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Finite Element Modeling of the Elizabeth Tower & Steinway Tower

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Abstract. Buildings constructed of stone typically last a very long time. However, modern buildings are no longer constructed of stone but of concrete, implying an "advancement" in construction. In fact, the inherent vibration resistance of stone challenges assumptions about the superiority of modern materials, so we conducted this research aiming to understand the oscillations of ancient towers compared to modern skyscrapers. ANSYS will be used to analyze the natural oscillation frequency and harmonic response of the constructed models similar to the Elizabeth Tower and the Steinway Tower.

Keywords: ANSYS, Modal Analysis, Harmonic Response, Elizabeth Tower, Steinway Tower

1. Introduction

London's Elizabeth Tower, commonly known as "Big Ben", was completed in 1859 and rises approximately 96 meters from a square base of just under 12 meters per side. Its masonry shell consists of about 2,600 m^3 of brick under roughly 850 m^3 of limestone, with a roughly 30-meter cast-iron roof and clock frame that supports the 13.7-ton bell [1]. At the opposite extreme of height and form lies New York's Steinway Tower (111 West 57th Street), which reached its final profile in 2021–2022. The slender residential tower soars approximately 435 meters from a footprint that narrows to about 60 feet (roughly 18 meters), giving it a height-to-width ratio of nearly 24:1. Its structure comprises a reinforced-concrete core with perimeter steel, and it incorporates an 800-ton tuned mass damper to reduce wind-induced sway [2-4].

Previous studies have generally focused on historic masonry structures using ambient vibration monitoring and finite-element model updating to understand how temperature effects, cracking, or aging influence dynamic behavior under gravity and wind loads, while investigations of super-slender towers have concentrated on wind-tunnel testing, aerodynamic optimization, and tuned mass damper performance to control drift and acceleration. Yet few researchers have applied a unified finite-element framework to compare a heritage clock tower built of brick and stone with a modern pencil tower. This study responds to that gap by undertaking a side-by-side finite element

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comparison of Elizabeth Tower and Steinway Tower built under the same assumptions, varying stiffness, mass distribution, and damping, to explore how differences in materials and wind environments affect their displacements, stresses, and vibration response.

2. Methodology

2.1. Settings

Since New York and London are not cities that experience devastating earthquakes (New York's greatest earthquake in history was of magnitude 5 in 1884 [5]; London's greatest was of magnitude 6.1 in 1931 [6]), our analysis did not take into account earthquakes. We perform modal analysis and harmonic response on the Elizabeth Tower and the Steinway Tower to analyze the wind factor and the building structure.

The maximum wind speed in London was recorded in 2022 by Storm Eunice [7] at 122mph, and the maximum wind speed in New York occurred in 1954 at a speed of 113mph [8]. We used these data to calculate the wind load on our model, respectively, 1.706×10^6 N for the Elizabeth Tower, and 1.427×10^7 N for Steinway Tower. We investigated the building's response to high wind load conditions to understand the effects of wind on modern and ancient buildings.

Concerning the damping of the buildings, Elizabeth Tower is not designed with a damper. Although the clock weighs a lot, it is not designed to alleviate the oscillation of the building. On the contrary, the Steinway Tower has an 800-ton damper in its antenna as a feature of a modern building. The damper moves in the opposite direction to counteract the oscillation of the building.

The core of our analysis is the equation of a mass-spring-damper system:

$$F(t) = Mx'' + Cx' + Kx. \tag{1}$$

Here in equation 1, F represents the force vector; M is the mass matrix; C is the damping ratio; and K is the stiffness matrix. We construct models of the buildings to simulate this equation using ANSYS.

2.2. Model

2.2.1. The Elizabeth Tower

We constructed a 3D model similar to the Elizabeth Tower in SolidWorks. Since there is no blueprint of the building available online, we used images [9] [10] of the tower and calculated the dimensions of each component of the tower (see Appendix A, Fig.10). The weight of the building is also estimated to be 8500 tons, based on the volume of limestone given, the density of limestone, and the weight of the clock. Our calculation of estimated weight divided by model volume results in an average density of 2634kg/m^3, within the density range of limestone. We applied Young's modulus of 50GPa and Poisson's ratio of 0.25 for limestone on the entire model.

2.2.2. The Steinway Tower

We constructed a 3D model similar to the Steinway Tower in SolidWorks using information from its constructor, SHoP [11]. However, no information is given about the interior volume or weight. Thus,

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we estimated the weight to be 93500 tons. The density we used is an average density of 790.9kg/m^3 calculated by estimated weight divided by model volume. We applied Young's modulus of concrete at 45 GPa and Poisson's Ratio of 0.22.

2.3. Modal analysis

Modal analysis provides insights into a structure's natural oscillation frequency and behavior.

The equation

$$F(t) = Mx'' + Cx' + Kx. \tag{1}$$

can be written as

$$Mx'' = -Kx. \tag{2}$$

when not considering damping or external force. Thus, equation 2 represents a simple harmonic motion, of which

$$T = 2\pi\sqrt{\frac{m}{k}}[12] \tag{3}$$

for one node. The maximum displacement provided by modal analysis is meaningless because displacement is an integrated value of velocity, and lacks information for a definite integral. Thus, the structure's oscillation frequency is our result for this analysis. Previous research concluded a curve fit of

$$f = \frac{46}{L}[13] \tag{4}$$

We can compare our results to better understand the behavior of ancient buildings compared to modern ones.

2.4. Harmonic response

A harmonic response analysis studies the structure's response to sinusoidal loads on one surface. The intention is to imitate the wind load upon the Elizabeth Tower and the Steinway Tower. This analysis produces maximum amplitude of sway in response to different frequencies of the sinusoidal loads, which typically takes place when the sinusoidal load frequency matches the building's natural frequency. We will conduct an analysis under a 0 damping ratio for both towers to compare the oscillation amplitude. Then, we analyze the effect of the damping ratio on the Steinway Tower by comparing results between 0, 0.01, 0.02 damping ratios.

3. Results

3.1. Modal analysis result

The result for natural frequency acting on the Elizabeth Tower is as shown:

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Table 1. Frequencies and corresponding maximum normalized deformation and displacement of the Elizabeth Tower

Mode #	Frequency(Hz)	Maximum normalized deformation ($\times 10^{-4}$ m)	Type of displacement
1	1.5849	9.0635	x-axis sway
2	1.5850	8.0565	x-direction displacement, z-axis torsion
3	5.5035	7.0494	x-direction displacement, z-axis torsion
4	5.5046	5.0353	x-axis sway
5	7.4677	4.0282	x-direction displacement, z-axis torsion
6	8.8687	3.0212	x-axis sway, y-direction displacement, z-axis torsion

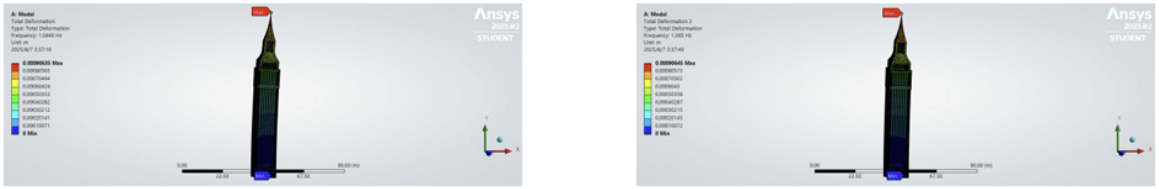


Figure 1. Modal maximum deformation of the Elizabeth Tower for Modes 1&2

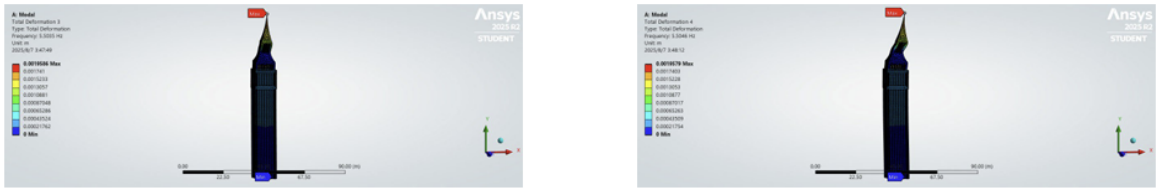


Figure 2. Modal maximum deformation of the Elizabeth Tower for Modes 3&4

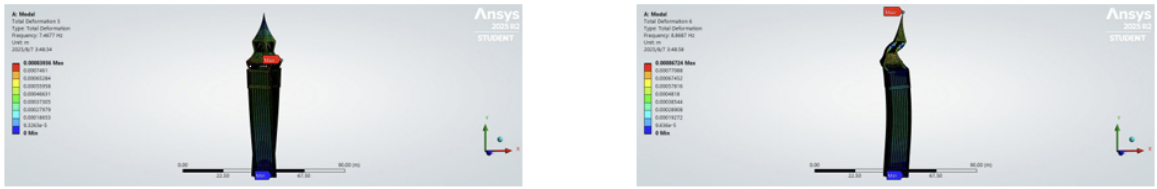


Figure 3. Modal maximum deformation of the Elizabeth Tower for Modes 5&6

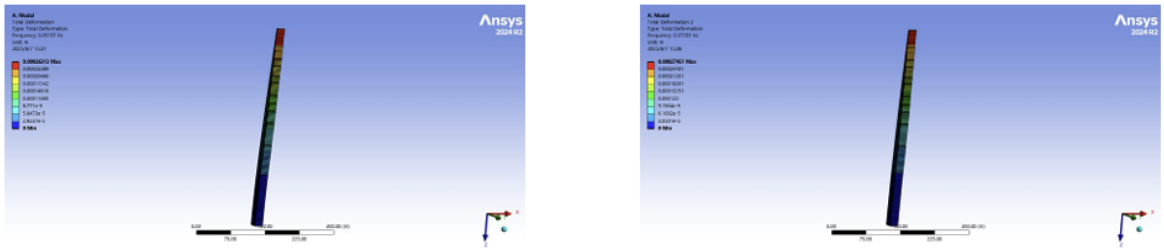


Figure 4. Modal maximum deformation of the Steinway Tower for Modes 1&2

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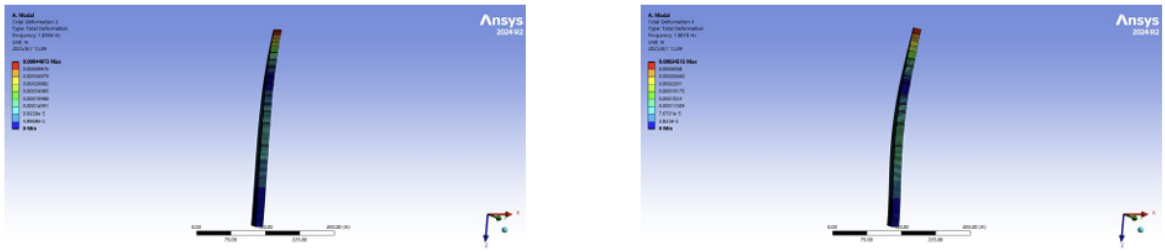


Figure 5. Modal maximum deformation of the Steinway Tower for Modes 3&4

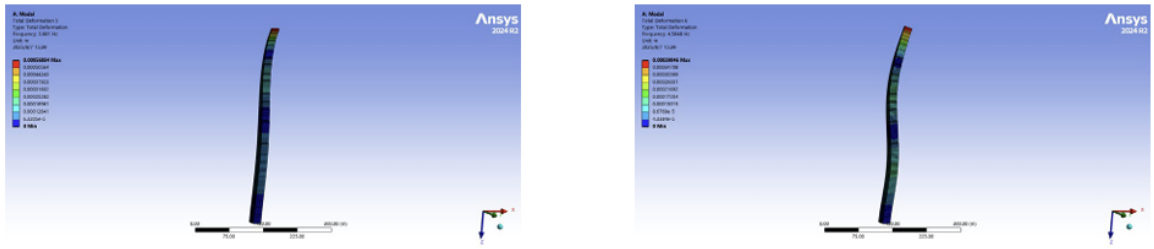


Figure 6. Modal maximum deformation of the Steinway Tower for Modes 5&6

The modal analysis shown in Figure 1-6 indicates the deformation at its maximum normalized displacement for different modes. The figures also provide a visualization of how the model deforms.

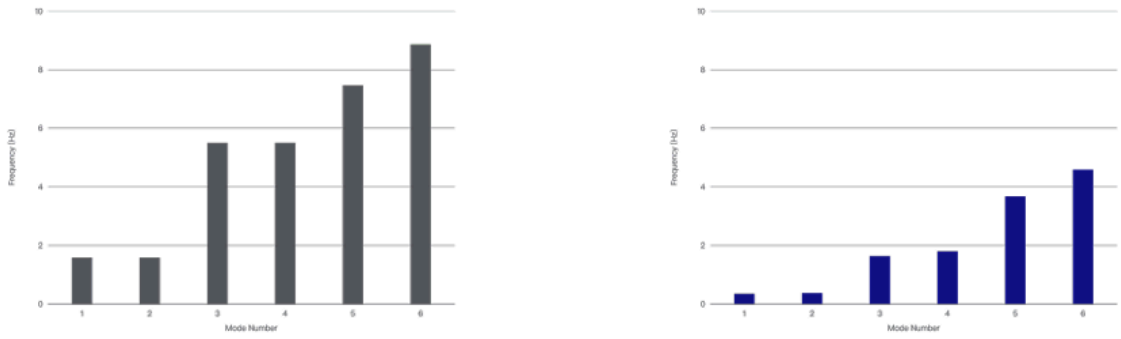


Figure 7. Comparison of natural frequencies (Hz) for modes 1–6 of Elizabeth Tower (left) and Steinway Tower (right)

The Elizabeth Tower has a wider frequency range (up to 8.869Hz) than the Steinway Tower (up to 4.5846Hz). Their frequencies are similar in modes 1&2 and modes 3&4. However, for the Steinway Tower, mode 6 shows a notably higher frequency than mode 5. Figure 7 presents a bar graph of these frequency changes.

3.2. Harmonic response analysis at 0 damping ratio for both towers

The Elizabeth Tower's amplitude spikes sharply to a peak (max displacement: 5.92×10^{-5} m) at 5.6Hz. The Steinway Tower hits a max displacement of 0.4779m around 0.3Hz, then decays. For phase angle, the Elizabeth Tower stays stable initially but shifts in the high-frequency band (near

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6Hz). The Steinway Tower's phase angle changes at low frequency (0.3Hz) and then stabilizes. Figure 8 visualizes these dynamic response differences.

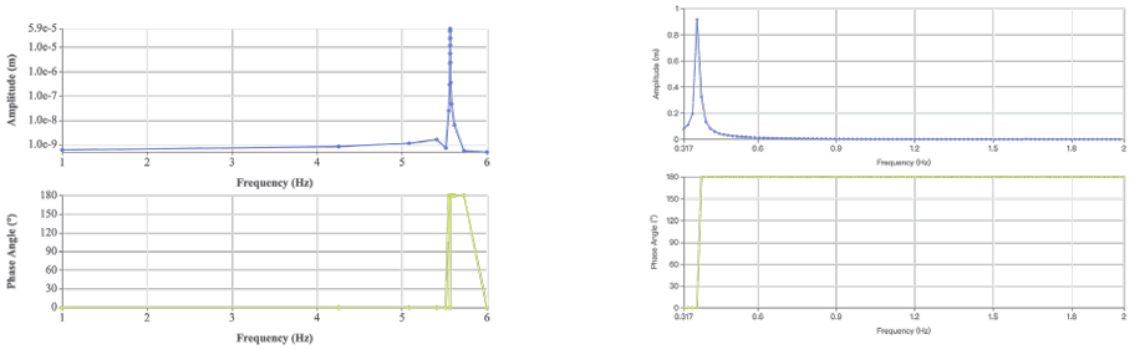


Figure 8. Comparison of amplitude–frequency graph and phase-angle–frequency graph of Elizabeth Tower (left) and Steinway Tower (right)

3.3. Harmonic response analysis at 0, 0.01, and 0.02 damping ratios for the Steinway Tower

Figure 9 compares the Steinway Tower's harmonic response across damping ratios 0, 0.01, and 0.02.

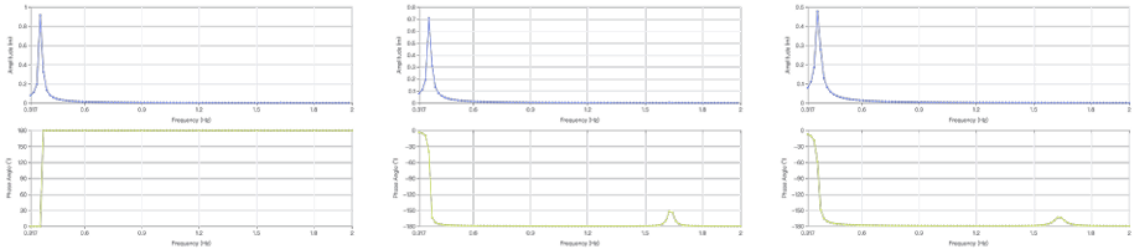


Figure 9. Amplitude–frequency and phase-angle–frequency graph for Elizabeth Tower at damping ratios 0, 0.01, 0.02.

For amplitude, ratio 0 has a sharp initial peak and an extra 1.5Hz peak with uneven decay; 0.01 lowers peaks (max 0.70994) and suppresses the extra peak for more uniform decay; 0.02 further cuts max amplitude to 0.4779, strongly suppressing peaks while keeping curve shape similar. For phase angle, ratio 0 jumps rapidly at 0.3Hz then stabilizes at a high value; 0.01 brings an earlier, gentler jump and lower stable angle; 0.02 accelerates the low-frequency jump and slightly lowers the stable angle, stabilizing sooner. As damping rises from 0 to 0.02, peaks shrink, extra oscillations are suppressed, decay smooths, phase jumps adjust, and structural vibration calms, with higher damping improving harmonic behavior to restrict vibration more effectively.

4. Conclusion

Elizabeth Tower exhibits a significantly smaller amplitude of vibration under applied forces compared to the Steinway Tower. Plus, the stone structure shows a higher frequency than other modern buildings. This is possibly due to limestone's higher stiffness compared to concrete.

The ANSYS results highlight that while modern skyscrapers like the Steinway Tower incorporate innovative technologies, some historical structures maintain exceptional lessons from traditional engineering with contemporary practices to optimize future architectural designs. A building's stability is influenced by multiple factors, including material composition, height, and design, with

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historical buildings potentially benefiting from the use of superior building materials near their site. The reason why concrete becomes a major construction material may not be relevant to better stability, but other factors such as being more convenient in transportation.

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Appendix A

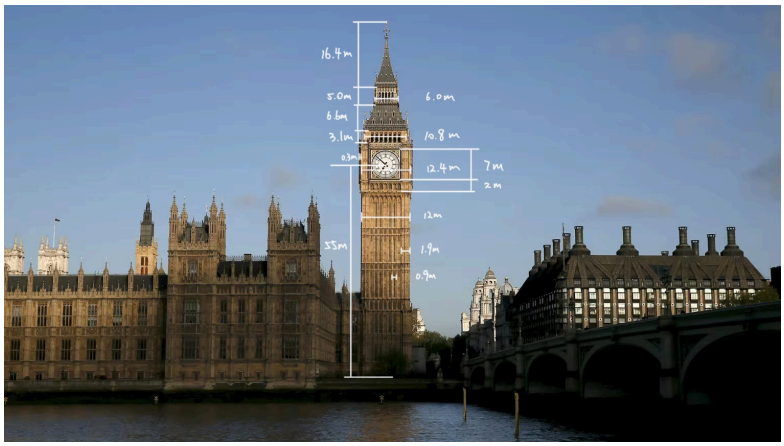


Figure 10. Reference figure used to perform height measurements