (m) | Centroid Y(m) | Centroid Z (m) |
|---|---|---|---|---|
| Face 1 | 704.16 | -19.658 | 394.81 | 94.283 |
| Face 2 | 126.35 | -5.6851 | 378.3 | 88.495 |
| Face 3 | 95.469 | -7.533 | 378.3 | 84.431 |
| Face 4 | 126.35 | -13.87 | 378.3 | 80.31 |
| Face 5 | 95.469 | -18.051 | 378.3 | 78.743 |
| Face 6 | 130.29 | -5.533 | 355.5 | 82.806 |
| Face 7 | 95.469 | -3.3805 | 355.5 | 87.541 |
| Face 8 | 130.29 | -1.5547 | 355.5 | 92.41 |
| Face 9 | 130.29 | -1.5547 | 355.5 | 96.155 |
| Face 10 | 172.41 | -3.3805 | 355.5 | 101.03 |
| Face 11 | 126.35 | -5.6851 | 378.3 | 100.07 |
| Face 12 | 95.469 | -7.533 | 378.3 | 104.13 |
| Face 13 | 126.35 | -13.87 | 378.3 | 108.26 |
| Face 14 | 95.469 | -18.051 | 378.3 | 109.82 |
| 104 Faces Summary | 61737 | -4.6161 | 189.75 | 36.564 |

Our Ansys model uses frequency, amplitude, and phase angle to describe harmonic loads. As a result, our setting for the harmonic response is as follows in Table 3:

**Table 3.** Harmonic response analysis settings.

| Modal Environment | Modal |
|---|---|
| Frequency Range Minimum | 0.1 Hz |
| Frequency Range Maximum | 1.7 Hz |
| Cluster Number | 20 |
| Damping Ratio | 0.0 / 0.01 / 0.02 |
| Pressure Magnitude | 735 Pa |

## 3. Results and discussion:

### 3.1. Modal analysis result

The result for natural frequency acting on the Twin Tower is as Table 4 shown:

**Table 4.** Frequencies and corresponding maximum normalized deformation and displacement.

| Mode# | Frequency (Hz) | Maximum normalized deformation (m) | Type of displacement |
|---|---|---|---|
| 1 | 0.25680 | 5.1971e-5 | x-direction displacement, z-axis torsion |
| 2 | 0.31777 | 5.2416e-5 | z-direction displacement, x-axis torsion |
| 3 | 0.36427 | 5.764e-5 | y-axis torsion, z-axis non-sway |
| 4 | 0.65195 | 8.3051e-5 | x-axis Sway, y-direction displacement |
| 5 | 1.2379 | 0.00014622 | z -axis sway |
| 6 | 1.2442 | 0.00013222 | x-axis sway |

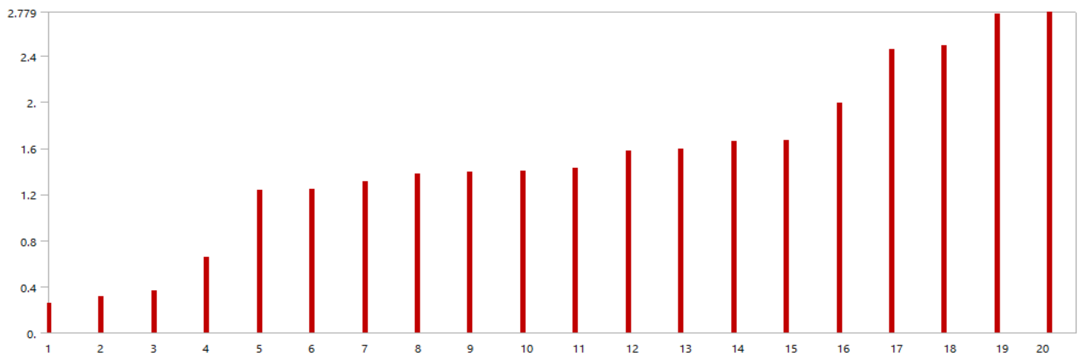
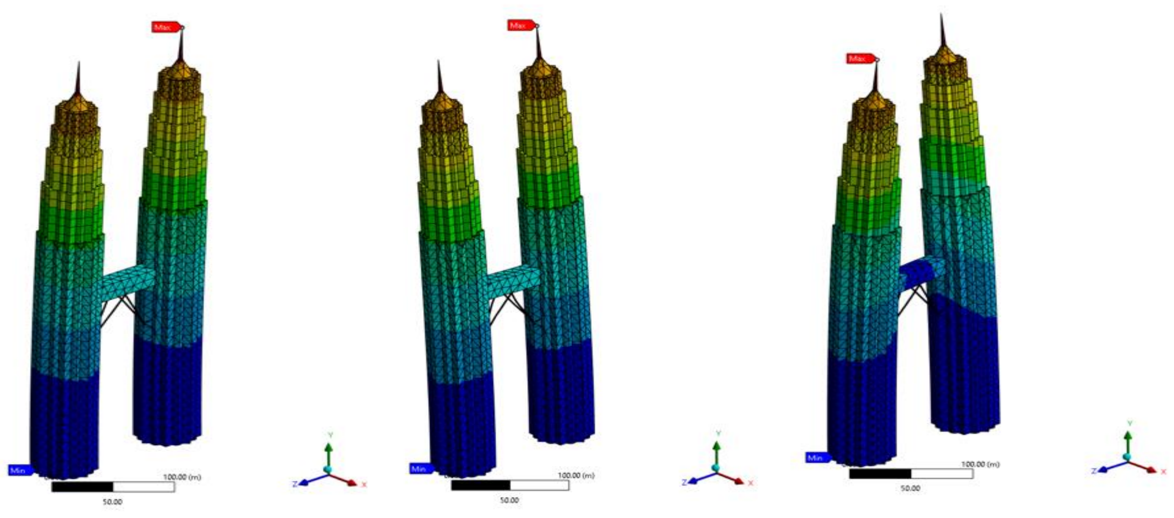
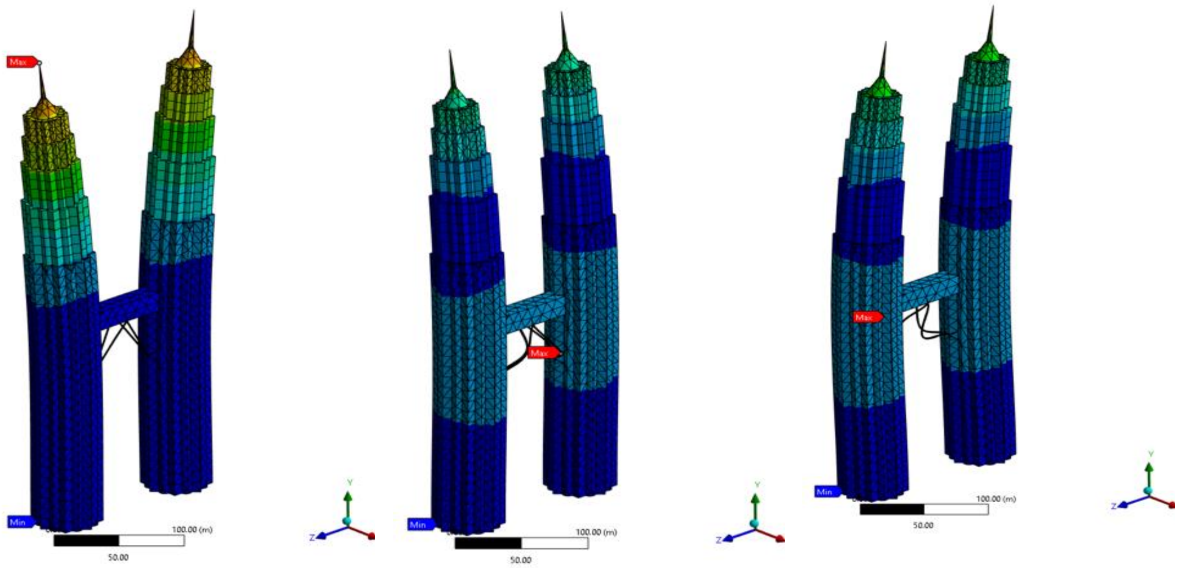



**Figure 3.** Mode number vs. frequency (Hz).



(a) (b) (c)

**Figure 4.** Mode 1 & 2 & 3 shapes, respectively.



(d) (e) (f)

**Figure 5.** Mode 4 & 5 & 6 shapes, respectively.

The modal analysis shown from Figure 3-5 indicates the deformation at various frequencies and its maximum normalized displacement. Shape graphs show where the maximum normalized displacement occurred and an idea of their deformation at a specific frequency.

### *3.2. Harmonic response result*

The analysis simulates the twin towers' situations under three different damping ratios. We expect resonance may lead to large peak harmonic responses around natural frequencies at zero damping ratio.

Result for frequency responses is shown in Table 5:

**Table 5.** Frequency response results.

| | 0.0 damping ratio | 0.01 damping ratio | 0.02 damping ratio |
|---|---|---|---|
| Maximum Amplitude | 61.607 m | 0.15402 m | 7.7021e-002 m |
| Frequency | 0.25679 Hz | 0.25677 Hz | 0.2567 Hz |
| Phase Angle | 180° | 90.577° | 91.153 ° |

Phase Response is shown in Table 6:

**Table 6.** Phase response results.

| | 0.0 damping ratio | 0.01 damping ratio | 0.02 damping ratio |
|---|---|---|---|
| Amplitude | 35.272 m | 0.15402 m | 7.7006e-002 m |
| Phase Angle | 180° | 90.577° | 90.007 ° |

Amplitude output is the largest at the calculated frequencies and corresponding phase angles.

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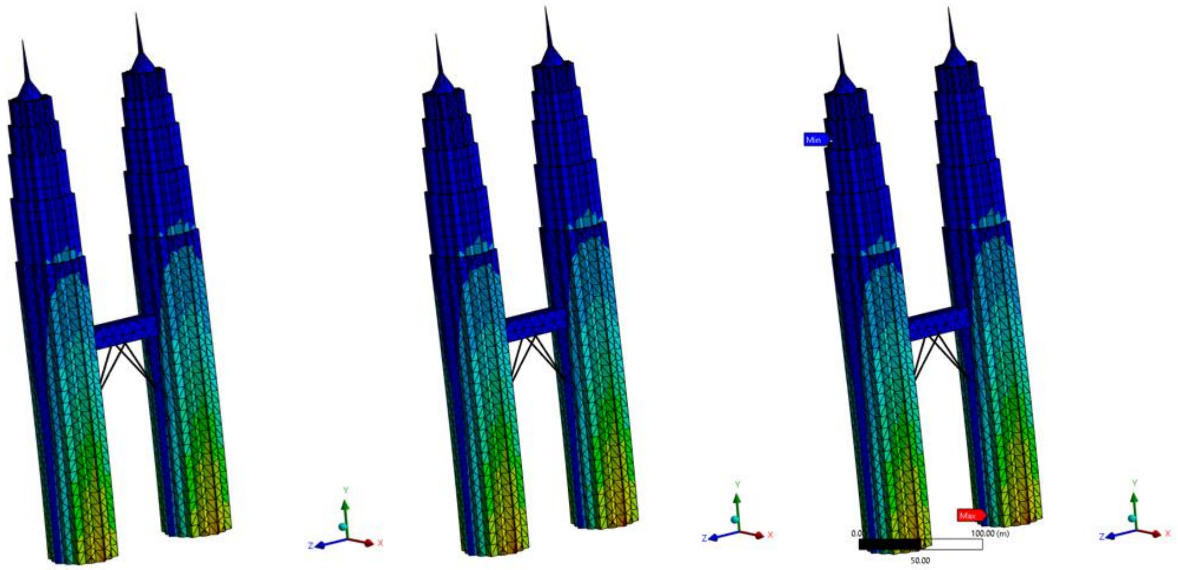


**Figure 6.** Equivalent stress at 0.00 & at 0.01 & 0.02 damping ratio, respectively.

Result for equivalent stress is shown in Table 7:

**Table 7.** Equivalent stress results.

| | 0.0 damping ratio | 0.01 damping ratio | 0.02 damping ratio |
|---|---|---|---|
| Minimum | 6.6374e+005 Pa | 2491. Pa | 1255.5 Pa |
| Maximum | 3.4461e+009 Pa | 1.2931e+007 Pa | 6.4671e+006 Pa |
| Average | 5.5503e+008 Pa | 2.0827e+006 Pa | 1.0416e+006 Pa |

Damping ratio plays a significant role in harmonic responses, there is nearly a 200% difference between 0.00 damping ratio and 0.01 damping ratio. Larger the amplitude, the larger the energy. Therefore, dampers are vital to the tower's safety and comfort.

The diagrams and Figure 6 also show the deformation of the twin towers under equivalent stress. The tower experiences more stress at the bottom of the towers, where the engineer should reinforce the concrete and strengthen the material.

## 4. Conclusion

The Petronas Twin Towers in Kuala Lumpur, Malaysia was subjected to modal analysis and harmonic response analysis to assess their structural stability and response to external stimuli. Six natural frequencies were used for modal analysis, ranging from 0.25680 Hz to 1.2442 Hz, to determine the towers' maximum normalized deformation and displacement. The harmonic response analysis was performed at a pressure amplitude of 735Pa, with damping ratios of 0.0, 0.01, and 0.02, to evaluate the building's frequency and phase response. The simulation results shown the *large deviation in deflection with different damping ratio*. Dampers play a critical role in reducing the amplitude of vibrations experienced by buildings during dynamic events, such as wind or earthquakes. Without dampers, buildings are *more susceptible to structural damage or failure* due to the effects of these loads. The installation of dampers in tall and complex structures has become increasingly common to ensure structural integrity and safety during extreme events. Results in our report showed the *significance of dampers in ensuring the safety and stability of tall buildings subjected to dynamic loads*.

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