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Dynamic Comparison of Three Major Turkic Minarets in the History of Minaret Evolution

[Yunus Dere, H. Abdullah Erdogan, M. Emin Basar]

Abstract— **Minarets are tower-like structures constructed next to mosques for the purpose of calling to prayer. The historical masonry minarets are constructed using brick or stone blocks. The structure of minarets has evolved throughout the history. Since minarets are slender and tall structures, they are vulnerable to fail under lateral dynamic effects such as earthquake and wind. It is therefore important to determine their dynamic characteristics. In this study, three major Turkic historical masonry minarets representing three different periods, namely Karakhanid, Anatolian Seljuk and Ottoman periods are studied through finite element modal analyses using Abaqus software. The natural frequencies and mode shapes of the minarets obtained from the modal analyses are compared.**

Keywords— **historical minaret, Turkic minaret, dynamic characteristics, modal analysis.**

I. Introduction

Minarets are the essential elements of Islamic architecture beside their function of calling to prayer. They have a significant place in the silhouette of cities as they have a high tower form. The first known minarets were constructed at the four corners of Fustat Amr mosque in A.D. 673 during the Amavis period in Egypt [1,2]. Many other examples of minarets appeared in Basra, Samarra and Cairo. In the early periods of minarets, they did not have a special form and constructed using stones, bricks and wood. Generally two distinct types of minarets can be mentioned. The first type has rectangular cross-section in plane, inspired by the bell towers or antique lighthouses. The second type has cylindrical body with a more delicate construction originated from Asia. This type can be called as the Turkic style minaret as they are commonly applied by Turks [3]. To some researchers, “Malviya” is the third type of minaret. This type is rare and abandoned after a couple of applications.

Turkic minarets are distinguished by their tallness and slenderness from the minarets constructed before Anatolian period and the minarets in other Islamic countries [4]. First examples of Turkic minarets are known to be built by Samanids in Middle Asia. These minarets were generally made of wood and they could not survive to date.

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The minarets constructed in Karakhanids period (A.D. 840-1212) are the oldest Turkic minarets in Middle Asia. Burana, Uzgen, Bukhara Kalyan and Vobkent minarets are among these minarets [5]. The Turkic minaret fashion having cylindrical form has originated from Middle Asia minaret convention, took its classical form during Karakhanids period [6], get sophisticated to a degree keeping its main characteristics from Karakhanids to Ottomans period [3]. During the Great Seljuks, higher and slender minarets were built compared to the Karakhanid minarets with bulky body [3]. Anatolian Seljuk minarets are more developed keeping its main form of Great Seljuks. In this period, the transition region from pulpit to the body has first appeared [4]. The minaret fashion of Anatolian Seljuks continued in the Seigniories and early Ottoman times. In the classical times of Ottoman, real improvements in the minaret design have been observed. In the Ottoman period, polygonal minaret pulpit forms are preferred. Ottomans did not prefer the common rectangular prismatic form pulpits of Anatolian Seljuks. Cylindrical and polygonal minaret bodies are commonly used and smoother transition from the pulpit to the body was applied. Anatolian Seljuks abandoned the octagonal pulpit plan used in Karakhanid, Great Seljuk and Ghaznavid minarets. Ottomans started to reuse the polygonal pulpit form. The pulpits became narrower and taller, usually higher than the rooftree of the mosque next to them. Another Ottoman convention is building minarets with three balconies and having multiple minarets for a single mosque. They used single, double and triple helical flight of stairs within a single minaret. During that period, minarets, among the most important elements of Islamic architecture, have reached their most advanced form. The classical minaret consists of these basic items: pulpit, transition segment, body, balcony, upper body of the shaft, spire and crescent shaped end ornament.

II. The Properties of Considered Minarets

Fundamental minaret examples, which are the milestones in the evolution of Turkic minaret custom are considered in this study in order to investigate their dynamic properties as well as their structural and formal improvements. The three minarets namely Bukhara Kalyan minaret, Konya Ince minaret and Edirne Selimiye minaret are chosen for this purpose. Kalyan minaret is one of the first examples of minarets constructed by Turks in the Middle Asia and belongs to Karakhanids period. Konya Ince minaret is one of the most important and advanced minarets of Anatolian Seljuk’s period. The minarets of Selimiye Mosque, which is the primary monument of the great architect Sinan were constructed in the classical Ottoman period.

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A. *Kalyan Minaret*

Kalyan Minaret is a Turkic minaret constructed with bricks on a polygonal pulpit and has a thick cylindrical body tapered toward the top (Fig. 1). It has a large diameter and a spiral staircase. The dimensions of the pulpit and the body are close to each other, therefore there is no transition region. As is common for Karakhanids minarets, it was constructed in the "baldaken" fashion where the balcony is carried by small extensions with muqarnas. After passing the top of this balcony using members with muqarnas, its top is covered with a small and dome like spire, then the minaret is completed. Upper body of the shaft does not exist in this minaret.

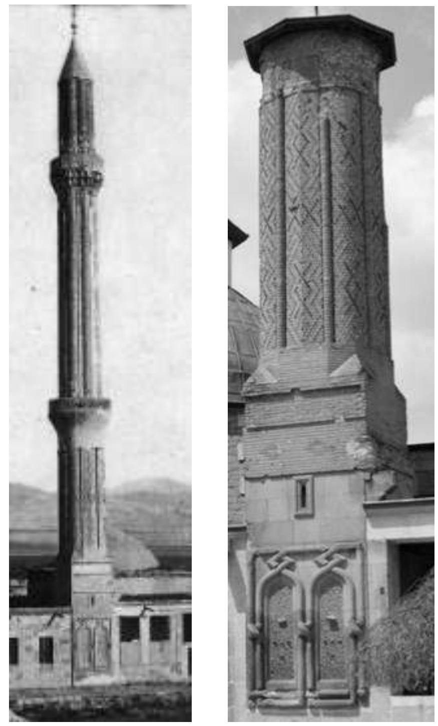
Figure 1. Kalyan minaret in Bukhara

B. *Ince Minaret*

The minaret constructed in 1264 by Anatolian Seljuks [7] has two balconies and a fairly slender minaret of its period (Fig. 2a). It was named "ince minaret" meaning "thin minaret" due to its slenderness. The minaret is made of bricks except its pulpit, which is made of stones. A short transition region, compared to its following Ottoman counterparts, is available. This minaret can be discerned from other Turkic minarets by its two balconies and the upper body of the shaft. It has the most developed form of its period. Around two-thirds of Ince minaret was collapsed by lightning in 1901. Fig. 2a shows its original form and Fig. 2b shows the present form.

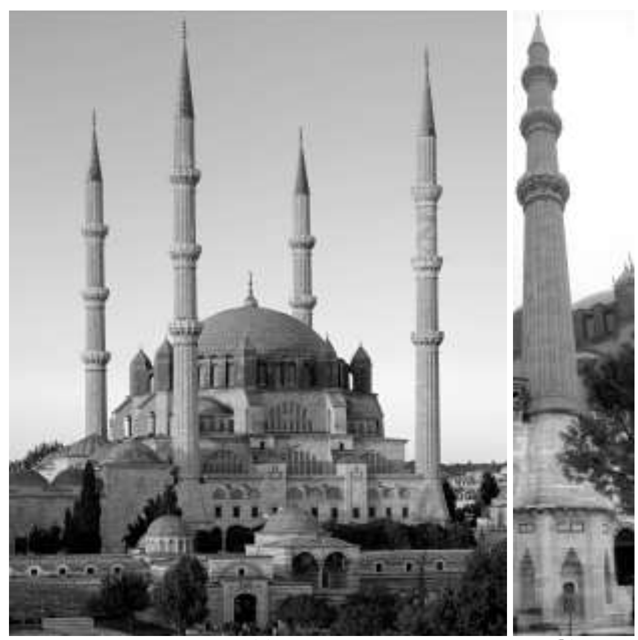
C. *Selimiye Minaret*

The minarets of Seigniories and Ottoman periods are usually constructed using stones with masonry technique. Edirne Selimiye Mosque (Fig. 3a), the most important mosque of classical Ottoman, and the master piece of architect Sinan, is one of the most significant mosques of its period. It has four minarets, two of which are constructed next to the mosque entrance. Each of these two minarets has three balconies and three stair flights [4]. Selimiye minaret (Fig. 3b) is one of the tallest stone masonry minarets in the world. It was constructed with quite advanced techniques where stones and steel ties are used together, compared to regular brick masonry construction.



(a) (b)

Figure 2. Ince minaret (a) Original form (b) Present form



(a) (b)

Figure 3. (a) Selimiye Mosque (b) A view of a single Selimiye minaret

III. Finite Element Analyses of the Minarets

Three historical minarets namely Kalyan, Ince and Selimiye Minarets, which are the best examples of their construction periods, are considered in this study. Since minarets are slender and towerlike structures, they are prone to collapse when they are subjected to severe lateral effects such as earthquakes or severe storms. Thus, understanding their dynamic behavior is very significant. Generally, static and buckling analysis of minarets under self-weight is not really interesting. In order to compare the natural frequencies and mode shapes of the minarets under consideration, they will be dynamically evaluated using modal analysis. The minarets have been modeled and analyzed using commercially available Abaqus v.13 finite element software.

A. *Modeling and Meshing*

The finite element model of minarets can be generated using solid or shell elements. In order to have a more realistic model with less geometrical assumptions, solid finite elements are preferred in this study. The geometrical dimensions and details of the minarets are extracted from the relevant literature [5,8]. The stairs within the minarets are thought to affect the dynamic behavior of the minarets, therefore they are included in the models. The 3D geometrical models of the minarets are first created in Autocad drawing software (Fig. 4). They are subsequently imported into Abaqus finite element analysis software.

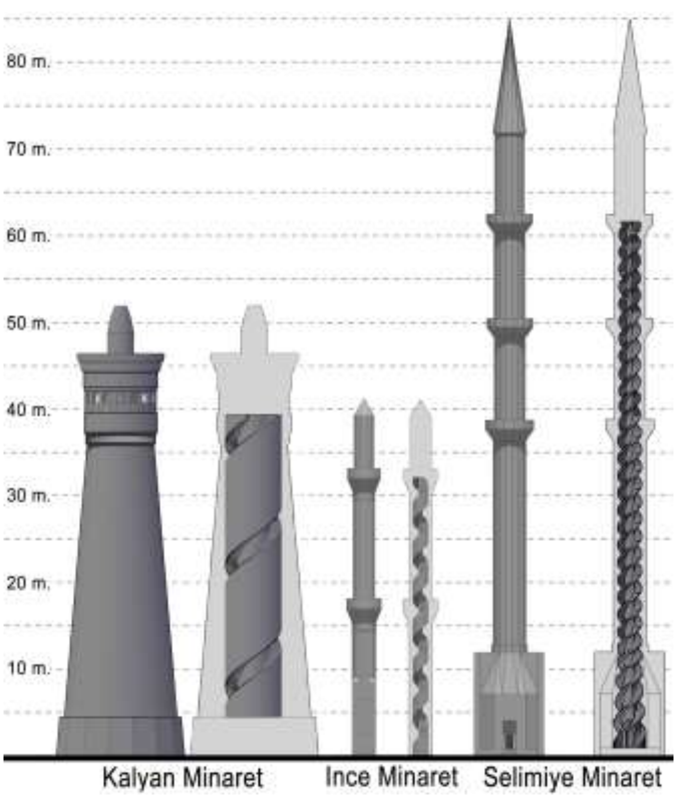


Figure 4. Minaret computer drawings

When creating a solid finite element mesh, tetrahedral and hexahedral elements with or without mid nodes (i.e. quadratic or linear) can be used. Hexahedral elements produce better results with less computation time and are therefore more preferable over tetrahedral elements. Since a hexahedral mesh is very difficult and time consuming to generate in the case of complex minaret shapes, especially when the stairs are included in the mesh, the minarets are modeled using tetrahedral finite elements. Quadratic tetrahedral elements (named C3D10 in Abaqus) are more suitable for modal analyses; therefore 10-node tetrahedral elements are used in the meshes. The number of nodes and elements used in the minarets are presented in Table I. The generated finite element meshes of the minarets are shown in Fig. 5. The interaction of the minaret pulpits with the adjacent mosque is disregarded and the bottom mesh nodes are fixed to the ground.

TABLE I. FINITE ELEMENT MESH PROPERTIES OF THE MINARETS

Minaret	Number of Nodes	Number of Elements
Kalyan	165440	110394
Ince	173412	112592
Selimiye	341958	218599

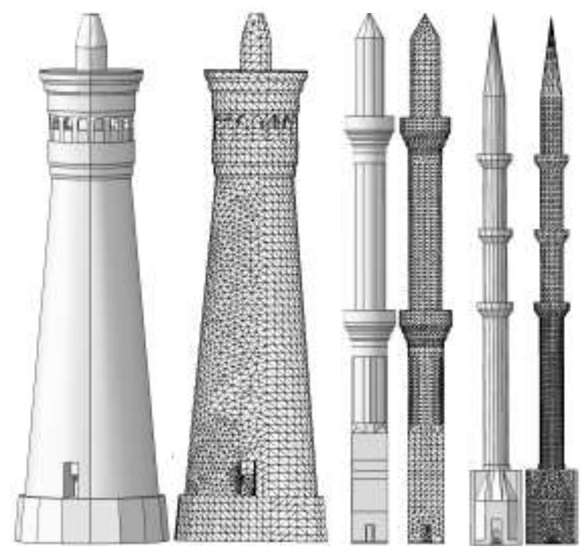


Figure 5. Minaret finite element meshes (not to scale): Kalyan, Ince and Selimiye Minarets (left to right)

B. *Material Properties*

A realistic material model has significant effect on the stiffness, and in turn, on the dynamic behavior of the minarets. The masonry walls of historical minarets are usually composed of bricks or stones and binding mortar. If the stresses in these materials under service loads are less than their allowable values throughout the analysis, linear elastic material assumption is believed to produce acceptable results, as in this study.

As masonry construction material, bricks in Kalyan Minaret and stones in Selimiye Minaret are used. Ince Minaret contains both brick and stone masonry. The lower part (up to 6.3m above ground) of the pulpit is made of stone masonry and the rest is made of brick masonry. Masonry is basically composed of units (bricks, stone blocks, etc.) and mortar having different material properties. During the construction of the computer models, it is hard to model mortar joints. In order to achieve a similar behavior of the real masonry structure assuming homogenous material, different methods for homogenization of masonry are suggested. Masonry can be modeled as anisotropic [9] or isotropic homogenous material [10]. In this work, brick and stone masonry are assumed to be isotropic homogenous material. The mechanical properties of the bricks, stones and mortar used in the minarets of this study are hard to determine without experimental tests. Some laboratory tests on historical bricks collected near Konya are carried out to determine the compressive strength and specific weight. The average compressive strength of bricks is obtained as 9.18MPa. The modulus of elasticity is calculated using the simple formula supplied for masonry bricks in [11]. Hence, the elasticity modulus is calculated as 1.836GPa. The average unit weight of the samples is calculated as 12.9kN/m^3. Kalyan Minaret is assumed to have the same brick material properties as those of Ince Minaret. The stone properties are assumed based on the reference [12]. Thus, the modulus of elasticity and unit weight of stones are assumed to be 7.360GPa and 25kN/m^3, respectively. Poisson ratios of both materials are assumed to be 0.2.

C. *Modal Analysis*

Natural periods of vibrations and mode shapes are quite important dynamic characteristics, which indicate how the minarets will respond to dynamic loads. If the natural frequency of the minaret is close to the frequency of vibration caused by the external dynamic effect such as an earthquake or wind, the amplitude of the minaret oscillation will get greater causing the minaret to be in the state of resonance. Since the minarets are generally light and tall structures with low bending resistance, they make large displacements under lateral loads. In the case of dynamic resonance, they can easily collapse. The natural frequencies and periods as well as mode shapes of the minarets are determined through modal analysis. In general, minaret bodies have symmetrical cross sections with circular or polygonal shapes. Therefore, their consecutive modal frequencies in orthogonal axes are quite the same. However, the shape of the pulpit may cause differences in the frequencies in orthogonal axes. Considering damping in the modal analysis may produce lower natural frequency from one mode to the other, but this effect can be neglected for damping ratios less than 20% which is valid for most structures [13].

The natural frequencies and periods obtained from the modal analyses are presented in Table II. The displaced mode shapes of the minarets for the 1st, 3rd, 5th, 6th and 7th modes are shown in Figs. 6-8 where 2nd and 4th mode shapes are omitted due to orthogonality mentioned earlier.

TABLE II. MODAL ANALYSIS RESULTS

	Selimiye Minaret		**Ince Minaret**		**Kalyan Minaret**	
Mode	***F (Hz)***	***T (sec)***	***F (Hz)***	***T (sec)***	***F (Hz)***	***T (sec)***
1	0.291	3.439	0.508	1.970	1.228	0.814
2	0.294	3.398	0.509	1.964	1.243	0.805
3	1.618	0.618	2.457	0.407	4.158	0.241
4	1.645	0.608	2.472	0.405	4.176	0.239
5	4.237	0.236	5.721	0.175	5.628	0.178
6	4.343	0.230	5.755	0.174	7.764	0.129
7	4.434	0.226	5.789	0.173	8.757	0.114
8	6.802	0.147	9.374	0.107	8.823	0.113
9	7.301	0.137	9.750	0.103	9.919	0.101
10	7.601	0.132	9.829	0.102	14.12	0.071

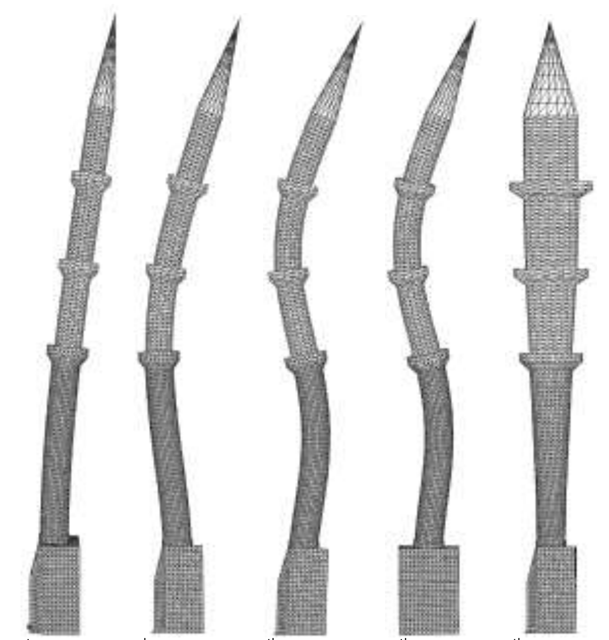


Figure 6. The mode shapes of Selimiye minaret

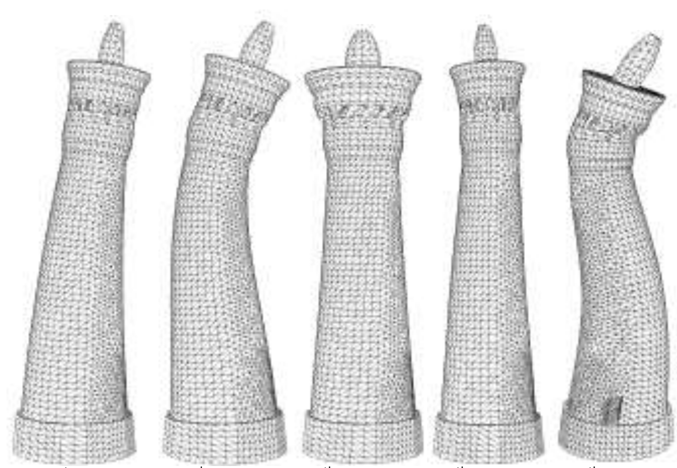


Figure 7. The mode shapes of Kalyan minaret

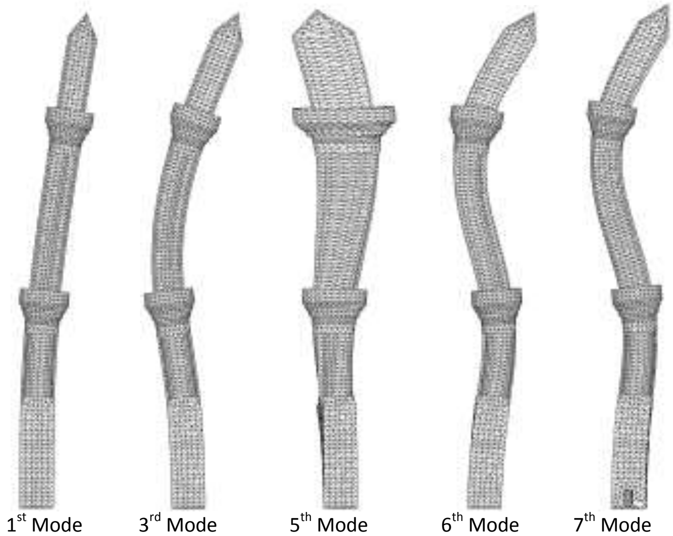


Figure 8. The mode shapes of Ince minarets

IV. Conclusion

The 7th mode of Selimiye minaret, the 5th and 9th modes of Kalyan minaret and 5th mode of Ince minaret are torsional modes, the 6th mode of Kalyan minaret, the 8th modes of Selimiye and Ince minarets are vertical modes and the rest are horizontal bending modes.

The balconies of the minarets play an important role in the mode shapes. They usually constitute the inflection points of the mode shapes, especially for the higher modes. The balcony of Kalyan minaret is the most forced of all. The 5th torsional mode of Kalyan minaret tries to shear the weak ties of arches around the balcony. As can be seen in Fig. 1, the half of the arched gaps are filled with bricks which reduces the torsional shearing effect to some extent.

It is expected that the taller the minaret, the lower the natural frequency. Although Kalyan minaret is taller than Ince minaret, the first natural frequency is higher than that of Ince minaret. This shows the fact that Kalyan minaret is stiffer than Ince minaret.

Selimiye is the tallest minaret among the considered minarets. Therefore, its first natural frequency is the lowest. The first natural frequency of Selimiye is very close to the typical natural frequency of a 30 storey building with a hight of 90 meters.

Earthquake ground motions are very complex. Therefore, the state of resonance cannot be easily investigated at each natural frequency of the minarets. A harmonic wind oscillation with a frequency very close to one of the natural frequencies may cause resonance.

The minarets considered evolved from Kalyan to Selimiye in terms of slenderness and construction material. It would not be possible to construct Selimiye with its current geometric dimensions and properties using brick masonry.

References

[1] K. A. C. Creswell, “The evolution of the minaret, with Special Reference to Egypt-I”, The Burlington Magazine for Connoisseurs, vol. 48, no. 276, pp.137-138, 1926.

[2] F. Gündüz, Minare, TDV ISAM Islam Encyclopedia, vol. 30, Istanbul, 2005, pp. 98-101.

[3] A. O. Uysal, "Anadolu selcuklularindan erken osmanli donemine minare bicimindeki gelismeler", Ankara Universitesi DTCF Dergisi, vol. 33, no. 1-2, pp. 505-533, Ankara, 1990.

[4] E. Başar, N. Kara, R. Sezer, and H. A. Erdoğan, “Anadolu selcuklu minarelerinin deprem acisindan degerlendirilmesi (Konya Ince Minareli Medrese'nin mescid minaresi)”, in ‘Selcuklu Caginda Mimarlik Sempozyumu proceedings book’, Editor: H. A. Erdoğan, Publication of Turkish Chamber of Architects Konya Division, Konya, 2007.

[5] Başar, M., XII-XIII. yy. Anadolu Minareleri, Selcuk University, unpublished Ph.D. thesis, Konya, Turkey, 1997.

[6] E. Esin, "Turk minaresinin Orta Asya’daki onculeri hakkinda", Edebiyat Fakultesi Arastırma Dergisi, Gabriel Ozel Sayısı, Ataturk Universitesi Ed. Fak. Yayim, pp. 104—147, Ankara, 1978.

[7] İ. H. Konyalı, Abideleri ve Kitabeleriyle Konya Tarihi, İstanbul, 1964.

[8] Ü. Kulaç, Steinerne wendeltreppen in Türkischen Minaretten. Verlag Ernst Vögel, 2002

[9] A. Anthoine, “Derivation of the in-plane elastic characteristics of masonry through homogenization theory”, International Journal of Solids and Structures, vol. 32, no. 2, Pages 137-163, January 1995.

[10] A. Koçak, Tarihi yigma yapilarin statik ve dinamik yukler altinda lineer ve non-lineer analizi: Kücük Ayasofya Camii Ornegi, Ph.D. Thesis, Yıldız Technical University, Istanbul, Turkey, 1999.

[11] Turkish Earthquake Code, 2007

[12] M. Oguzmert, Yigma Minarelerin Dinamik Davranisi, M.Sc. Thesis, Istanbul Technical University, Istanbul, Turkey, 2002.

[13] A. K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, New Jersey: Prentice-Hall, 1995.

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