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Research Article

The Effects of Construction Techniques and Geometrical Properties on the Dynamic Behavior of Historic Timber Minarets in Sakarya, Turkey

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Sakarya City, as the host of many civilizations, has many historic monuments. The city is in the most active earthquake zone in the region. The minarets of mosques are the most important structures because they are slender. Therefore, they are sensitive to lateral loads, and earthquakes and strong winds may cause damage to these structures. The highest number of mosque minarets partly or totally collapsed in the 1999 Kocaeli and Düzce earthquakes that occurred in Turkey. The region is rich in trees, so timber has been used in the construction of different structures in Sakarya City and the vicinity for many years. In this study, five historic timber minarets in Sakarya City were experimentally and computationally examined to determine the effects of the construction techniques and geometrical properties on the dynamic behavior of the minarets. Ambient vibration tests of timber minarets were performed, and the construction techniques and geometrical features were examined; the results of these are discussed below. It was determined that the outer wall construction technique, body height, slenderness, and cross-sectional area play important roles in the dynamic behavior of timber minarets. Finally, an empirical formula was derived from the relationships for rapid estimation of the fundamental period of timber minarets.

1. Introduction

Minarets are towers that are close to or built into mosque structures and are used by the muezzin to call out the adhan to indicate that it is time to pray in Islam. The earliest mosques were built without minarets, and the muezzin performed his duty in many other locations, such as in front of or on the roof of the masjid. In Islamic architecture, the first minarets were constructed at the corners of the Mosque of ʿAmr at Fustat by Maslama, the Governor of Egypt, during the reign of Mu'awiya in 673 A.D. Over time, numerous magnificent minarets have been constructed from different materials and structural systems in various regions of the world [1].

Minarets, which were first built in a square shape, were later built in conical and cylindrical shapes. They were typically constructed using stone and brick materials, and timber was rarely used in their construction because it is less resistant to fire and water than stone and brick. As a result, the use of timber minarets is very limited [2].

Minarets built adjacent to mosques are slender structures that are sensitive to horizontal loads. Structural safety assessments of historic minarets have gained importance in the last decade because of their weakness under strong winds and intense earthquakes.

In this context, structural health monitoring is important to determine the dynamic behavior of these structures. Few investigations on the seismic and dynamic behavior of timber minarets exist in the literature, as the most commonly studied minarets are masonry and reinforced concrete minarets. Dogangun et al. [3] analyzed historic unreinforced masonry minarets that were 20, 25, and 30 m in height using two ground motions recorded during the 1999 Kocaeli and Düzce earthquakes in Turkey. A number of tests have been applied to historical masonry and reinforced concrete minarets by Bayraktar et al. [4–7]. In these studies, the enhanced frequency domain decomposition (EFDD) and stochastic subspace identification (SSI) methods have been used for the structural identification of minarets.

Şahin et al. [8] studied the dynamic characteristics of a reinforced concrete minaret through finite element analysis and field ambient vibration measurement. Digital signal processing software SignalCAD was used for analyzing raw measured data obtained from ambient vibration testing. In the dynamic characteristic identification, ModalCAD software developed in MATLAB was used. Oliveira et al. [9] performed ambient vibration tests to determine the characteristics of seven minarets with heights ranging from 23 m to 67 m in Istanbul, Turkey. Motaal [10] studied to investigate the effects of soil stiffness, pile length, diameter, and arrangement on the minaret and pile dynamic behavior. Reinforced concrete and 60 m height El-Rahman El-Raheem Mosque minaret was selected to carry out the study. The most recent study was conducted by Livaoglu et al. [11] regarding the effect of geometrical features on the dynamic behavior of seven historic masonry minarets in Bursa, Turkey. Ambient vibration tests were performed with the aim of defining the modal parameters of the minarets.

Investigations of the dynamic behavior of tall timber structures are concentrated on observation towers, multistory timber buildings, and traditional timber towers. Che et al. [12] studied the dynamic characteristics of a typical example of an ancient timber architecture structure, the Yingxian Wooden Pagoda in Western Shanxi Province, by using microtremor measurements and the finite element method. Yu et al. [13] studied the structural mechanics characteristics of ancient wooden architecture structures in China. They studied the mechanical, structural, and computational connection models, and static and dynamic tests on the structure models and on-site measurements were performed to determine the behavior of these structures. Gaile [14] aimed at identifying the performance of steel and timber lightweight observation towers that are open to the public in Latvia. The tower structure as well as its technical conditions, dynamic parameters, and dynamic response to human movement along the tower height were investigated. The main parameter that denoted the response level of the tower to human movement was the tower self-weight. Feldman et al. [15] evaluated the dynamic properties of tall timber multistory buildings and timber towers under wind-induced vibration. The factors that influenced the dynamic parameters, such as the construction type, height, and vibration amplitudes, were discussed. Zhang et al. [16] used a prediction method in the frequency domain for predicting the vibrations in the Buddhist sutra depositary at Yangzhou Zhunti Temple by using a double-confirmation analysis method based on the autospectrum.

In this study, five historic timber minarets built using different construction techniques and geometrical properties are experimentally and computationally analyzed. The minarets are located close to each other in Sakarya, Turkey. Sakarya City is located in the North Anatolian Fault Zone, which is one of the most active strike-slip faults in the world. Throughout history, many devastating earthquakes have occurred in this region. Damaging earthquakes in this region include the Sakarya-Hendek earthquake in 1943 ($M_s = 6.6$) and the Sakarya-Akyazı earthquake in 1967 ($M_s = 6.8$), as well as the Kocaeli ($M_s = 7.8$) and Düzce earthquakes in 1999 ($M_s = 7$) [17], each causing numerous deaths. Many of the historic monuments and minarets in the area were damaged or demolished as a result of these earthquakes. It is important to understand the dynamic behavior of these structures. In this study, the authors aimed to understanding the effects of the construction techniques and geometrical properties of timber minarets on their dynamic behavior and proposed an empirical formula derived from these relationships for rapid estimation of the fundamental period of timber minarets.

2. Construction Techniques and Architectural Features of Timber Minarets

The architectural styles and structural systems of Turkish minarets vary depending on the construction material and available techniques, as well as the abilities and background of workmen, among other factors. Therefore, contiguous or separate minarets have been built from stone, brick, or timber materials; they can be cubic, cylindrical, or polygonal. However, in Turkish architecture, Classical Ottoman minarets may be assumed to be the final stage of the Turkish minarets with slim, cylindrical, polygonal shafts, and conical roofs. Classical masonry minarets have the following nine segments: a foundation, pulpit, transition element, cylindrical body, balcony, upper part, spire, end ornament, and stairs. The foundation is constructed using very thick stone blocks that are firmly connected. In many instances, this segment is connected to the bearing walls of the mosque. The pulpit is the top of the bottom part of a minaret, which is typically square or, less frequently, octagonal. Minarets from the Early Ottoman period have eight-, ten-, twelve-, or sixteen-faced polygonal pulpits. Transition elements provide uninterrupted and smooth transitions between the pulpit and the cylindrical or polygonal body. Therefore, the pulpit and body shapes influence the geometric shape. Transitions between polygonal pulpits to a cylindrical body were ensured using a cut pyramid and an inverted as well as plane triangular element or various systematic Turkish triangular-shaped elements. The purpose of placing the balcony segments above the ground at definite height levels is to help project the sound of the muezzin over extended distances. Although this purpose has lost its effectiveness in recent years due to the use of loudspeakers, balconies still survive because they are aesthetically pleasing. Balcony decorations are vitally important as they contribute to the magnificence of minarets, and artisans exhibited their talents by producing these decorations. Balconies consisting of a slab and parapets behave as a cantilever. The upper part of a minaret is the segment that is located between the last balcony and the spire, which generally includes a cylindrical or polygonal body; however, different geometric properties were used during the Seljuk period.

Minaret spires are generally considered to be a roof with a timber structural system and are lead coated. Thus, the spire generally has different structural properties from those of the upper part of the minaret body. The end ornament is a metal device that is generally made of metal on top of the minaret with a symbol at the end. Stairs are one of the main structural elements of the minarets that provide a means to climb to the balcony. Different structural materials have been used, such as timber, steel, and masonry. The restraint conditions of stairs with rungs for the body of the minaret affect their performance when subjected to lateral loads [1, 2].

There are differences in the construction of masonry and timber minarets. Timber minarets have no transition segment. The outer wall designs of the cylindrical body and upper part have the same thickness and are built using the same construction techniques, unlike masonry minarets. A timber core is only used in the upper part in masonry minarets, but in timber minarets, the timber core is one piece and is continuous from the foundation to the top of the minaret. Stairs are arranged between the core and outer wall. The outer walls are constructed with different techniques. The sections of a timber minaret can be seen in Figure 1.

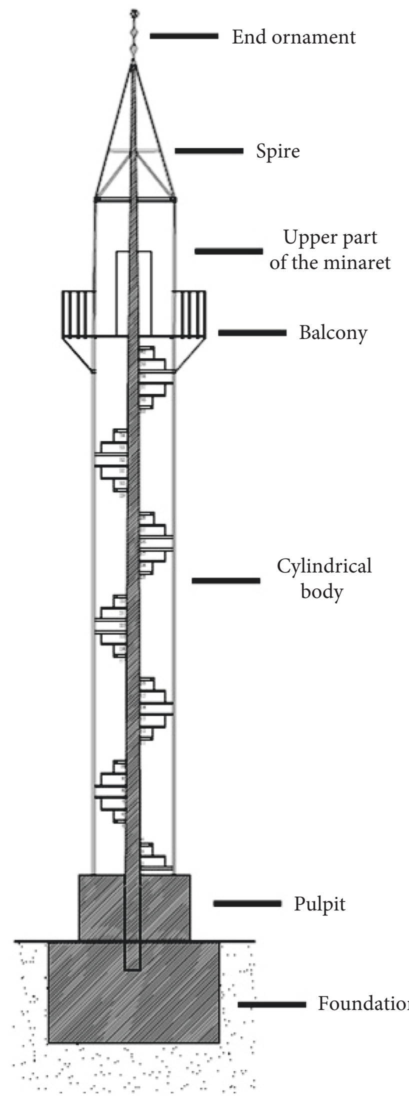


Figure 1: The sections of a timber minaret.

3. Studied Timber Minarets

The studied five timber minarets are located in Sakarya City, and they are close to each other. The investigated minarets have different geometrical properties. The height of the minarets and other geometrical properties have various dimensions. Except for the outer wall of the minarets, the other sections have similar construction techniques. The outer walls are constructed with different techniques. The most frequent usage is $8{\sim}10 \times 4{\sim}5$ cm wide columns at $10{\sim}15$ cm intervals in a circular plan and $4 \times 4{\sim}5 \times 5$ cm horizontal beams at $75{\sim}200$ cm vertical intervals between the columns; bracing elements are used with different angles and at different intervals. In the other technique, no bracing elements are used between the columns, but a 2 cm thick cladding timber material is used on the outside of the timber columns (Figure 2).

The geometric properties, construction dates, outer wall construction techniques, weights, and positions relative to mosques that are used in construction are presented in Tables 1–5.

4. Experimental and Computational Analysis of Timber Minarets

The dynamic parameters of the studied timber minarets were both experimentally and computationally investigated. The experimental study was performed in situ using sensitive sensors and a data acquisition system to determine the dynamic structural properties. In addition, laboratory and in situ ultrasonic tests were performed to find out the material properties of timber elements. After the experimental approach, the structures were analyzed using a finite element method.

4.1. Experimental Approach. The dynamic parameters, such as the fundamental frequency, mode shapes, and damping ratios of timber minarets, were investigated using nondestructive test methods. This technique is called operational modal analysis. The modal parameters were determined by the frequency-domain decomposition technique. This is often called the peak-picking technique. The relationship between the input $x(t)$ and output $y(t)$ can be written as follows [18, 19]:

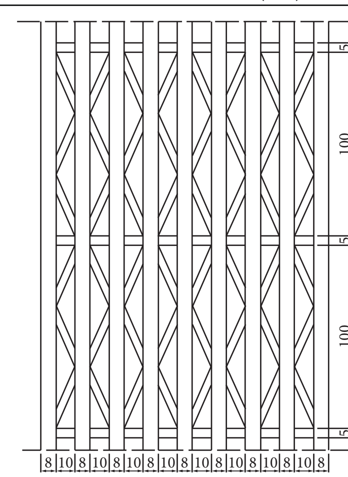
$$[Gyy(w)] = [H(w)]^* [Gxx(w)] [H(w)]^T, \tag{1}$$

where Gxx is the power spectral density (PSD) matrix of the input, Gyy is the PSD matrix of the output, H is the frequency response function (FRF) matrix, and * and ^{T} denote complex conjugations and transpositions, respectively. The Heaviside partial fraction theorem is used under the assumption that the input is random both in time and space with a zero mean white noise distribution so that its PSD is a constant matrix. Then, after mathematical manipulations, the output PSD can be reduced to a pole/residue form as follows:

Ağa Mosque Ali Kuzu Mosque Fethiye Mosque Teşvikiye Mosque Güllük Mosque

Figure 2: The studied mosque minarets.

Table 1: The geometric properties and construction techniques of the Teşvikiye Mosque minaret.

		Body	Upper body	Spire	Construction techniques and the dimensions of the circular outer wall (cm)
Teşvikiye Mosque minaret (1953)	Height (m)	7.92	2.32	2.42	
	Outer diameter (m)	1.16	1.16	—	
	Outer wall thickness (m)	0.05	0.05	—	
	Weight (kN)	8.00	2.50	2.40	
	Timber core diameter (m)	0.30	0.24 – 0.20	0.20 – 0.10	
	Location	Adjacent to the mosque			

$$[Gyy(w)] = \sum_{k=1}^{m}\left(\frac{[A_k]}{jw-\lambda k} + \frac{[A_k]^*}{jw-\lambda k^*} + \frac{[B_k]}{-jw-\lambda k} + \frac{[B_k]^*}{-jw-\lambda k^*}\right), \quad (2)$$

where A_k is the k-th residue matrix of the output PSD. The response spectral density matrix can be written in the form below, considering a lightly damped system [19]:

$$[Gyy(w)] = \sum_{k=Sub(w)}\left(\frac{dk\psi k\psi k^T}{jw-\lambda k} + \frac{dk^*\psi k^*\psi k^T}{jw-\lambda k^*}\right), \quad (3)$$

where dk is a scalar constant and ψk is the k-th mode shape vector. Thus, performing singular value decomposition of the output PSD matrix at discrete frequencies $w = w_i$, the following can be obtained:

$$\left[\widehat{G}yy(jw_i)\right] = U_i S_i U_i^H, \quad (4)$$

where matrix U_i is a unitary matrix holding the singular vector u_{ij} and S_i is a diagonal matrix holding the scalar singular values s_{ij}; the superscript ^{H} denotes complex conjugation and transposition. Near the peak corresponding to the k-th mode in the spectrum, only the k-th mode is dominant, and the PSD matrix approximates to a rank-one matrix as follows [19]:

Table 2: The geometric properties and construction techniques of the Güllük Mosque minaret.

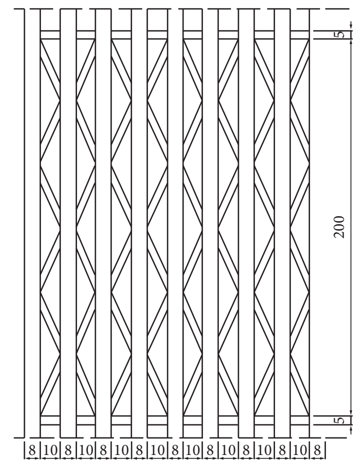
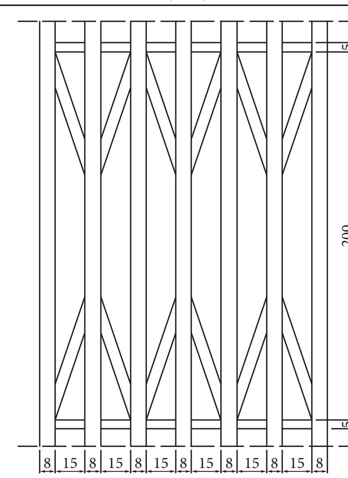
		Body	Upper body	Spire	Construction techniques and the dimensions of the circular outer wall (cm)
Güllük Mosque minaret (1966)	Height (m)	13.35	3.27	2.94	
	Outer diameter (m)	1.20	1.20	—	
	Outer wall thickness (m)	0.05	0.05	—	
	Weight (kN)	13.10	4.02	1.98	
	Timber core diameter (m)	0.30	0.24 – 0.20	0.20 – 0.10	
	Location	Adjacent to the mosque			

Table 3: The geometric properties and construction techniques of the Fethiye Mosque minaret.

		Body	Upper body	Spire	Construction techniques and the dimensions of the circular outer wall (cm)
Fethiye Mosque minaret (middle of the 20th century)	Height (m)	9.05	3.25	2.70	
	Outer diameter (m)	1.06	1.06	—	
	Outer wall thickness (m)	0.05	0.05	—	
	Weight (kN)	7.03	2.65	1.42	
	Timber core diameter (m)	0.30	0.20 – 0.16	0.16 – 0.10	
	Location	Adjacent to the mosque			

$$\widehat{G}yy(jw_i) = s_i u_{i1} u_{i1}^H, \quad w_i \longrightarrow w_k. \tag{5}$$

The first singular vector at the r-th resonance is an estimate of the r-th mode shape [19]:

$$\widehat{\phi} r = u_{r1}. \tag{6}$$

In the case of repeated modes, the PSD matrix rank is equal to the multiplicity number of the modes. The modal frequencies can be identified via the peaks of the singular value plots, while the corresponding singular vectors give the mode shapes. It is worth noting that natural frequencies and mode shapes can be estimated using such a method since the enhanced frequency-domain decomposition technique allows for the estimation of damping ratios [19].

In dynamic tests for very low noise sensors, the Sensebox 7001/02/03 series is used. This series is an ideal solution for forced vibration dynamic identification, shake-table tests, machinery health monitoring, and structural health monitoring of relatively less rigid structures. A wide selection of options exists from $a \pm 2\,\mathrm{g} - 400\,\mathrm{g}$ measurement range and 0–4000 Hz bandwidth. The Dynamic Data Acquisition/Structural Health Monitoring Device Testbox 2010 series data acquisition system has been used for applications in structural monitoring, civil engineering, earthquake engineering, and other dynamic applications [20]. Modal analysis tests were performed at the balcony of the minaret. The sensors were placed at the x (north), y (east), and z directions inside the balcony door. The sensors and their placements are shown in Figure 3.

Table 4: The geometric properties and construction techniques of the Ali Kuzu Mosque minaret.

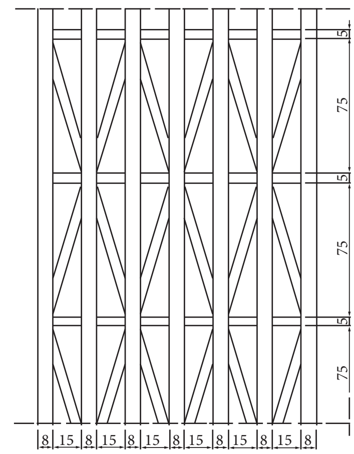
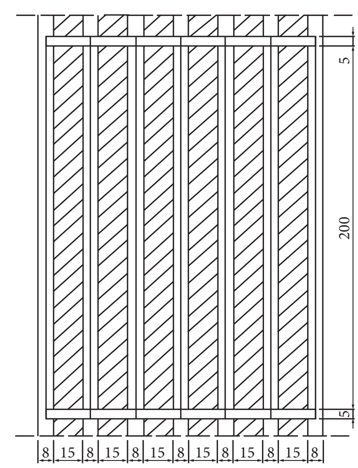
		Body	Upper body	Spire	Construction techniques and the dimensions of the circular outer wall (cm)
Ali Kuzu Mosque minaret (1955)	Height (m)	12.86	3.04	3.06	
	Outer diameter (m)	1.34	1.34	—	
	Outer wall thickness (m)	0.05	0.05	—	
	Weight (kN)	14.73	3.27	2.03	
	Timber core diameter (m)	0.30	0.22 – 0.18	0.18 – 0.10	
	Location	Adjacent to the mosque			

Table 5: The geometric properties and construction techniques of the Ağa Mosque minaret.

		Body	Upper body	Spire	Construction techniques and the dimensions of the circular outer wall (cm)
Ağa Mosque minaret (1870–restorated 2010)	Height (m)	7.68	2.62	2.66	
	Outer diameter (m)	1.46	1.46	—	
	Outer wall thickness (m)	0.05	0.05	—	
	Weight (kN)	16.04	4.20	1.91	
	Timber core diameter (m)	0.30	0.24 – 0.20	0.20 – 0.10	
	Location	Adjacent to the mosque			

The ambient vibration tests were performed under environmental forces, such as traffic and wind. The tests should be long enough to reduce the noise effects, and also, it is required for the accurate damping estimations. Therefore, the measurement durations were 30 minutes, and the frequency span was chosen as 0–100 Hz. The singular values of the spectral densities of all the test setups are shown in Figure 4.

Laboratory and in situ ultrasonic tests were performed to find out the material properties of timber elements used in the construction of the minarets. The density was measured according to the EN 384 standard [21]. Ultrasonic tests were conducted using a V-meter, with cylinder-shaped transducers. The indirect method parallel to the grain and the direct method perpendicular to the grain were used in the tests (Figure 5).

The relationship $E_{\text{din}} = u^2 . \rho$ was used in the calculations, where E_{din} represents the dynamic modulus of elasticity (N/mm^2), u is the propagation velocity of the longitudinal stress waves (m/sn), and ρ is the density of the specimens (kg/m^3) [22]. The average results are presented in Table 6.

4.2. Computational Approach. The three-dimensional finite element models of the studied five timber minarets were prepared using the SAP2000 v20 finite element analysis program [23]. They were modeled with the beam elements having six degrees of freedom at every node. The finite element model that belongs to one of the minarets investigated in this study can be seen in Figure 6.

The obtained experimental modes from in situ tests are controlled using both modal assurance criteria (MAC) table

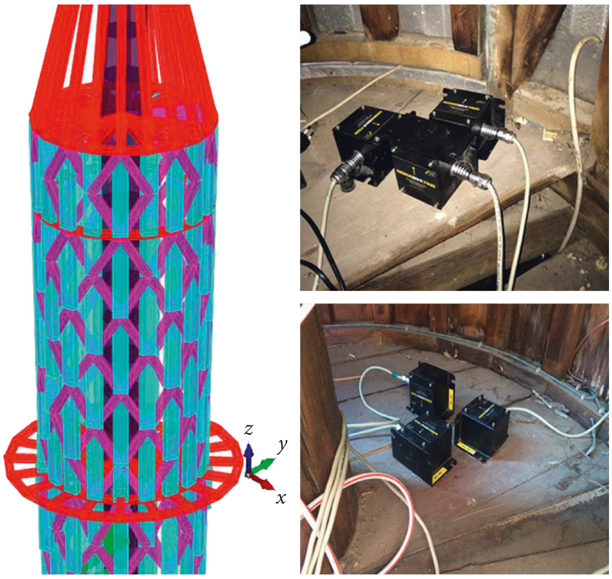


Figure 3: The sensors and their placements on the balcony floor.

and the complexity plots. The linear elastic material model was assumed for the minaret analysis because the experimental results for the in situ tests were also in the elastic range. After the finite element models were prepared, the modal analysis of the minarets was performed. The natural frequencies, mode shapes, and mass participation factors were obtained from numerical analyses. The boundary conditions were updated depending on the experimental results to represent the real behavior of the minarets. The material properties were obtained from the test results and other sources [24, 25]. The comparison of the seven modes frequencies of the studied minarets between the experimental and computational approaches is presented in Table 7. The first four modes are the bending modes, the fifth mode is the torsion mode, and the sixth and seventh modes are the bending modes. When comparing the experimental and computational results, there is a good harmony among mode shapes and natural frequencies. The errors between the results ranged up to a minimum of 1% to a maximum of 10%.

The first seven modes and frequencies of one of the studied minarets obtained from modal analysis are shown in Figure 7.

5. Discussion

5.1. Effect of Construction Techniques on Dynamic Behavior. Minaret structural systems are based on a circular plan using a timber core in the center and timber walls on the exterior. The stairs are arranged between the inner core and outer walls. The main difference in the construction of timber minarets is in the outer wall design. The builders used different design techniques. The outer walls of the studied five minarets were also constructed with different techniques, which play a role in the dynamic behavior. The main factors that affect this behavior are the stiffness-to-mass ratio and damping. The relationship between the stiffness-to-mass ratio and the frequency is determined with the classical formula $f = 1/2\pi * \sqrt{(k/m)}$, where f is the frequency and m and k are the mass and stiffness, respectively. Comparisons show that minarets with high stiffness-to-mass ratios also have higher frequencies than minarets with low stiffness-to-mass ratios. Figure 8 shows the stiffness-to-mass ratios and frequencies of the studied minarets represented by their outer walls.

The minarets of the Teşvikiye Mosque have the highest stiffness-to-mass ratio. The timber columns of the outer wall are arranged at 10 cm intervals, and the horizontal beams are arranged between the columns at 100 cm intervals. Bracing elements are continuously used throughout the minaret height. Although the only difference between the construction techniques of the Teşvikiye Mosque and Güllük Mosque minarets is the frequency of horizontal beams, the stiffness-to-mass ratio of the Teşvikiye Mosque was over 2 times than that of the minaret of the Güllük Mosque. The minaret of the Ağa Mosque had the second highest stiffness-to-mass ratio. The outer wall of the Ağa Mosque was built with timber columns arranged at 15 cm intervals with horizontal timber beams arranged every 100 cm between columns. Additionally, a 2 cm thick timber cladding material was used outside the outer walls. This cladding material increased both the stiffness and mass of the structure. The minarets of the Fethiye and Ali Kuzu Mosques had the lowest stiffness-to-mass ratios. The lack of effective usage of bracing elements and less column usage were the factors leading to the lowest stiffness-to-mass ratios.

The damping ratio also affects the dynamic behavior. The damping ratios varied between 1.2 and 2.0. The minaret of the Ağa Mosque had the highest damping ratio of 1.967. The usage of the timber cladding material and steel connections led to a high damping ratio; however, the other minarets have similar ratios.

5.2. Effect of the Geometrical Properties on Dynamic Behavior. Minarets are tall and slender structures; therefore, their geometric properties, such as height, cross-sectional area, and height/width ratio, are important regarding the dynamic minaret behavior. Minarets behave like cantilevers in which the stiffness can be calculated by the formula $k = 3EI/L^3$, where k is the stiffness, E is the modulus of elasticity, I is the moment of inertia, and L is the height. In this study, without normalization, the test results show that the highest minarets have the lowest frequencies. However, the effect of height on the frequency can be seen more clearly by eliminating the other parameters from the frequency. Various minarets have similar heights; therefore, the relationship between the height and frequency can be seen in more detail. In Figure 9, regression analysis between the height of the minarets and the normalized frequencies shows that height affects the dynamic minaret behavior.

In this study, the minaret height-to-width ratios were investigated to determine their effects on the dynamic behavior; minarets have high height-to-width ratios with low frequencies that are affected by their height and slenderness. The relationship between the normalized

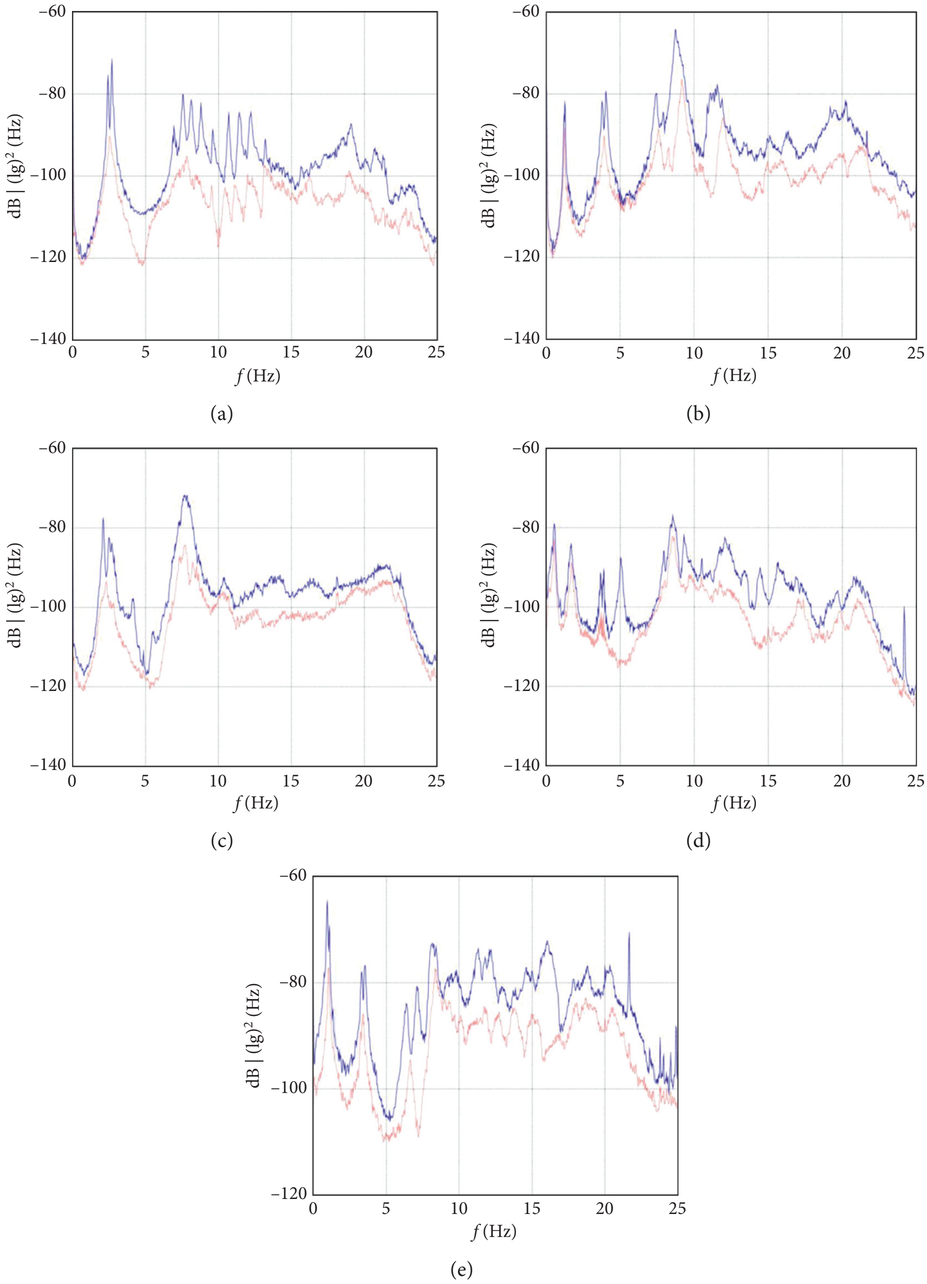


Figure 4: The singular values of the spectral densities of all of the test setups: (a) Teşvikiye Mosque minaret; (b) Güllük Mosque minaret; (c) Ağa Mosque minaret; (d) Ali Kuzu Mosque minaret; (e) Fethiye Mosque minaret.

frequencies and slenderness of the studied minarets can be seen in Figure 10.

The cross-sectional area also affects the dynamic properties. In the examined minarets, the cross-sectional area of the Ağa Mosque minaret was higher than that of the other minarets. These effects are particularly evident, and the first period percentage of mass participation was expected to be higher. Table 8 shows the mass participation factors that were obtained from the numerical analyses. It can be seen that the Ağa Mosque minaret has a 75% mass participation factor in the first mode, which is 10% higher than those of the other minarets.

6. Empirical Formula for Computing the Fundamental Frequencies of Minarets

The construction techniques and the geometrical properties were important parameters for understanding the dynamic behavior of these structures. Based on the data collected from the experimental and computational approaches, a simple formula was developed to estimate the first frequency of vibration.

The fundamental frequency of a minaret is expected to be a function of the moment of inertia, the height of the minaret, modulus of elasticity, cross-sectional area, and

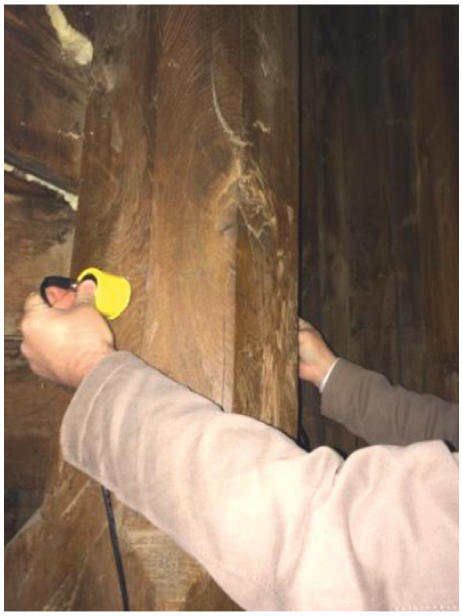


Figure 5: In situ ultrasonic test of timber core (the direct method).

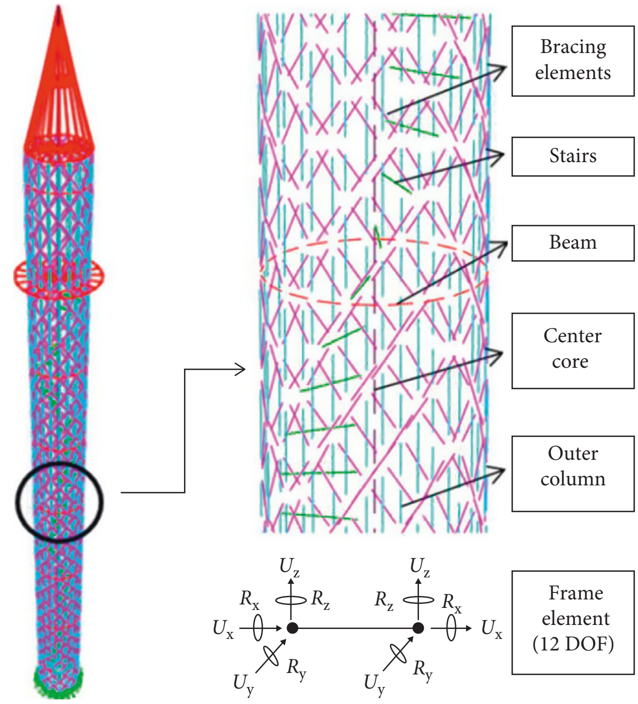


Figure 6: The finite element model and DOF system of the Güllük Mosque minaret.

Table 6: The material properties of the timber elements used in the construction of minarets.

Mosques	Modulus of elasticity (kN/m^2) Parallel to the grain Indirect method	Modulus of elasticity (kN/m^2) Perpendicular to the grain Direct method	Unit weight (kN/m^3)
Teşvikiye Mosque	3960000	520000	5.90
Güllük Mosque	4520000	530000	5.83
Fethiye Mosque	4010000	450000	5.87
Ali Kuzu Mosque	3520000	420000	5.92
Ağa Mosque	5070000	610000	6.01

density. The height of the minaret was given by the length from the top of the pulpit to the base of the spire (body + upper body in Tables 1–5); the cross-sectional area, and the moment of inertia were calculated by using the base of the body, density, and modulus of elasticity, which were given by the data collected from the experimental approaches (Table 6).

Based on the parameters obtained from the experimental and in situ measurements, a new equation was developed for determination of the fundamental frequency:

$$f = \propto \cdot H^{-3/2} \cdot \sqrt{\frac{E \cdot I}{\rho \cdot A}}, \quad (7)$$

where $\propto$ is a constant, depending on the construction techniques of the outer walls of the minarets, H is the height of the minaret (body + upper body), E is the modulus of elasticity (parallel to the grain), I is the moment of inertia, A is the cross-sectional area, and ρ is the density.

The parameter $\propto$ was calculated as 0.15 for the Teşvikiye and Güllük Mosque minarets and 0.10 for the Ali Kuzu, Ağa, and Fethiye Mosque minarets. The Teşvikiye and Güllük minarets had similar construction techniques, and the distinctive features of the outer walls were the frequent use of the outer columns and the bracing elements (Figure 2; Tables 1 and 2). On the contrary, the lesser used bracing elements can be seen in the construction of the outer walls of the Ali Kuzu and Fethiye Mosque minarets (Figure 2; Tables 3 and 4). Conversely, 2 cm thick timber was used as a cladding material in the construction of the outer walls of the Ağa Mosque minaret. It was observed that the parameter $\propto$ could be taken as 0.10, as in the Ali Kuzu and Fethiye Mosque minarets. In Figure 11, the fundamental frequencies of the minarets obtained from the experimental in situ values and Equation (7) were compared with each other. The errors ranged up to a maximum of 9%.

7. Conclusions

Minarets are sensitive structures that are under lateral forces and collapse during intense earthquakes and strong winds. There are few studies regarding the construction techniques and dynamic behavior of minarets, and many studies have concentrated on masonry minarets. Although reinforced concrete minarets are more common than masonry minarets, they also collapse frequently under lateral forces. Therefore, the use of timber in minaret construction has gained importance. In this study, five timber minarets located in Sakarya City, Turkey, were experimentally and computationally investigated to determine the effects of the construction techniques and geometric properties of the minarets on their dynamic behavior. Ambient vibration tests were conducted to determine the dynamic characteristics of the

Table 7: First seven modes frequencies (experimental approach versus computational approach).

Mode number	Teşvikiye		Güllük		Fethiye		Ali Kuzu		Ağa	
	Exp.	Comp.	Exp.	Comp.	Exp.	Comp.	Exp.	Comp.	Exp.	Comp.
1	2.42	2.46	1.27	1.18	0.93	0.96	0.72	0.78	2.10	2.15
2	2.69	2.47	1.27	1.19	1.05	1.01	0.74	0.79	2.32	2.15
3	11.40	11.64	7.15	6.50	3.22	3.93	3.71	4.09	9.59	10.35
4	12.21	11.65	7.24	6.51	3.52	3.96	3.91	4.14	9.69	10.45
5	13.70	13.75	10.30	9.52	5.20	5.02	5.08	4.50	11.96	11.52
6	22.85	21.04	15.01	14.66	8.15	8.41	8.15	7.94	12.13	12.58
7	23.07	21.21	15.02	14.70	8.42	8.45	8.42	8.26	13.10	12.60

Exp. = experimental approach; Comp. = computational approach.

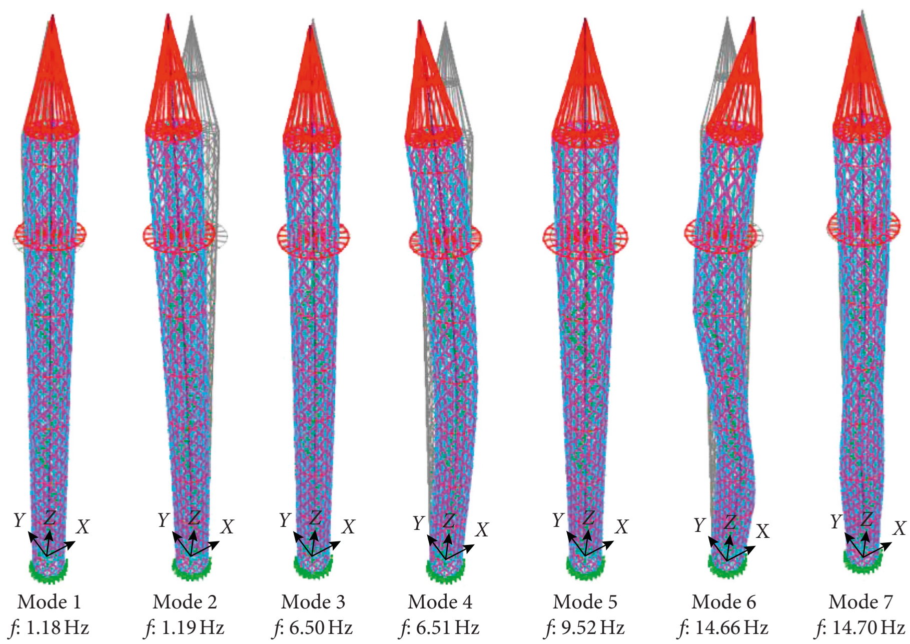


Figure 7: The first seven modes and natural frequencies of the Güllük Mosque minaret.

Table 8: The mass participation factors of the studied minarets.

Mosques	First mode		Second mode		Sum of first three modes	
	x	y	x	y	x	y
Teşvikiye Mosque	63.83	63.81	20.64	20.67	85.36	85.22
Güllük Mosque	62.68	62.65	20.48	20.51	88.58	88.56
Fethiye Mosque	69.98	69.87	14.44	14.60	89.22	89.25
Ali Kuzu Mosque	66.48	66.11	18.43	19.34	87.91	90.06
Ağa Mosque	75.07	74.78	11.93	12.22	87.30	88.20

minarets. Laboratory and in situ ultrasonic tests were performed to determine the physical and material properties. The finite element models of the studied five timber minarets were prepared and modeled with the beam elements having six degrees of freedom at every node. The obtained experimental modes from in situ tests are controlled using both modal assurance criteria (MAC) table and the complexity plots. The linear elastic material model was assumed for minaret analysis because the experimental results for the in situ tests were also in the elastic range. The boundary conditions were updated depending on the experimental results to represent the real behavior of the minarets. Using all data, an empirical formula was derived for the rapid estimation of the fundamental period of timber minarets. This formula shows that the construction technique of the outer wall is as important as the material and geometric properties of the minarets. The frequent usage of the outer columns at 10 cm intervals and bracing elements in the construction of the outer walls of the Güllük and Teşvikiye Mosques minarets resulted in higher fundamental frequencies than the others. On the contrary, in the other minarets, the usage of 15 cm outer column intervals, the usage of timber cladding material in the Ağa Mosque minaret instead of bracing elements, and less usage of bracing elements in the Ali Kuzu and Fethiye Mosque minarets are the construction differences affecting the dynamic behavior. The formula leads to an upper limit with an error of 9%.

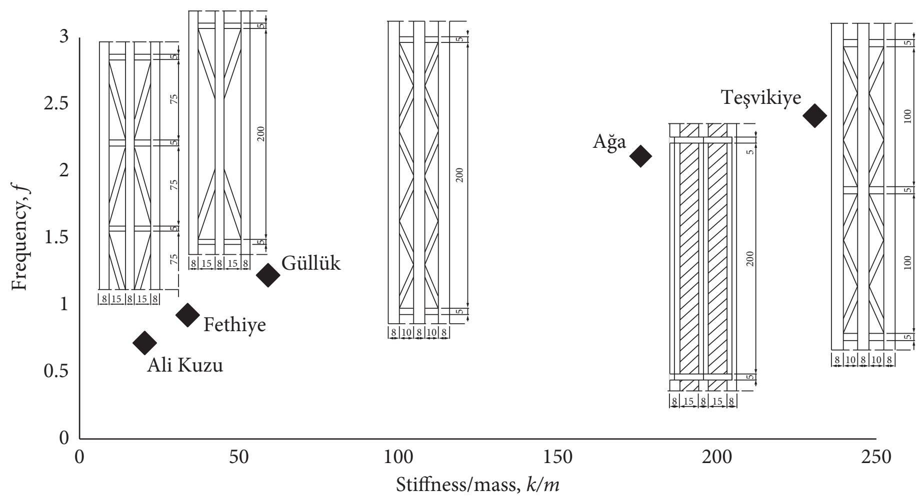


Figure 8: The relationship between the stiffness-to-mass ratios and frequencies.

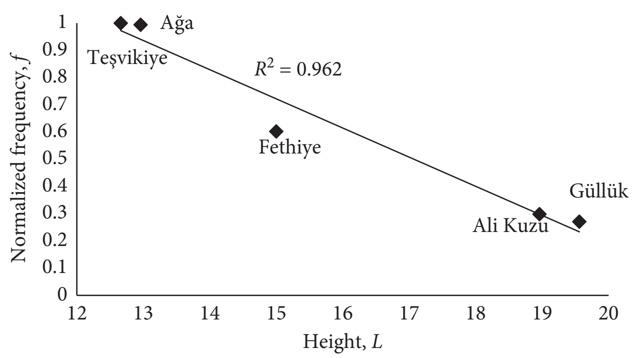


Figure 9: The relationship between the normalized frequencies and heights.

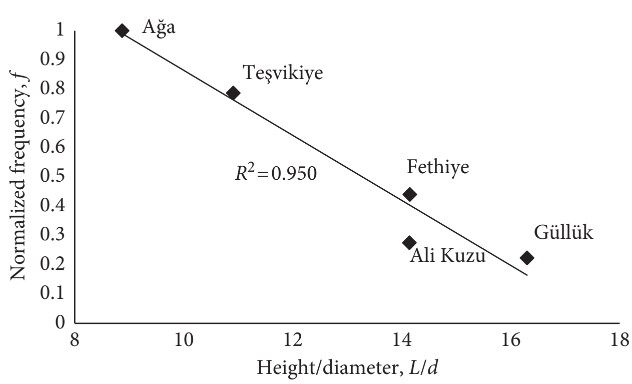


Figure 10: The relationship between the normalized frequencies and heights to diameters.

In addition, minaret height, slenderness, and minaret cross-sectional area affect the dynamic behavior of minarets. The frequent usage of horizontal beams in the outer wall construction of timber minarets increases the rigidity of the structure and affects their dynamic behavior. The usage of steel connectors provides high damping ratios.

In conclusion, the construction techniques and geometric properties of timber minarets greatly affect their dynamic behavior. Better design criteria development and

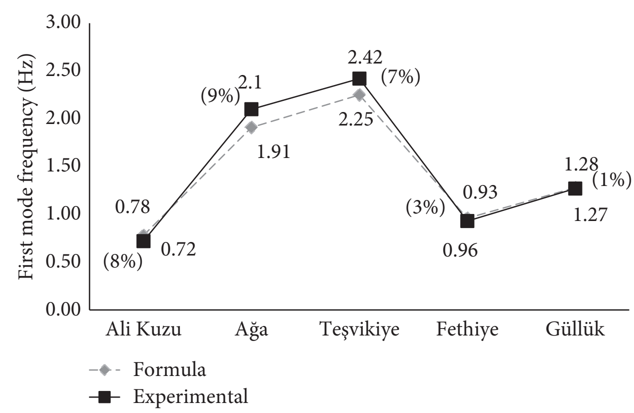


Figure 11: The fundamental frequencies (formula versus experimental results).

retrofitting guideline preparation with a different modeling under different ground motions and strong winds will help to ensure better minaret safety.

Data Availability

All data generated or analyzed during the study are included in this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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