COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Kos Island, Greece, 12–14 June 2013

EARTHQUAKE BEHAVIOR OF HISTORICAL MINARETS IN ISTANBUL

Eser Çaktı[1], Carlos S. Oliveira[2], Jose V. Lemos[3], Özden Saygılı[4], Serkan Görk[5] and Esra Zengin[6]

[1,4,5,6]Boğaziçi University
Kandilli Observatory and Earthquake Research Institute, Department of Earthquake Engineering, Çengelköy, Istanbul, Turkey
[1]eser.cakti@boun.edu.tr, [4]ozdenatess@gmail.com, [5]serkangork@hotmail.com.tr, [6]esrazengin@gmail.com

[2]Instituto Superior Tecnico
Lisbon, Portugal
csoliv@civil.ist.utl.pt

[3]Laboratório Nacional de Engenharia Civil
Lisbon, Portugal
vlemos@lnec.pt

Keywords: Minarets, Dynamic Analysis, Non-linear Modeling, Istanbul, Earthquake Response

Abstract. *Minarets are slender structures. Old ones are mostly made of cut-stone-block masonry and occasionally of brick masonry, while the new ones are generally of reinforced concrete. They have suffered significant damage during past earthquakes, the most recent event being the 23 October 2011 Van, Turkey earthquake. Istanbul is home to many historical and contemporary minarets. Evaluation of their dynamic behavior is significant due to the expectation of a large event in the near future. In a recent study [1] we performed an extensive dynamic characterization campaign in 11 historical minarets in Istanbul, which allowed for the determination of frequencies, modes of vibration and damping. Finite element modeling and analysis of seven of these minarets were performed. Linear dynamic structural analyses were conducted to access their earthquake risk level. This paper summarizes our on-going studies on the same subject, which are: (1) The minaret damage that took place during the 2011 Van earthquake; (2) The new minaret campaign in Istanbul carried out in 30 historical and modern day minarets; (4) Earthquake damage assessment of the minaret of 16th century Mihrimah Sultan mosque based on discrete element modeling, and simulated and real earthquakes; (5) Permanent strong motion instrumentation of the Hagia Sophia Museum and Maltepe Mosque minarets.*

1 INTRODUCTION

Classical Ottoman minarets are essentially composed of a masonry wall tube and an inner core surrounded by a helicoidal stairway going up counter-clock wise, made of single steps spanning from the inner core to the wall. In some cases there are two parallel stairs as it happens in one of Hagia Sophia minarets. The basic elements of the minaret are: footing, boot/pulpit (*kaide*), transition segment (*küp*), cylindrical or polygonal bodyshaft, stairs, balcony (*şerefe*), upper part of the minaret body (*petek*), spire/cap (*külah*) and end ornament (*alem*) (Figure 1). They may be built in cut stone, brick or a mixture of both. The contemporary minarets are reinforced concrete. The top is usually a 3-D timber structure covered by 5-mm-thick lead sheets. In some cases the top can be of stone masonry as is the case with the Nur-u Osmaniye Mosque. Iron clamps hold wall blocks together. Above the upper balcony, the helicoidal stairway stops as well as the stone core. A wooden cylindrical column with slightly smaller diameter gives vertical continuity to the inner core until the base of the spire, serving also as support to a rudimentary vertical wooden stair [2].

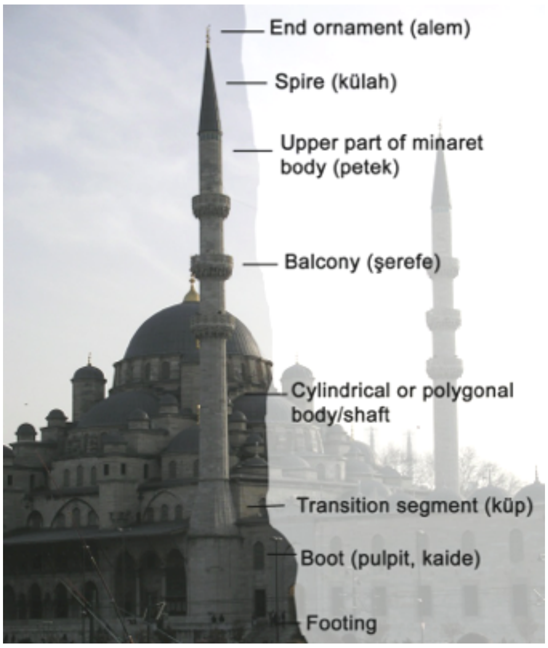

Figure 1: Main elements of a classical Ottoman minaret [1].

Minarets in Istanbul suffered from ground shaking in the past. Most notably in the 1509 earthquake, the Hagia Sophia minarets collapsed [3]. In the 1766 and 1894 earthquakes the minaret of the Mihrimah Sultan Mosque fell [4].

The most recent earthquake, in which minaret damage took place, is the 23 October 2011 Van earthquake. There was widespread damage to the mosques and their minarets. Both masonry and reinforced concrete minarets collapsed in the Van earthquake. Of 194 mosques surveyed in the Van province, 17% received heavy damage, 31% had medium damage and 30% light damage. The majority of them are not historical. Of 76 minarets, affected by the earthquake, 50 had to be demolished as they had either collapsed or had received damage beyond repair. 26 minarets were repaired. The location of the failure in the minarets that received heavy damage during the Van earthquake was mostly found to be at the region near the bottom of the cylinder, where a transition was made from a circular to a square section or where the minaret connects to the adjacent building or is part of it at the lower section. 360° planar cracks at this region were common. The majority of collapses occurred due to failure around the balcony. Circular cracks along the body and cracks in the pulpit were also common. In Figure 2 images of damaged minarets are shown.

Figure 2: Minaret damage during the 23 October 2011 Van, Turkey earthquake

Istanbul is home to a great number of historical and contemporary minarets. As studies revealed high odds for a strong earthquake event to occur in the next 30 years [5]. It is important to better understand how these structures behave during strong shaking before proposing some retrofitting policy.

2 MINARET CAMPAIGN

Oliveira et al [1] carried out an ambient vibration survey that encompassed 11 minarets located in the historical peninsula of Istanbul. Over the summer and autumn months of 2012 we have extended the survey to 41 minarets by adding 30 further minarets to the inventory. 23 of the minarets are historical. They are of stone-masonry. We have also surveyed 7 minarets that are constructed within the last 50 years. All contemporary minarets are of reinforced concrete. Figure 3 shows the locations of historical and contemporary minarets surveyed in the new campaign and of the historical minarets covered in the survey of Oliveira et al [1], marking them by different colours. In the ambient vibration measurements we have used two three-component Guralp 6TD type seismometers. The first instrument was at the ground level. The second instrument was located at the balcony level. The measurement duration varied between 10min and 15min. The sampling frequency was 200 Hz. In each minaret, in addition to recording its ambient vibrations, we have also measured the step height, number of steps, wall thickness and body diameter.

To find drawings of historical monuments is often difficult. They are either non-existent or non-accessible or when the data are available they generally do not possess the required information or detail. Therefore, we have taken our own measurements and estimated the body height from the number and height of the steps. The body diameter is estimated from the wall thickness, core thickness and the step width. We were able to compare our height estimates for the 14 minarets with their exact heights provided by Kuşüzümü [6] and Sav [7]. We find that our estimations of the body height based on on-site measurements are always within 8% of their exact values. The majority of the minarets are located on C or D type soils.

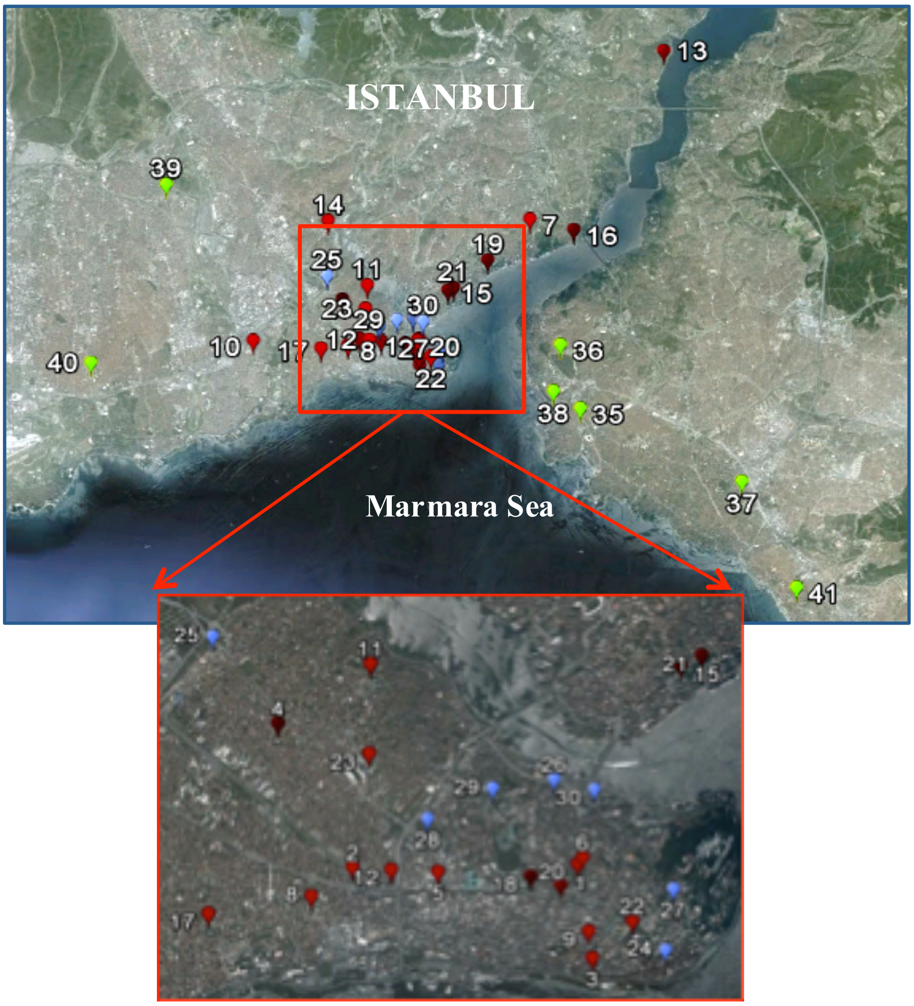

Figure 3: Locations of the mosques, the minarets of which are the subject of this study. The historical minarets covered in the recent survey are shown in red; contemporary minarets are shown in green; minarets surveyed during the previous campaign are in blue..

In each minaret we had three-component recordings from the ground level and the balcony level. Preparation and processing of ambient vibration data involved instrument correction, visual checking, baseline correction and band-pass filtering between 0.1Hz and 10Hz. Dominant frequencies of vibration in north-south and east-west directions were assessed from smoothed Fourier amplitude spectra and transfer functions. The frequencies in two orthogonal directions are very close to each other, as would be expected in symmetrical structures such as minarets. The average ratio of the larger frequency to the smaller one is 1.03.

Derivation of a simple relationship between a geometrical property of a minaret, such as one or more its dimensions, or its stiffness, and its natural vibrational frequencies is desirable. It may provide a simple means for the calculation of the natural frequency of a minaret, when only its basic geometry is known. It is also useful to understand the correlation between its frequency and several of its geometry and stiffness related parameters.

In Figure 4 we plot measured frequencies against body height and slenderness ratio defined as the ratio of the body height to the body diameter. In order to understand the difference between historical and contemporary minarets we create two groups for them.

According to Clough and Penzien [8] the first frequency of vibration for a cantilever is given by eq.1

$$f = \frac{1}{2\pi}(1.875)^2\sqrt{\frac{EI}{\bar{m}L^4}} \tag{1}$$

where E is the modulus of elasticity, I the second moment of area, $\bar{m}$ the mass per unit of length and L the total height of the cantilever.

I of a minaret can be defined can be given by Eq. 2

$$I = \frac{\pi}{4}\left[\left(\frac{\emptyset_{ext3}}{2}\right)^4 - \left(\frac{\emptyset_{ext3}}{2} - wallth_{3.1}\right)^4\right] \tag{2}$$

where $\emptyset_{ext3}$ is the external diameter of the cylindrical body of the minaret and $wallth_{3.1}$ is the wall thickness at the base of the cylindrical body [1]. Assuming that E and $\bar{m}$ are more or less the same for minarets of similar construction material, we define the stiffness parameter S as

$$S = \sqrt{\frac{I}{L^4}} \tag{3}$$

to assess the dependency between experimental frequencies and stiffness parameter. The comparison is shown in Figure 4.

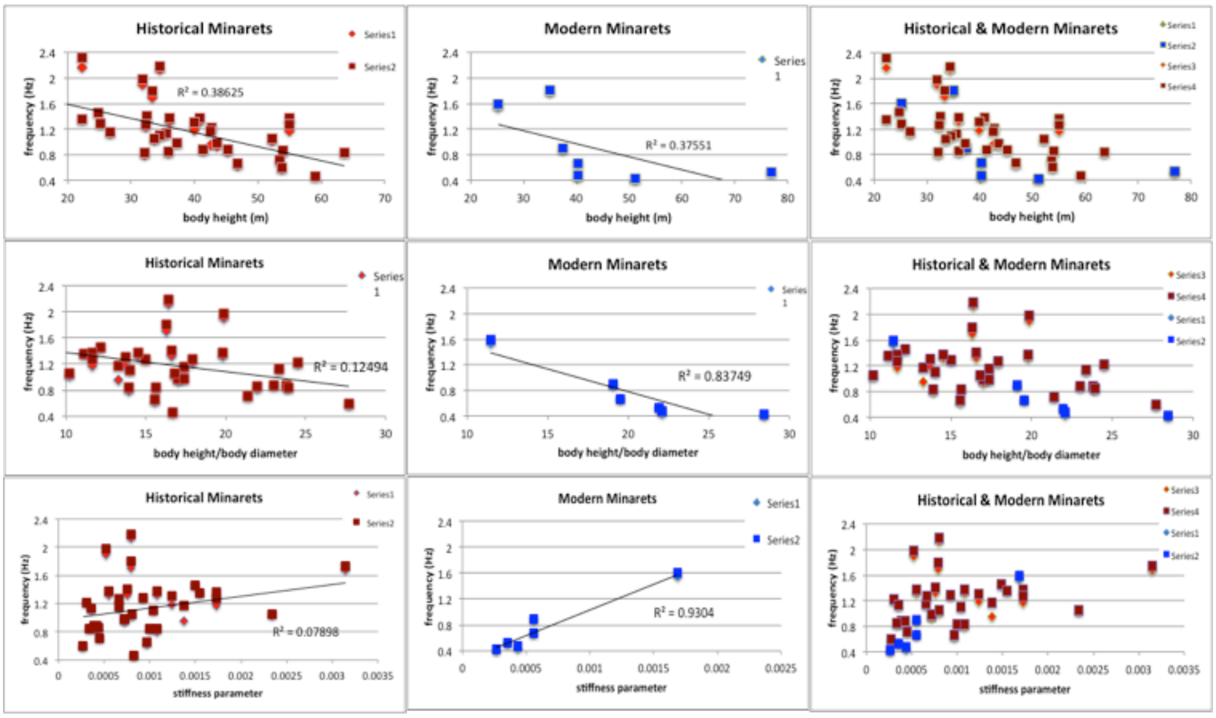

Figure 4: The change of fundamental vibration frequencies with respect to body diameter (upper row), slenderness ratio (middle row) and stiffness parameter (lower row) for the historical minarets (left column), contemporary minarets (center column) and their combination (right column).

There are several interesting features worth discussion in Figure 4. With the introduction of reinforced concrete into minaret practice, it was possible to design and build more slender minarets with lower fundamental frequencies of vibration in comparison to masonry minarets. This is evident in Figure 4 (right column) from their frequency versus body height/slenderness ratio/ stiffness parameter behaviour. The body height is not a good predictive parameter for the contemporary minarets as compared to the slenderness ratio and the stiffness parameter (Figure 4, center column). For the historical minarets, however, it seems that the body height is a better estimator, as it yielded the highest R^2 as 0.39. Although we have limited data representing contemporary minarets, it seems that their behaviour is more stable. This is probably related to the fact that they are of reinforced concrete. The behaviour of masonry minarets is more difficult to predict, yet it can be said that they have their trends.

Oliveira et al. 2012 with data from 11 minarets has presented another fitting equation

$$f = \alpha . A^{c} . I^{\beta} . H^{\delta} \tag{4}$$

where A is the area of the cylindrical cross-section and I is the inertia. The constants were defined as α=38, β=0.7 and δ= -1.1. These values were determined through an iterative process that minimizes the difference between the experimental results and the empirical equation. When we consider the minarets of campaigns 2009 and 2013, Eq. (4) would lead to the values in Table 1.

Campaign	Set	No. minarets	α	c	β	δ
Oliveira et al, 2012	Historical	11	38	-0.5(fix)	0.7	-1.1
2009 data	Historical	11	48.28	-0.631	0.586	-0.968
	Historical	11	42.78	-0.5(fix)	0.51	-0.96
2013 data	All	37	35.95	-0.5(fix)	0.148	-0.879
	Historical	31	18.06	-0.5(fix)	0.374	-0.67
	Modern PC	6	328.6	-0.5(fix)	0.58	-1.572

Table 1: Fitting values of eq. (4) for the different campaigns.

3 MIHRIMAH SULTAN MOSQUE AND MINARET

Mihrimah was the daughter of Suleiman the Magnificent and Hürrem Sultan. She was born in 1522 in Istanbul and died in 1578 in the same city. She was a politically influential and wealthy person. There are two mosque complexes in Istanbul founded by Mihrimah Sultan. The subject of this section is the Mihrimah Sultan Mosque in Edirnekapı located near the land walls of the old city (Figure 5). Architect Sinan built the complex between 1556-1560 according to Müller-Wiener [4] and between 1562-1565 according to its foundation documents [9]. Earthquakes repeatedly caused harm to the mosque, its minaret and adjacent units. The earthquakes of 1719, 1766 and 1894 led to partial collapses [4]. Most recent damage occurred during the 1999, M=7.4 Kocaeli earthquake. The mosque had to be closed to public and had to undergo a comprehensive restoration scheme [9].

The 39.86m tall minaret of the Mihrimah Sultan Mosque is of cut-stone masonry. It received damage during the 1719 earthquake. Its upper 18-step section had to be repaired. It collapsed as a result of earthquakes of 1766 and 1894. An image of the minaret taken after the 1894 earthquake and before its repair in 1907 can be seen in Figure 6. During the recent restoration works, the section of the minaret above the transition segment (küp) was completely disassembled and was rebuilt following the original geometry with new stones [9].

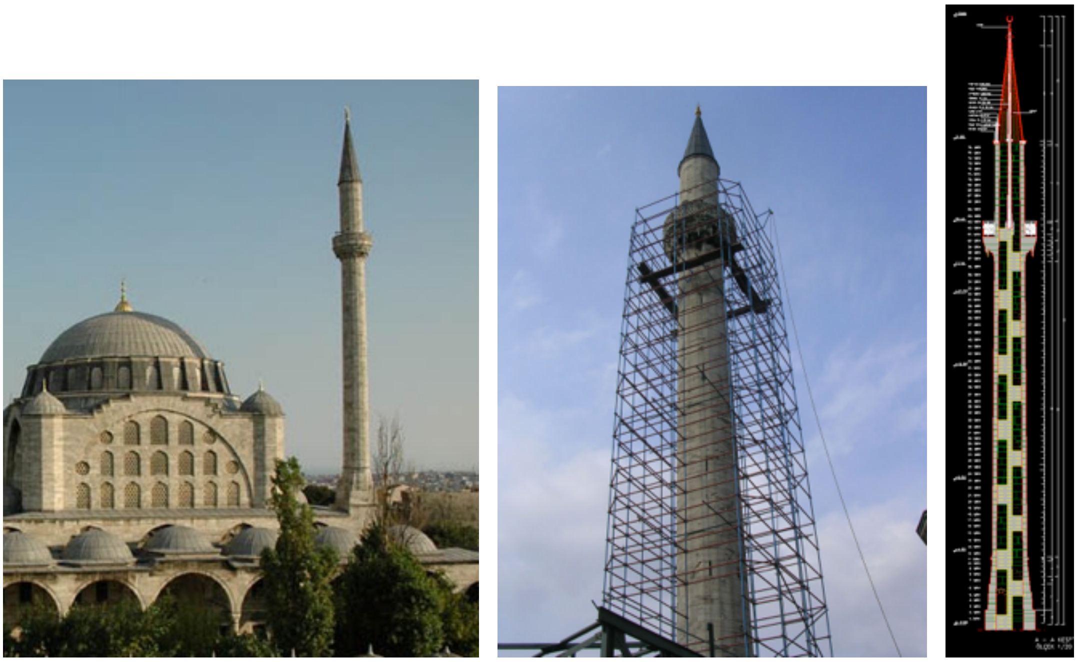

Figure 5: Mihrimah Sultan Mosque (left), its minaret before its dissassemblage (center), cross-section of the minaret (right).

Figure 6: Image of Mihrimah Sultan Mosque with the minaret that collapsed in the 1894 earthquake, from the period between 1894 and 1907 [10].

3.1 Ultrasonic Testing in the Mihrimah Minaret

We have carried out ultrasonic tests in the Mihrimah minaret in January 2013. The timing is significant in the sense that our results are representative of the minaret in its current state, i.e. the footing, the pulpit and the transition segment are original, and the part above the transition segment is new. We have utilized Pundit Lab+ Ultrasonic testing instrument with 54kHz UPV and 250kHz shear wave transducers. The tests are carried out in three different sections of the minaret: in the pulpit, in the transition segment and in the body. 37 direct ultrasonic pulse velocity (UPV) measurements are taken in the pulpit, 20 in the transition segment and 58 in the body. The numbers of readings were 97, 32 and 113 for regions 1, 2 and 3 respectively

The results suggest that the properties of stone used in the pulpit, in the transition segment and in the body are different from each other. The variation in our readings with respect to different regions is justified, as the Vp measurements carried out by two different sensor types

(54kHz and 250kH) confirm each other. It should be noted that the pulpit and the transition segment are original, while the body is newly built. We should point out that there is no evidence that the pulpit and the transition segment date from the same period. We can only say, that the stone used in the transition segment is probably similar to the stones used in the construction of the body. On the other hand, the properties of stone used in the pulpit and the body are clearly different from each other.

4 DISCRETE ELEMENT MODELLING OF THE MIHRIMAH MINARET

4.1 Discrete Element Modeling

It is a complex topic in modeling of masonry structures the choice of a suitable model representing the structure. The method employed in analytical modeling depends on the scale of the problem, the availability of the mechanical properties and the intended calculations. The macro models are used for plastic analysis and they represent the mechanical properties of masonry as a homogeneous material. Discrete models consider the discretization of block or brick masonry walls in terms of rigid or deformable bodies and planar interface or contact elements representing the mortar joints between the blocks. Nonlinear structural behavior of masonry structures depends mostly on the joints where the failure processes are more likely to occur. While deformable discrete models require intensive computation because of the description of each block by means of several finite elements, they are quite capable of treating the complex behavior of masonry walls, considering its elasticity and the progressive damage phenomena that take place after the initiation of cracking.

4.2 Modeling of the Mihrimah Minaret

The numerical models for simulation of the mechanical behavior of Mihrimah minaret were created with the 3DEC software [11]. 3DEC is a three-dimensional numerical modeling program based on the discrete element method for analysis of dis-continuum systems.

Rigid blocks were employed in the numerical model because they significantly reduce computation time in explicit time stepping algorithms. In this study, Mohr–Coulomb type failure criteria were used to represent the mortar interfaces, where the nonlinear behavior is assumed to be concentrated. The deformability of the system is characterized by the joint normal and shear stiffness parameters, which were based on experimental data, and then calibrated in order to match the measured natural frequencies. The nonlinear behavior is characterized by the tensile strength, cohesion and friction parameters.

For static analysis, 3DEC employs a dynamic relaxation algorithm. For dynamic analysis, an explicit time integration algorithm is used with mass proportional Rayleigh damping. The seismic input was applied by prescribing the velocity records in the 3 directions to the centroids of rigid blocks of foundation. The values of a set of variables such as velocity, displacement, normal stress, shear stress, normal displacement, shear displacement, were stored during a model run. Besides providing histories at given locations, it is also possible to find the distribution of peak values of joint displacements and stresses throughout the structure in order to analyze the damage processes.

The model of the Mihrimah minaret is first created in SAP2000 and calibrated for experimental periods and modes of vibration [1]. We have adopted it to 3DEC. The model parameters used in the 3DEC model is given in Table 2. The model can be seen in Figure 7a. Damping ratio was assumed as 0.04. Density is taken as 2 ton/m^3. The iron bars connecting the stone blocks were also represented in the numerical model.

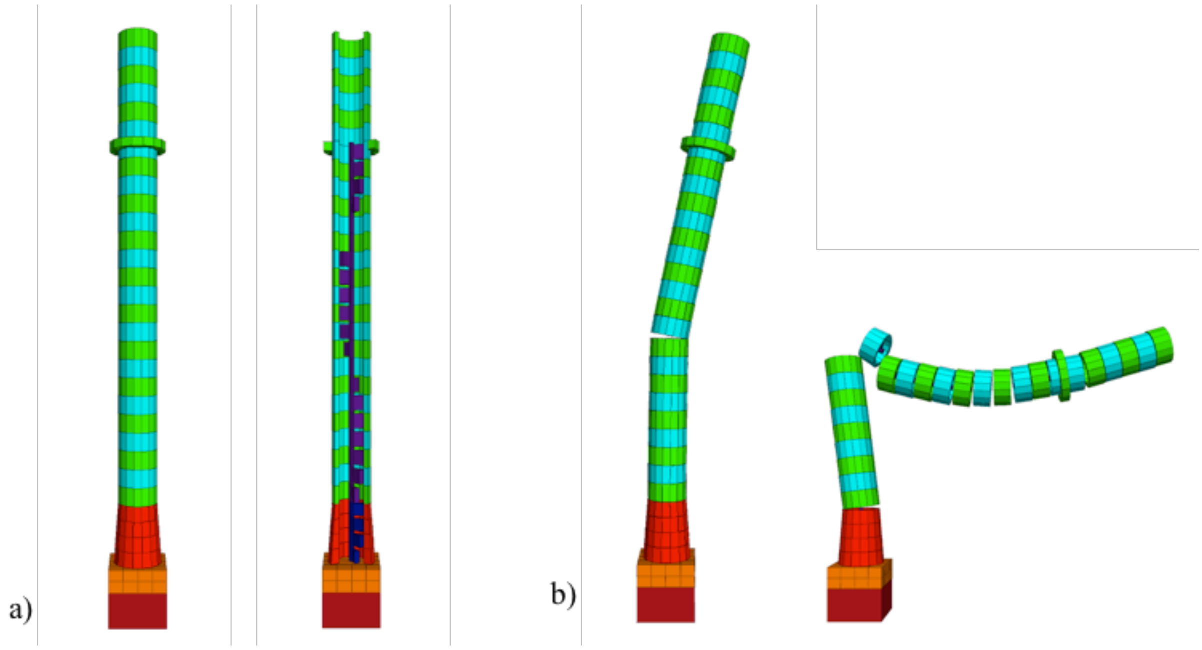

Figure 7: a) 3DEC model of the Mihrimah minaret, general view and cross-section. b) Collapse under simulated earthquake, at 24 s left, at 28 s right.

Location		K_N (MPa/m)	K_S (MPa/m)	Cohesion (MPa)	Tension (MPa)	Friction angle (°)
Wall (body)	**Horizontal joints**	8100	3200	1.0	0.5	35
	Vertical joints	10800	4300	1.0	0.5	35
Wall (trans. segment)	**Horizontal joints**	9900	3900	1.0	0.5	35
	Vertical joints	10200	4100	1.0	0.5	35
Core (trans. segment)	**Horizontal joints**	9900	3900	1.0	0.5	35
Core (body)	**Horizontal joints**	8100	3200	1.0	0.5	35
Core - stair (trans. segment)	**Vertical joints**	14800	5900	1.00E+20	1.00E+20	35
Core - stair (body)	**Vertical joints**	14800	5900	1.00E+20	1.00E+20	35

Table 2: Modeling parameters at the joints

5 CHARACTERISATION AND SELECTION OF INPUT GROUND MOTION

We have used 10 different ground motion time histories as input in the non-linear dynamic analyses. They are all consistent with the earthquake hazard levels and conditions that would be expected at or near the site of the Mihrimah Sultan Mosque in the occurrence of a large earthquake near Istanbul. Two time-history analyses were made with ground motions from the 1999 Kocaeli earthquake: the Yarımca record with a PGA of 0.322 g; and the Fatih record, with a PGA of 0.189 g. Additionally five simulated ground motion time histories were used as input. They are broadband hybrid simulations due to five rupture scenarios to take place on the central Marmara and northern boundary segments of the North Anatolian Fault in the Marmara Sea. The largest simulated PGA is 0.39 g. Finally we have simulated three ground motion time histories using the stochastic approach by code EXSIM to represent three ruptures on the central Marmara segment. The response spectra of all records used in the analysis are shown in Figure 8.

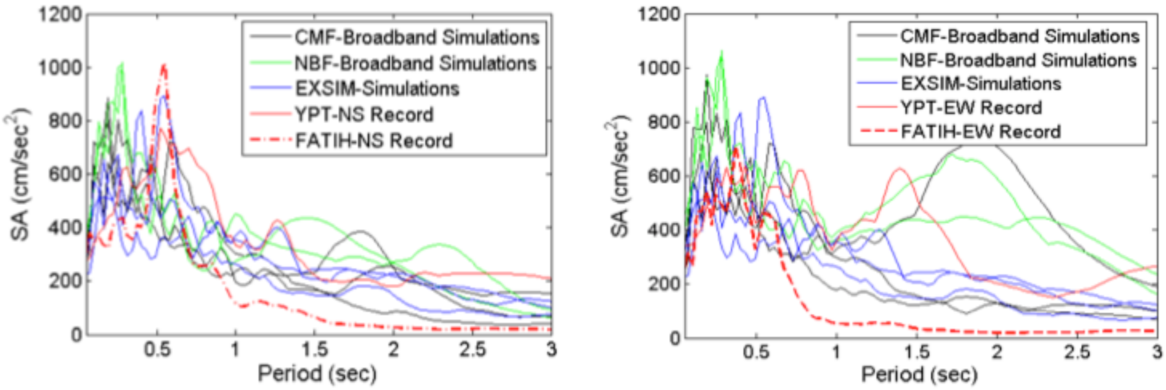

Figure 8: Response spectra of simulated and recorded ground motions used in non-linear dynamic analyses (left: NS components, right: EW components). Note that EXSIM simulates the random component. Therefore three stochastic simulations are shown in both plots.

6 NON-LINEAR DYNAMIC ANALYSIS

We have run the model under 10 earthquakes and assessed its response in terms of peak displacement amplitudes, peak stress amplitudes, their locations and collapse mechanisms. Our preliminary observations are as in the following. There are three zones along the minaret where we observe excess deformations and stresses: at the transition between the body and the so-called transition segment; balcony and its vicinity (just below or above); and at about mid-height of the body. The collapse may occur at any of them depending on ground motion characteristics. This is something we will be concentrating on in the near future. An example for collapse can be seen in Figure 7b. The agreement between the image of the minaret after its collapse in the 1894 earthquake (Figure 6) and the image of the numerical model during collapse (Figure 7b) is remarkable. There is significant rotation in the body, as evidenced by the displacement vectors shown in Figure 9. Among the cases studied, Yarımca record led to largest displacements and stresses. Peak normal joint displacements reached 6.5 cm at about 13 m from the ground level. Shear displacements of 3.2 cm took place above the balcony (Figure 10). The results suggest that failure takes place due to excessive normal deformations and rocking at the base of the minaret body and due to shear deformations at upper levels. Tensile failure on the horizontal joints was widespread, as indicated by the joint normal displacements (separation) observed. Compressive stresses in the horizontal joints attained peaks of about 5 MPa (Figure 10). The disintegration of blocks and as a result their differential displacements are evident from displacement magnitudes and joint shear displacements. Employment of real earthquakes or broadband simulations in the assessment of tall and slender structures is important. The model behaved almost elastically under stochastically simulated earthquakes, while under real and simulated records joint failures developed commonly.

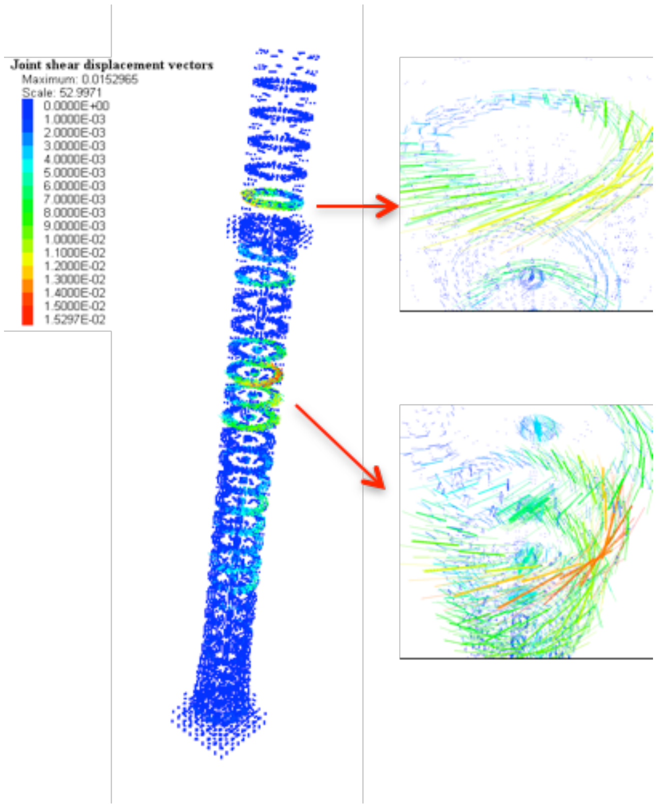

Figure 9: Joint shear displacement vectors, under a simulated earthquake on the northern boundary segment.

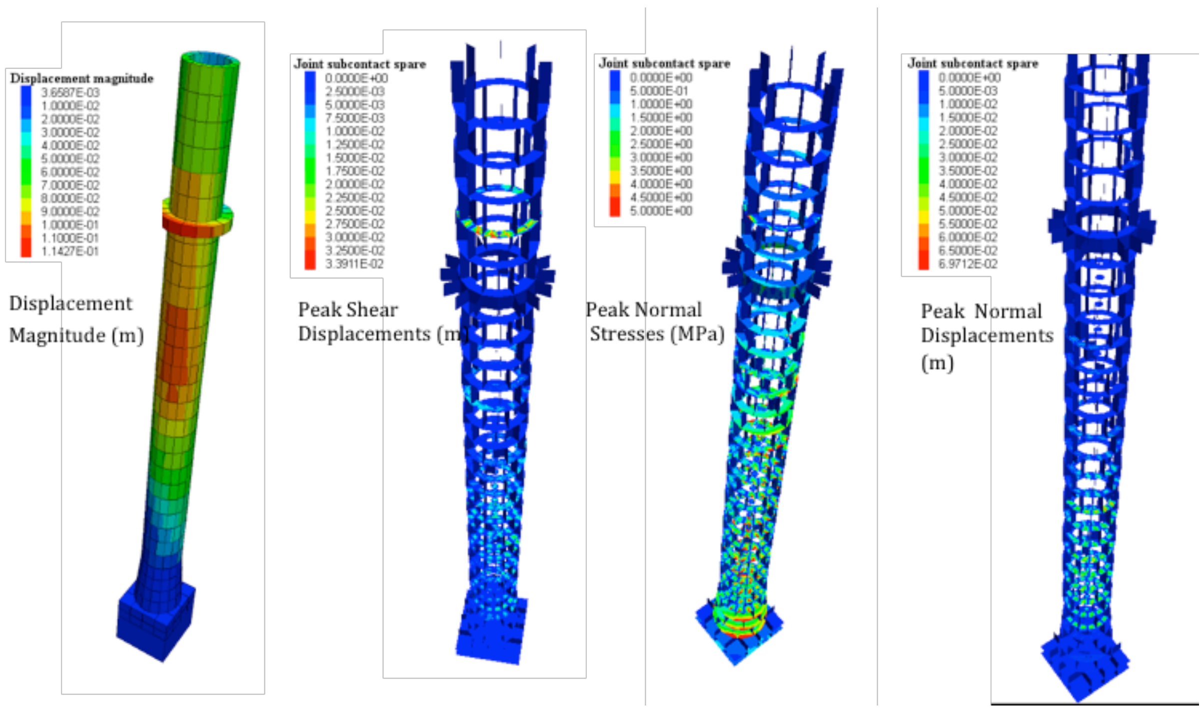

Figure 10: Model response under Yarımca record from the Kocaeli earthquake, Block displacements, maximum joint shear displacements, maximum joint normal stresses and maximum joint normal displacements.

7 CONCLUSIONS

In this paper, we have focused on the modeling and earthquake behavior of the minaret of the Mihrimah Sultan Mosque. We continue to work on understanding the effect of input ground motion on the minaret response, and on the dependence of damage pattern on the minaret geometry.

Very slender, reinforced concrete minarets have been or are being constructed in Istanbul and in other cities of Turkey that are prone to significant earthquake hazard. There is often little and no-control on their design and construction as there are no codes or guidelines concerning them. More research is definitely needed to assess their earthquake performance. Development of codes and guidelines for the maintenance and assessment of old minarets, and design and construction of new ones is also necessary, having witnessed the damage that past earthquake caused to them, and the construction of many new slender minarets.

We will install permanent structural earthquake monitoring networks in two minarets. One system will be installed in one of the Sinan minarets of the Hagia Sophia Museum. The other will be in one of the four minarets of the Maltepe Mosque. Maltepe Mosque has the tallest and most slender minarets among the ones that we have studied. Figure 11 illustrates foreseen systems.

Figure 11: Strong motion instrumentation for the minarets of the Hagia Sophia Museum (top) and of the Maltepe Mosque (bottom).

ACKNOWLEDGEMENTS

We would like to acknowledge following institutions and individuals:

- Istanbul Regional Directorate of Foundations and Istanbul Directorate of Religious Affairs for providing access to the minarets for ambient vibration surveys.
- ITASCA for providing access to 3DEC®.
- Murat Sav of Istanbul Regional Directorate of Foundations for enabling the UPV measurements and his comments and discussions on the minaret of the Mihrimah Sultan Mosque.
- Ahmet Korkmaz, Nafiz Kafadar and Emre Özdemir for their assistance during the ambient vibration tests in the minarets.
- Oktay Çırağ, Emrah Zorbacı and Mehmet Vefa Bektaş for their assistance with the ultrasonic tests in the minaret of the Mihrimah Sultan Mosque.
- State Planning Organization for providing support for instrumentation used in the field tests.
- Boğaziçi University, Instituto Superior Tecnico and Laboratório Nacional de Engenharia Civil for supporting our mutual study visits.

REFERENCES

[1] C.S. Oliveira, E. Çaktı, D. Stengel, M. Branco, Minaret Behaviour under Earthquake Loading: the Case of Historical Istanbul. *Earthquake Engineering and Structural Dynamics.* **41**, 19-39, 2012.

[2] F. Uluengin, B. Uluengin, M B, Uluengin, Classical structural details in Ottoman monument architecture [in Turkish]. Istanbul, Turkey: Yem Publication, 2001.

[3] N. Ambraseys, C. Finkel, The Marmara Sea Earthquake of 1509. Terra Nova, 2i 1989.

[4] W. Müller-Wiener, Bildlexikon Zur Topographie Istanbuls, Deutsches Archaologisches Institute, Verlag Ernst Wasmuth Tübingen, 1977.

[5] T. Parsons, Recalculated probability of M⩾7 earthquakes beneath the Sea of Marmara, Turkey. Journal of Geophysical Research, Vol. **109**, B05304, doi:10.1029/2003JB002667., 2004.

[6] K.H. Kuşüzümü, Yapım Teknikleri Açısından Istanbul Minareleri. *Vakıf Restorasyon Yıllığı*. **1**, 56-64, 2010.

[7] M. Sav, Personal Communication, 2013.

[8] R. Clough, J. Penzien, Dynamics of Structures. McGraw-Hill: U.S.A., 1975.

[9] M. Sav, K.H. Kuşüzümü, Restorasyon Çalışmaları Çerçevesinde Mihrimah Sultan Camii. Vakıf Restorasyon Yıllığı. **1**, 45-55, 2010.

[10] C. Gurlitt, İstanbul'un Mimari Sanatı, Translation: R. Kızıltan, Ankara, 1999.

[11] 3DEC Version 4.10: User's guide. Itasca Consulting Group; 2007.