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NON-LINEAR EARTHQUAKE RESPONSE OF THREE MINARETS IN ISTANBUL

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Abstract

Minarets are important elements of mosques. These slender structures have suffered notable damage as a result of past earthquakes. In this paper three historical masonry minarets located in Istanbul, Turkey are studied in the inelastic range using the Discrete Element Method. They are the minarets of the Hagia Sophia Museum, Süleymaniye Mosque and Mihrimah Sultan Mosque. The selected minarets are 16th century structures having different heights and body diameters. Dynamic behavior is simulated by means of ten different loading configurations as real and simulated earthquake time histories. Nonlinear dynamic response is characterized by the relative horizontal and normal dislocations of adjacent drums along the minaret body, as well as by its top displacement, all normalized by the body diameter. Damage patterns and collapse mechanisms are studied.

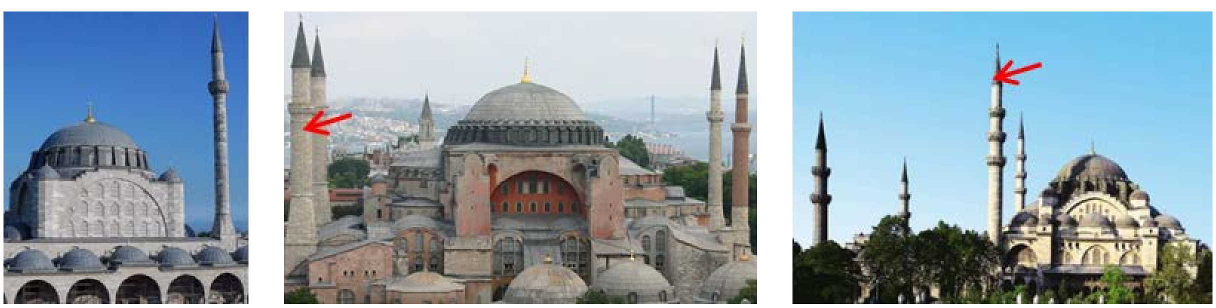
Keywords: slender structures; masonry; nonlinear dynamic modeling

1. Introduction

Masonry buildings constitute an ever-diminishing percentage of the building stock in Turkey as a consequence of high-rate urbanization, urban transformation undertakings and local construction culture. Historical heritage buildings are an important group of the masonry building stock in which a variety of structural types and systems are represented. Apart from the static structural issues these buildings are facing, those located in areas of moderate to high seismic hazard are under the threat of earthquakes. A large number of such structures, mostly mosques and minarets, calls for evaluation of seismic behavior for their maintenance, preservation and protection purposes. This paper outlines some of the critical parameters based on comparative analyses related to damage and collapse mechanisms of minarets. Earthquake safety investigations of masonry structures have been a popular subject for research in recent years [1-9]. Available numerical modeling methods such as finite element, boundary element and finite difference techniques are based on continuum assumption. Although they have been proved as capable to solve complicated problems in various fields of science and engineering, the continuum-based methods are not always suitable for cases which involve complex discontinuity. Discrete element method (DEM) is particularly useful in overcoming the limitations of continuity approaches and becoming more and more popular in masonry structure analyses [10-15].

2. Description of the minarets

Three historical masonry minarets in Istanbul (Turkey) from the 16th century are studied in the inelastic range under seismic loading. The first minaret belongs to the “Mihrimah Sultan Mosque” which is approximately 40 m high including its spire. Its body diameter is 2.30 m (Fig. 1(a)). The second minaret is that of “Hagia Sophia”. Four minarets were added to Hagia Sophia after its conversion to a mosque. This paper is concerned with one of the twin minarets constructed by Architect Sinan. It rises to about 73 m starting from the ground level including the 11.6 m spire. Its body diameter is 4.86 m. (Fig. 1(b)). The last minaret indicated in Fig. 1(c) belongs to “Süleymaniye Mosque”. It is about 74 m tall including its 10.76 m spire. Its body diameter between the transition segment and the second balcony is 3.86 m. The diameter of the body starting from the second balcony all the way to the top is 3.12 m. The minarets are adjacent to the main structure at their pulpit and stand free starting with their transition segment.

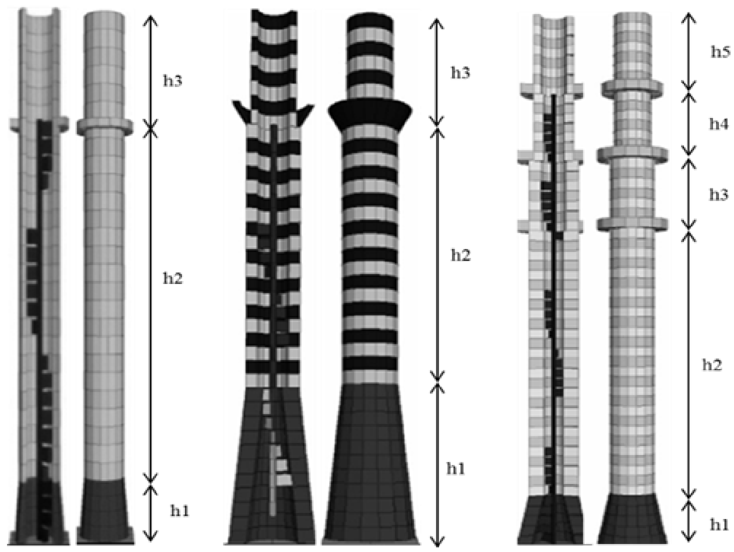


(a) (b) (c)

Fig. 1 – Images of the Mihrimah Sultan Mosque (a), Hagia Sophia (b) and the Süleymaniye Mosque (c) in Istanbul, Turkey

3. Numerical modeling of masonry minarets

Three dimensional discrete element code, 3DEC, is utilized to study the damage patterns and collapse mechanisms of the three minarets. Their geometry is based on the models developed for finite element analysis by Olivera *et al.* [8]. Each minaret including interior spiral stairs is remodeled in 3DEC as shown in Fig. 2. In masonry structures it is expected that deformations predominantly occur at the joints as opening and interlocking of interfaces, sliding, and rotation of blocks. Therefore rigid blocks are assumed. The iron bars connecting the stone blocks are represented in the numerical models using axial elements. For each minaret model, elasticity modulus of axial elements is assumed as 230 GPa and tensile strength is assumed as 100 MPa. Joint normal stiffness (k_N), and shear stiffness (k_S), cohesion, tensile strength and friction angle are major parameters of constitutive relations used for modeling joints. Characteristics of mortar are represented using Coulomb slip model. For dynamic analyses mass proportional damping is used to damp the natural oscillation modes of the models, corresponding to 4% of the critical damping. The geometrical properties of minarets are given in Table 1.



(a) (b) (c)

Fig. 2 – Model of the Mihrimah (a), Hagia Sophia (b) and Süleymaniye minarets (c)

Table 1 – Geometrical properties of the minaret models

Location	**MIHRIMAH MINARET**			**HAGIA SOPHIA MINARET**			**SÜLEYMANIYE MINARET**		
	Height (m)	Wall thickness (m)	Exterior radius (m)	Height (m)	Wall thickness (m)	Exterior radius (m)	Height (m)	Wall thickness (m)	Exterior radius (m)
Transition segment (h1)	3.44	0.3	1.41	11.96	1.6	3.97	5.1	1.15	2.87
Body (h2)	21	0.3	1.15	19.77	1	2.43	27.3	1.15	1.93
Body (h3)	6.3	0.3	1.15	8.67	0.6	2.43	7.2	0.95	1.93
Body (h4)	-	-	-	-	-	-	6.9	0.75	1.56
Top (h5)	-	-	-	-	-	-	8.1	0.75	1.56

4. Discrete element analysis of minarets

The seismic response of minarets is analyzed in terms of behavior patterns such as collapse, sliding along the block interfaces, opening of cracks and stress levels using ten different ground motion time histories. Records employed in the dynamic analyses are in accordance with local earthquake hazard levels. Two time-history analyses are made with ground motions from the 1999 Kocaeli Earthquake: Yarımca record with a PGA of 0.35 g; and Fatih record, with a PGA of 0.19 g [9]. Furthermore five broadband hybrid simulations due to five rupture scenarios to occur on the central Marmara (CMF1, CMF2, CMF3) and northern boundary segments (NB1, NB2) of the North Anatolian Fault in the Marmara Sea are used as input. The largest simulated PGA is 0.39 g. Finally three ground motion time histories simulated using the stochastic approach by code EXSIM (SC1, SC2, SC3) to represent three ruptures on the central Marmara segment are used.

Two parameters were used in order to quantify dynamic behavior: the maximum relative dislocation of adjacent drums normalized by the drum diameter at their interface, and the maximum displacement at the top of the minaret normalized by the drum diameter. The first parameter, the relative dislocation of adjacent drums normalized by the drum diameter at their interface, u_d, is defined as;

$$u_d = \frac{max(resu_i)}{D_i} \tag{1}$$

where $resu_i$ is the relative drum dislocations at the end of the seismic loading and $D_i$is drum diameter.

The second parameter is calculated using the equation of;

$$u_{top} = \frac{u_{max}}{D_{drum}} \tag{2}$$

where u_{top} is the maximum top displacement at the end of the seismic loading normalized by the diameter of the top drum of minaret, D_{drum}.

A two-stage program was carried out: dynamic nonlinear analysis of the minaret models (1) under 10 earthquake time histories, and (2) under scaled versions of earthquake time histories to force the models to failure. In the first part, seismic response of the minarets was investigated using peak displacement amplitudes, peak stress amplitudes and their locations. Second part allowed to understand the collapse mechanisms associated with the Mihrimah Sultan, Hagia Sophia and Süleymaniye minarets.

No collapse or local failure was observed in the first stage of analysis. Yet significant normal displacements and shear displacements were evident. Residual block displacements were particularly interesting as they reached about 40 cm for the Mihrimah and Süleymaniye minarets and 55 cm for the Hagia Sophia minaret, suggesting heavy damage. Analysis results in terms of incurred ranges of peak values are given in Table 3.

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). The disintegration of blocks for the Mihrimah minaret and damages for the Süleymaniye and Hagia Sophia minarets as a result their differential displacements were evident from displacement magnitudes and joint shear displacements. Yarımca record caused highest response values in the Mihrimah and Süleymaniye minarets. In the Hagia Sophia minaret, the records of NBF1 and NBF2 led to largest displacements and stresses.

Table 3 – Ranges of peak shear displacements, peak normal displacements, peak normal stresses and residual block displacements under ten earthquake records

Peak shear displacement (cm)			Peak normal displacement (cm)		
Mihrimah	Süleymaniye	Hagia Sophia	Mihrimah	Süleymaniye	Hagia Sophia
0.11-1.65	0-9.6	0.17-7.21	0.28-7.03	0.03-17.1	0.44-7.32
Peak normal stresses (MPa)			**Displacement magnitude (cm)**		
Mihrimah	Süleymaniye	Hagia Sophia	Mihrimah	Süleymaniye	Hagia Sophia
4.3 -53	10.7-108	7 – 97	0.15 – 38.6	0.01 – 39.6	0.48 – 55.2

Fig. 3 shows maximum normalized relative displacement,u_d, versus maximum normalized top displacement, u_{top} (left column) and the variation of maximum normalized normal drum displacement versus normalized relative drum displacement (right column) for the Mihrimah, Hagia Sophia and Süleymaniye minarets. An almost linear relation between u_d and u_{top} is evident starting soon after the onset of relative drum displacement in all minaret cases. In the Mihrimah minaret relative drum dislocations of adjacent drums were more or less homogeneously distributed along the minaret body. For the minaret of Hagia Sophia, most of the maximum relative dislocations of adjacent drums occurred close to the balcony where interior spiral stairs end. In the Süleymaniye minaret, maximum relative drum displacement was 8.25 cm under the Yarımca record and observed near the top of the balcony. As can be seen from Fig. 3 Süleymaniye minaret sustained larger drum dislocations than the other two. Mihrimah minaret had smallest drum dislocations. Both Mihrimah and Süleymaniye minarets were displaced in the order of 50% of their body diameter at their top.

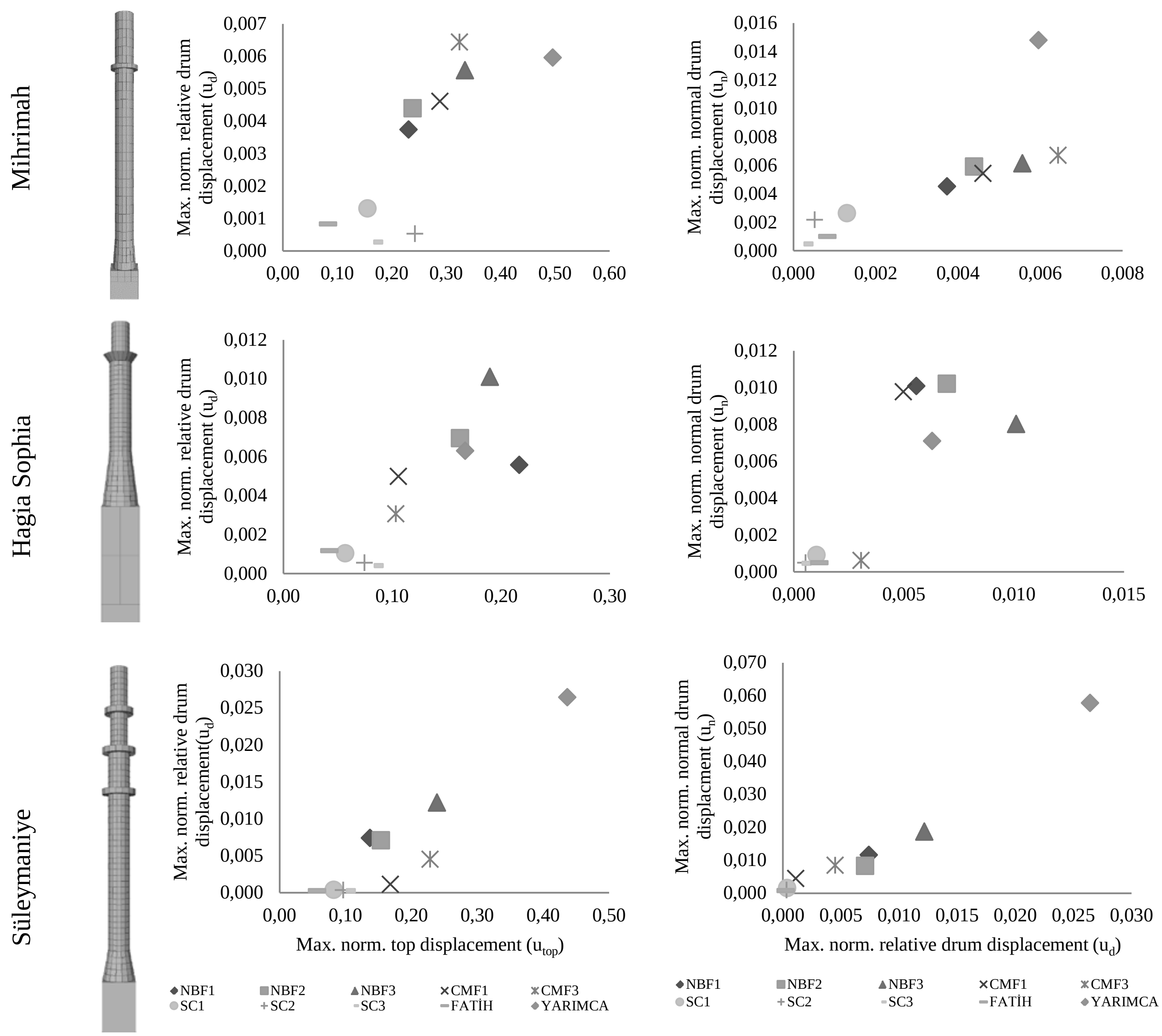


Fig. 3. Scatter plot of maximum normalized relative displacement versus normalized top displacement for minaret and maximum normalized normal drum displacement versus normalized relative drum displacement for the minarets of the Mihrimah, Hagia Sophia and Süleymaniye respectively.

The normal dislocations of adjacent blocks are indicative of vertical separation and rocking. From the right column of Fig. 3 it can be observed that the Süleymaniye minaret sustains largest normal displacements among the three minarets. They were observed close to the top of the balcony. For the Mihrimah minaret, maximum normal dislocations of adjacent drums occurred close to the transition part under six ground motions out of ten. For the Hagia Sophia minaret highest normal dislocations took place at the transition part. The finding that there is almost a one-to-one relationship between horizontal and normal drum dislocations is also worth noting, leaving out the Yarımca record in the cases of Mihrimah and Süleymaniye minartes.

In the second part, to carry each model to failure, the input velocities were scaled up progressively and analysis was repeated until instability in the model is reached. Fig. 4 illustrates minarets in the state of collapse. Collapse starts with a PGV of about 100 cm/s in the case of Mihrimah minaret, at about 190 cm/s for the Hagia Sophia minaret and at about 110 cm/s for the Süleymaniye minaret. These are large ground velocities. Particularly levels that force the Hagia Sophia minaret model to collapse can be unrealistically high, and can be interpreted as collapse of the twin minarets of the Hagia Sophia is probably an unlikely expectation. The Mihrimah and Süleymaniye minaret models tend to collapse at around 100 cm/s PGV. It appears that they are relatively more susceptible to collapse, based on the results of our analyses.

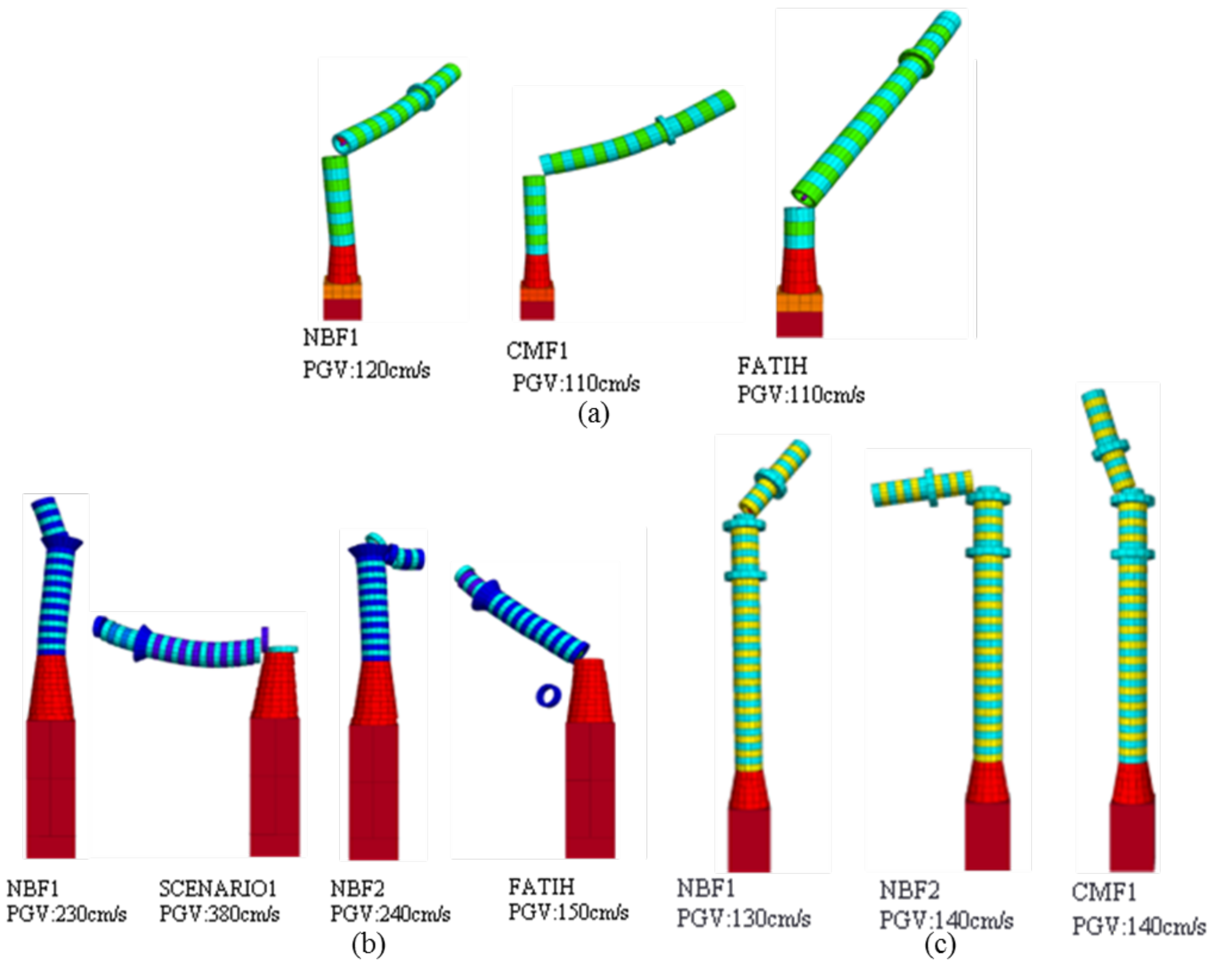


Fig. 4 – Collapse mechanisms of the Mihrimah (a), Hagia Sophia (b) and Süleymaniye minarets (c) under scaled earthquake inputs.

In the Mihrimah minaret, collapse takes place following the development of a complete separation of the minaret into two parts somewhere between the transition part and the balcony, and the fall of the upper part as a result of ongoing ground motion cycles. In the Hagia Sophia minaret there are two collapse patterns. In the first pattern the part of the minaret right above the balcony gets separated and collapses. In the second pattern a major separation occurs between the transition segment and the body. The part of the minaret above the transition segment falls down, probably following rocking. The Süleymaniye minaret has a reduced wall thickness staring at its second balcony. All collapses were associated with this part of the Süleymaniye minaret.

5. Conclusion

Dynamic analyses were performed by means of ten different loading configurations as real and simulated earthquake time histories. No collapse or local failure took place in minarets under real earthquakes and broadband simulations. Their response was assessed in terms of peak displacement amplitudes, peak stress amplitudes and their locations. To establish if the failure mechanism was local or global the deformed shapes during and at the end of the seismic excitation were helpful. They allowed quantitative data about failure pattern, which may be result of sliding, bending, cracking under direct tension or partial collapse of one block of the minaret. To force each model to collapse, the input velocities were scaled up progressively and analysis was repeated until instability in the model is reached. Shear is the dominant mode of failure observed in minarets. Stress concentrations and large deformations were observed close to the transition part, near the middle of the minarets' body and above the balcony. Damage to the blocks took place due to shear deformations at heights above mid-body. All results suggest that although some very valuable case specific conclusions can be drawn, there is a need for further case studies to be able to parameterize and/or systemize the damageability ad collapse of minarets.

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