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Collapse mechanism estimation of a historical slender minaret

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Abstract. The aim of this study is to accurately estimate seismic damage and the collapse mechanism of the historical stone masonry minaret "Hafsa Sultan", which was built in 1522. Surveying measurements and material tests were conducted to obtain a 3D solid model and the mechanical properties of the components of the minaret. The initial Finite Element (FE) model is analyzed and numerical dynamic characteristics of the minaret are obtained. The Operational Modal Analysis (OMA) method is conducted to obtain the experimental dynamic characteristics of the minaret and the initial FE model is calibrated by using the experimental results. Then, linear time history (LTH) and nonlinear time history (NLTH) analyses are carried out on the calibrated FE model by using two different ground motions. Iron clamps which used as connection element between the stones of the minaret considerably increase the tensile strength of the masonry system. The Concrete Damage Plasticity (CDP) model is selected in the nonlinear analyses in ABAQUS. The analyses conducted indicate that the results of the linear analyses are not as realistic as the nonlinear analysis results when compared with existing damage.

Keywords: historical structure; masonry; operational modal analysis; concrete damage plasticity; seismic damage estimation; tall structure

1. Introduction

The protection and evaluation of the structural safety of historical masonry structures have become compulsory in order to hand down these structures to future generations. In particular, minarets built centuries ago are slender structures with little resistance against external effects such as earthquakes, wind etc. Doğangun and Sezen (2012) were determined that three old minarets collapsed due to the 1999 earthquakes in Turkey. Ambient vibration testing and the FE method are useful techniques for establishing dynamic parameters and safety and damage evaluation of masonry structures (Atamturktur *et al.* 2010). Many researchers have performed a series of OMA tests on historical structures and compared the results of initial frequencies with an FE model of the structures to calibrate the FE models (Oliveira *et al.* 2012, Hacıefendioğlu *et al.* 2016, Livaoğlu *et al.* 2016, Erdogan *et al.* 2016, Altunışık *et al.* 2017a, Fragonara *et al.* 2017). Oliveira *et al.* (2012) performed in situ OMA tests on historical minarets and calibrated the FE models. Then the authors developed an empirical formula to estimate the first modal frequency using the section and height of the minarets. Response spectrum and linear time history analyses of the minarets were carried out. Compression stresses obtained for all minarets were below reference maximum values. However, it was followed that tensile stresses were very high especially for minarets with low dead loads. It was brought forward that in real seismic events tensile stresses would not be very high because cracks occurring in the minaret might cause energy dissipation. Finally, it was concluded that nonlinear analyses for minarets should be carried out. Altunışık *et al.* (2017a) performed linear and nonlinear FE analyses of the Zağanos Bastion in Trabzon, Turkey. The Drucker and Prager material model was used to reflect nonlinear behavior. Experimental frequency values were determined by ambient vibration tests and the maximum difference between the experimental and numerical frequencies was obtained as 26%. According to these results, FE models were calibrated using ambient vibration tests and the bastion was re-analyzed according to the updated FE model, which represents the actual behavior of the structure. The maximum tensile and compression stresses exceeded the allowable limits in some regions of the masonry. Erdogan *et al.* (2016) investigated the existing damage pattern and collapse mechanism of an historical memorial in Çanakkale. The memorial was modeled with the ANSYS/LSDYNA program using a finite discrete element model. Seismic behavior of the memorial was investigated under the real earthquake accelerations. OMA was carried out in order to define modal characteristics of the memorial and the modal parameters were calibrated in accordance with OMA. The calibrated FE model confirmed the damages observed in the monument. In addition, the memorial was retrofitted using lead bars. Fragonara *et al.* (2017) conducted a study on the bell-tower of S. Maria Maggiore in Mirandola, Italy after the 2012 Emilia earthquake. Ambient vibration tests were performed immediately after the earthquake and again after provisional retrofitting. It was observed that natural frequencies

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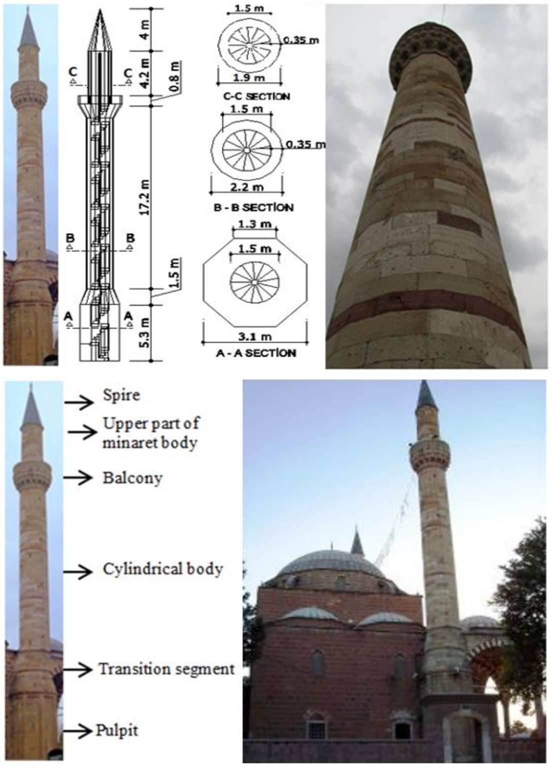


Fig. 1 Minaret of Hafsa Sultan mosque and geometric properties

increased after provisional retrofitting. In conclusion, the model updating procedure was confirmed as an effective tool for investigating the behavior of structures after retrofitting or restoration.

The aim of this study is to accurately estimate the damage and collapse mechanism in historical masonry minarets subjected to seismic loads using a calibrated FE model with ambient vibration tests. Hafsa Sultan minaret in the city of Manisa was selected as the application. Material properties of the minaret were determined by material tests and from the literature. OMA was performed to calibrate the initial FE model. LTH and NLTH analyses of the calibrated FE model were carried out using the Düzce (1999) and Akhisar/Manisa (2016) acceleration records. Nonlinear analyses were carried out using the CDP model. Seismic damage patterns of the stone masonry minaret were obtained for both earthquakes. The results of Düzce earthquake show that the tensile stresses on the masonry components exceeded the critical values at the joint of the body and transition segment and that this damage type is the most common for minarets which are tall and slender.

2. Geometric and mechanical properties of Hafsa Sultan minaret

2.1 History and geometric properties of the minaret

Manisa was one of the oldest settlements in Anatolia and held special significance for the Ottoman Sultans who were educated there. Süleyman the Magnificent ordered

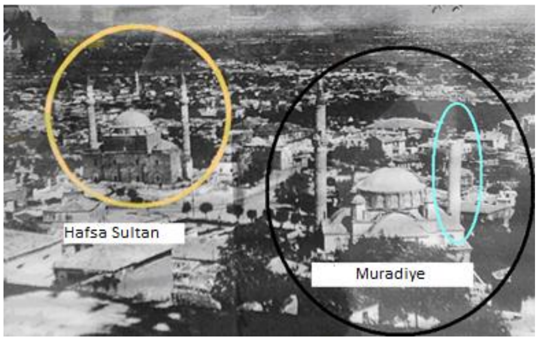
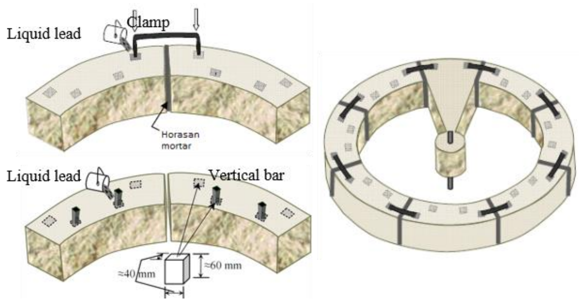


Fig. 2 Hafsa Sultan and Muradiye Mosques after earthquake in early 20th century (Nuhoğlu *et al.* 2008)



(a) Samples of connection clamps used in Ottoman minarets (Doğangün *et al.* 2008)

(b) Connection of minaret walls

(c) Stair connection (Nuhoğlu *et al.* 2008)

Fig. 3 Iron clamps between the stones in Hafsa Sultan minaret

architect Acem Ali to build the Hafsa Sultan Mosque in memory of his mother. The Hafsa Sultan mosque and minaret were constructed between 1522 and 1523 AD. The load carrying system of the minaret consists of cut stone masonry. The height of the minaret is 33 m and radius of minaret is different along pulpit, cylindrical body and upper part of minaret. The pulpit has a hexagonal section with a 1.3 m side length and diameter of 3.1 m, cylindrical body has a diameter of 2.2 m and upper part of minaret body has a diameter of 1.9 m. The thickness of the cylindrical body wall is 0.35 m. Photographs and drawings of the minaret are presented in Fig. 1.

When the minaret and mosque of Hafsa Sultan were restored between 1973 and 1977, disintegrated stones were replaced with isotope equivalent material (Nuhoğlu *et al.* 2008). After an earthquake at the beginning of the 20th century, the minaret of Muradiye mosque, which is very near the Hafsa Sultan mosque, was significantly damaged. However, the minarets of Hafsa Sultan mosque weren’t affected in anyway as seen in Fig. 2 (Nuhoğlu *et al.* 2008).

It is thought that there are two main reasons of the

Table 1 Initial material parameters of masonry walls (Nohutcu *et al.* 2015)

Compression strength (MPa)	Tensile strength (MPa)	Tensile strength with clamp (MPa)	Modulus of elasticity (MPa)	Shear modulus (MPa)	Density (kg/m^3)	Poisson ratio
7.42	0.742	2.00	1500	600	2200	0.17

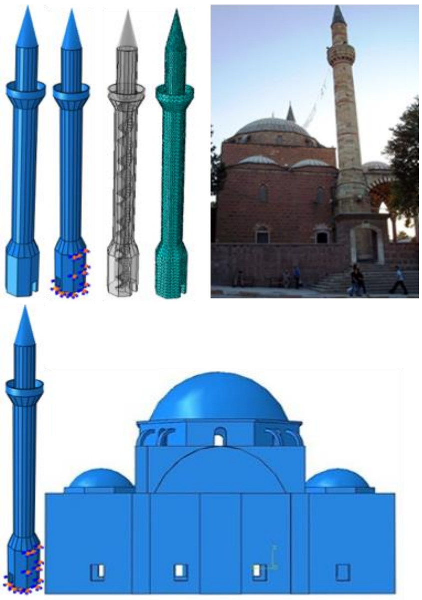


Fig. 4 Three-dimensional solid model and FE model of minaret

situation. Firstly, the minaret and mosque of Hafsa Sultan aren't linked as rigid each other. So, minaret of Hafsa Sultan can unrestrainedly move unlike Muradiye mosque. The other reason may be the iron clamp and vertical bar technology that connects the stones with each other as seen in Fig. 3. As the Ottomans could enhance the behavior of slender masonry structures like minarets, they developed a special technique for linking adjacent stone blocks with iron clamps and vertical bars in both directions as shown in Fig. 3 (Nuhoğlu *et al.* 2008, Doğangün *et al.* 2008). So, masonry minarets were strengthened using horizontal and vertical clamps. The clamp technology increases the tension strength of the masonry between 2 and 10 times according to the number, section, and shape of the clamps and tension and shear strength of the stone.

2.2 Material properties of the minaret

The masonry system of the minaret is composed of smooth cut stones with a width of 35 cm and height of 25 cm. Stones are linked with iron clamps and vertical bars that have sections of 2×3 cm and 3×3 cm, respectively (in Fig. 3). The ultimate tensile strength of a clamp was determined to be about 250 MPa by a tensile test conducted in the laboratory and according to this, the tensile strength of the masonry was estimated to be about 2 MPa. Other material properties of the masonry system were studied by (Nohutcu *et al.* 2015). Table 1 presents the material parameters of the masonry walls.

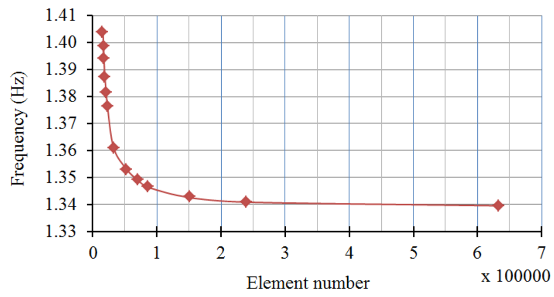


Fig. 5 Frequency and mesh size convergence graphic

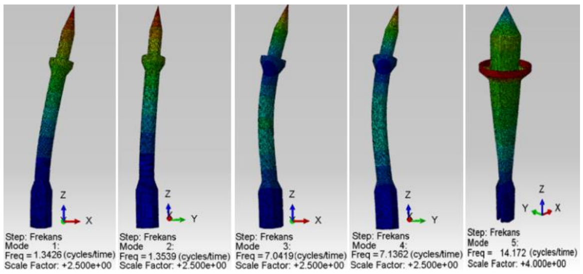


Fig. 6 Mode shapes and frequency values obtained from the initial FE model

3. FE analyses

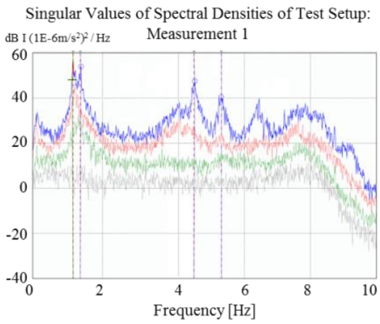
3.1 Non-calibrated initial FE model of the minaret

According to the drawings obtained from in situ survey measurements, three-dimensional solid and finite element models of the minaret were prepared using ABAQUS (2010) software as seen in Fig. 4. Convergence analysis was conducted for the purpose of determining the most appropriate range of mesh in the FE model of the minaret. In the convergence analysis, the mesh size was initially selected as 0.65 m. Modal analyses were carried out for each range of the mesh and the convergence graphic is presented in Fig. 5. According to the convergence analysis, the optimum range of the mesh in numerical analyses was determined as 0.25 m. In the FE model, it was assumed that the minaret was supported by the base as fixed in x, y, z directions. Therefore, soil-structure interaction wasn't taken into account. Roller supports on the surfaces of contacts of the mosque and minaret in the FE model were defined as seen in Fig. 4, because walls of mosque restrained horizontal movements in this direction of minaret. Although the roller supports allowed movements of the minaret in a vertical direction, they restrained movements occurring towards the mosque wall. But, the minaret can freely move in other horizontal direction.

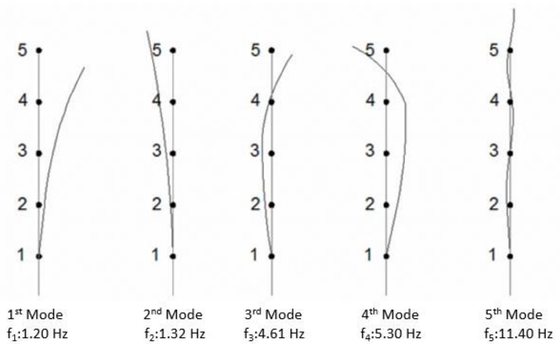
In this study, a total of 61,107 four-node tetrahedral (C3D4) solid elements and 19,809 nodes were used. The first five numerical frequency values and mode shapes of minaret were obtained by using modal analysis method as seen in Fig. 6. The first and fourth mode shapes were in the x direction while the second and third mode shapes were in the y direction. Fifth mode was obtained as torsion mode.

3.2 Operational modal analysis and FE model calibration of the minaret

Fig. 7 Locations and directions of the accelerometers on the minaret and data accusation system



(a) Singular values of spectral densities matrices obtained from EFDD method



(b) Experimental mode shapes

Fig. 8 Results of operational modal analysis

Ambient vibration test was carried out on the minaret using the OMA method. OMA, which characterizes the dynamical behavior of the structures in service, is an accepted and useful tool to determine the modal parameters. In addition, the test are one of the most suitable methods for the determination of modal parameters because additional information about the input excitation is not required (Nuhoğlu *et al.* 2008). Locations of accelerometers and data accusation system on the minaret are presented in Fig. 7. The locations of accelerometers are determined with FE modal analyses. In this study, the “Enhanced Frequency Domain Decomposition (EFDD)” technique presented in detail by (Brincker *et al.* 2000; Peeters, 2000; Jacobsen *et al.* 2006) is used.

Singular values of spectral densities matrices obtained by the EFDD method and the experimental mode shapes are given in Fig. 8(a) and Fig. 8(b), respectively.

OMA was carried out using an EFDD algorithm with the ARTEMIS Modal Pro (2014) software program. Most important part of model calibration is selection of material parameters such as modulus of elasticity, density, geometrical parameters such as sections and modeling parameters such as boundary conditions. Günaydin *et al.* (2017) proposed that main parameters for minimizing the differences between the dynamic characteristics obtained as numerical and experimental were material properties such as modulus of elasticity and density. It is suggested that sensitivity analyses should be done to determine which parameters (elasticity modulus, boundary condition, density etc.) have major effect on the structural responses (Altunışık *et al.* 2017a, Altunışık *et al.* 2017b). The procedure can be used for the next studies. As a result of survey in situ, it was determined that density of material could be used as 2200 kg/m^3. Therefore, only modulus of elasticity of the minaret was increased to 7,700 MPa from 1,500 MPa following a number of tests and the FE model was calibrated accordingly.

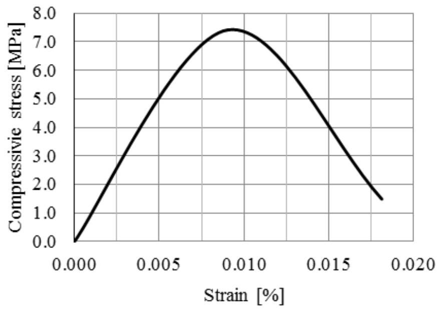
Table 2 Comparison of numerical and experimental frequency values

Mode	Frequency [Hz]			Error (%)		Damping ratios [%]
	FEM initial	FEM calibration	OMA EFFD	Before FE calibration	After FE calibration	
1	1.342	1.20	1.20	11.8	0	0.81
2	1.353	1.25	1.32	2.50	-5.3	0.42
3	7.041	4.998	4.61	52.7	8.4	0.35
4	7.136	5.065	5.30	34.6	-4.4	0.46
5	14.172	11.09	11.40	24.32	-2.7	0.76

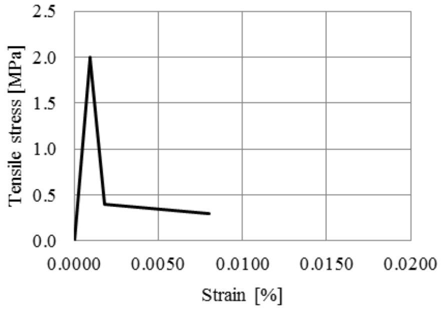
Table 2 presents the first five numerical and experimental frequency values and damping ratios obtained before and after the model calibration of the minaret. It can be seen that the calibrated frequencies are very close to those of the experiment in Table 2. The max difference after calibration is 8.4% and it is thought that the difference may be occurred due to restorations and cracks.

4. Seismic analyses and damage pattern estimation of the minaret

Seismic damage and collapse mechanism of the minaret were determined by means of linear and nonlinear FE models in ABAQUS (2010). The NLTH analyses of the minaret were carried out using the Concrete Damage Plasticity (CDP) model. Resta *et al.* (2013) investigated the



(a) Compression



(b) Tension

Fig. 9 The material models used for masonry

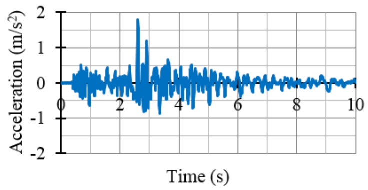
Table 3 Material parameters for masonry in CDP model (Valente and Milani, 2016)

Dilation angle	Eccentricity	f_{bo}/f_{co}	K	Viscosity
10^0	0.1	1.16	0.666	0.002

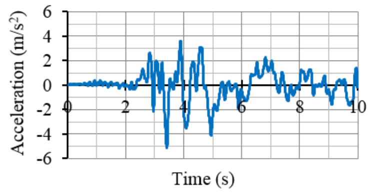
adaptation of the CDP constitutive model from concrete to masonry with the help of experimental data in the literature. As a conclusion, it was proved that the CDP constitutive model could be used effectively within FE analysis in order to investigate both dynamic and static behavior of masonry structures. Tiberti *et al.* (2016) studied the causes behind the collapse of Finale Emilia Castle during a sequence of earthquakes in 2012. For reconstruction of the castle, FE analyses including nonlinear dynamic and nonlinear pushover were performed. FE analyses were utilized with two different meshes, a fine tetrahedral mesh and a coarse hexahedral mesh. It was found that both mesh types had similar results. According to the results of pushover and nonlinear dynamic analyses, it was found that FE damage patterns showed several features in common with the real ones. Valente and Milani (2016) investigated the seismic vulnerability of eight towers with different simplified procedures based on non-linear static analyses. It was assumed that the masonry had very low tensile strength. In other words, masonry system may exhibit nonlinear behavior even at very low levels of earthquake loads. The damage plasticity material model that shows softening in both tension and compression was used in order to model masonry material. Nonlinear static and simplified methods suggested by Italian Guidelines on Cultural Heritage were compared for the safety evaluation of historical masonry towers in seismic zones. It was concluded from the results that both approaches were in a good agreement.

In order to model the nonlinear behavior of masonry minaret, the CDP material model that exhibits the softening under compression and tension stresses was used. Material properties of the masonry used in the minaret were adapted according to the study carried out by authors and Mortezai and Kalantari (2015) as shown in Fig. 9. Material parameters of masonry used in the CDP model are summarized in Table 3.

In addition, implicit integration technique which uses Newton-Raphson iterations to enforce equilibrium and is

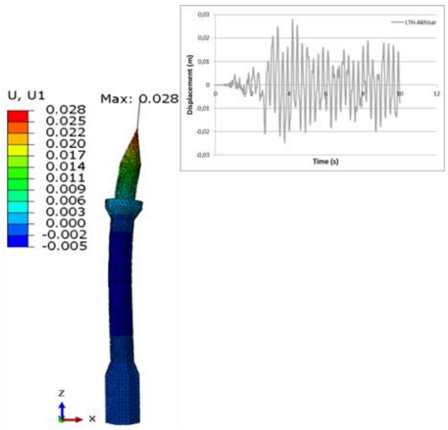


(a) Akhisar/Manisa

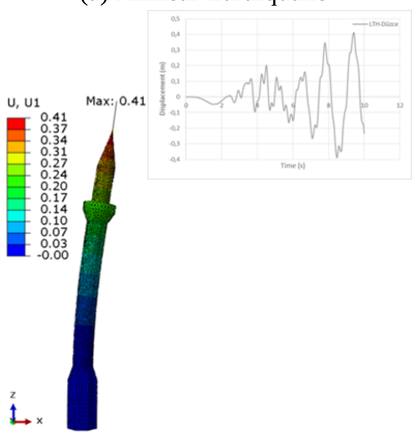


(b) Düzce

Fig. 10 Ground accelerations of earthquakes



(a) Akhisar Earthquake



(b) Düzce Earthquake

Fig. 11 Displacements of the minaret subjected to both earthquakes (m)

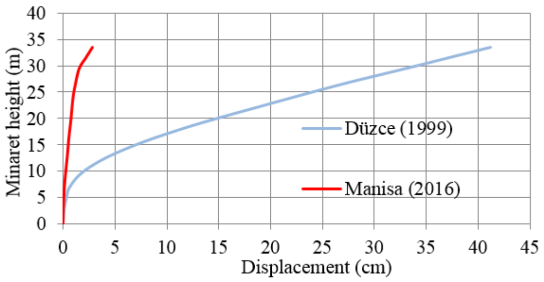
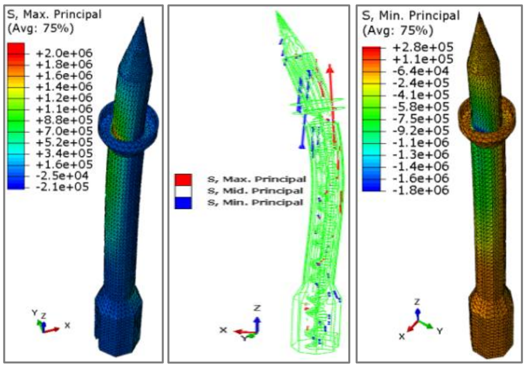
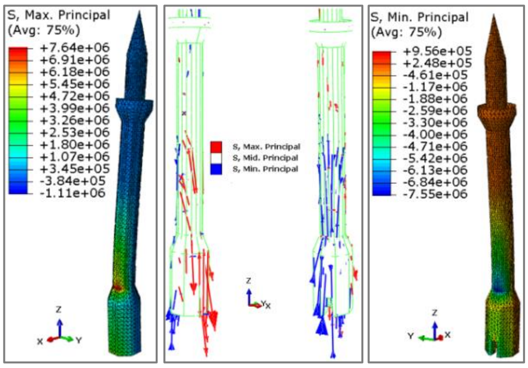


Fig. 12 Lateral displacements throughout the height for LTH analyses



(a) Akhisar earthquake



(b) Düzce earthquake

Fig. 13 Distribution of principal stresses in minarets

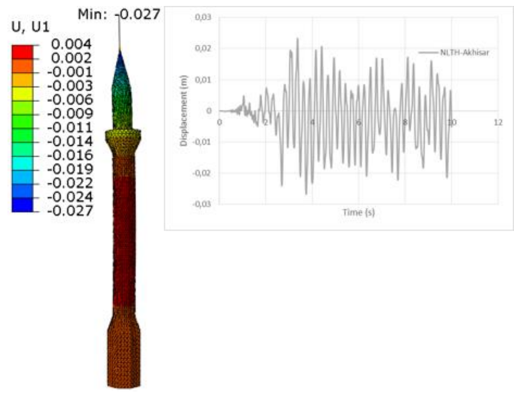


Fig. 14 Displacements of the minaret subjected to Akhisar earthquake (m)

faster than explicit technique was preferred in this study. Soil properties of the minaret were determined as groups C and Z2 soil classes. The max acceleration records in 10 seconds of the Akhisar/Manisa (2016), Düzce (1999) earthquakes were used to determine the seismic damage patterns and collapse mechanism of the minaret with LTH and NLTH analyses. Ground accelerations of the earthquakes are shown in Fig. 10. The Akhisar (M_w 4.6) and Düzce (M_w 7.2) earthquakes occurred on 12 September, 2016 and 12 November, 1999, respectively. Although acceleration records were applied to the minaret for both horizontal directions, most unfavorable results were presented in the paper.

4.1 LTH analyses of the minaret subjected to Akhisar and Düzce earthquakes

The maximum lateral displacements in the U1 direction were 2.8 cm during the Akhisar earthquake and 41 cm during the Düzce earthquake (Fig. 11). The lateral displacements obtained throughout the height of the minaret with LTH analysis for both earthquakes are presented in Fig. 12.

As a result of the Akhisar earthquake, it was observed that the maximum tensile stresses were concentrated on the intersection of the balcony and the cylindrical body and the minimum compression stresses were concentrated on the opposite side of this region (Fig. 13(a)). As a result of the Düzce earthquake, maximum tensile stresses were concentrated on the intersection of the transition segment and the cylindrical body as shown in Fig. 13(b).

The maximum and minimum principal stresses that occurred in the minaret subjected to the Akhisar earthquake did not exceed limit compression (7.42 MPa) and tensile stresses (2 MPa). It was observed that stresses were concentrated on the intersection region between the balcony and upper cylindrical body. During the Düzce earthquake, the minaret was considerably forced with these principal stresses. Maximum tensile stresses exceeded the limit tensile stress about 3.5 times on the intersection region of the transition segment and cylindrical body. So, LTH analysis showed that the minaret could suffer damage seriously under such an earthquake effect.

4.2 NLTH analyses of the minaret subjected to Akhisar and Düzce earthquakes

4.2.1 Akhisar earthquake

According to NLTH analysis results of the minaret subjected to the Akhisar earthquake, the maximum lateral displacement was obtained as 2.7 cm (in Fig. 14). Critical maximum and minimum principle stress contours are presented in Fig. 15.

In NLTH analyses, the maximum and minimum stresses that occurred in the minaret subjected to the Akhisar earthquake were concentrated on the balcony and upper part of the cylindrical body. However, these stresses did not exceed limit values. So, it was concluded that such an earthquake couldn't significantly damage to the minaret.

4.2.2 Düzce earthquake

NLTH analysis of the minaret subjected to the Düzce earthquake showed that the maximum lateral displacement

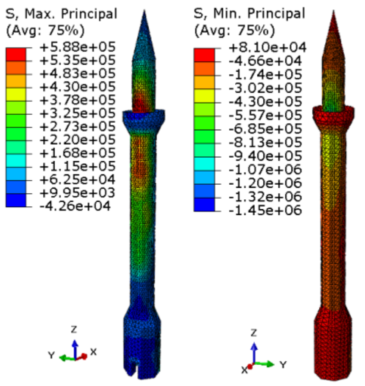


Fig. 15 Maximum and minimum principal stresses of minaret (Pa)

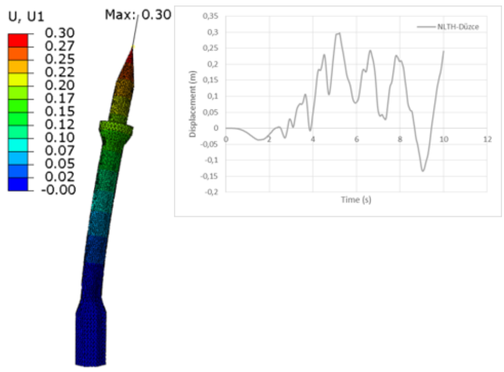


Fig. 16 Displacements of the minaret subjected to Düzce earthquake (m)

was 30 cm in the U1 direction as seen in Fig. 16.

Maximum and minimum principle stresses that occurred in the minaret during the Düzce earthquake are presented in Fig. 17. Maximum stresses that occurred in the minaret exceeded the limit tensile stress value about 1.4 times. Maximum stresses were concentrated on the transition segment. On the contrary, minimum stresses did not exceed the limit value. It was concluded that the minaret subjected to such a devastating earthquake could be significantly damaged by tensile stresses.

5. Discussion

The minaret of the Hafsa Sultan mosque - one of the most important structures of the Ottoman period - was investigated using the OMA method and the FE model of the minaret was calibrated. The calibrated FE model was subjected to the conditions of the Düzce and Akhisar earthquakes and LTH and NLTH analyses were carried out. Having a lower magnitude the Akhisar earthquake did not cause significant damage in any region of the minaret in both analyses. In addition, the stresses were concentrated around the balcony. However, Düzce, which was a devastating earthquake, caused significant damages in some regions of the minaret in both analyses. In particular, tensile and compression stresses were concentrated in the transition segment. In real seismic events, it follows that minarets collapse due to damages in the transition segment as shown

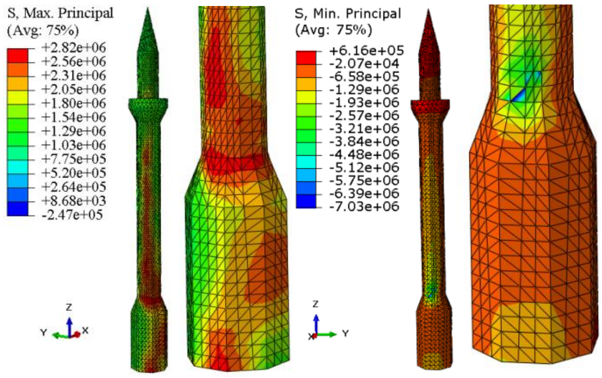


Fig. 17 Maximum and minimum principal stresses in minaret (Pa)

Fig. 18 Damage patterns of masonry minarets (Doğangun and Sezen 2012)

in Figs. 18(a) and 18(b) (Doğangun and Sezen 2012).

Tensile stresses occurring during the Düzce earthquake exceeded limit tensile stresses approximately 1.4 times in NLTH analysis and 3.8 times in LTH analysis. Compression stresses occurring in LTH analyses exceeded limit values 1.02 times. Maximum displacement that occurred in LTH analysis was calculated as 1.37 times greater than that of NLTH analysis. In conclusion, it is determined that both analysis methods can accurately estimate regions where damage may occur in the minaret. However, LTH analysis has led to exaggerated results in terms of stresses and displacements. Therefore, it is suggested that NLTH analysis should be preferred over LTH analysis.

6. Conclusions

Seismic damage estimation in historical stone masonry minarets was investigated with an FE model calibrated using ambient vibration tests. Two different ground motions that occurred in Akhisar (2016), Düzce (1999) were performed in LTH and NLTH analyses with the CDP material model. For CDP analyses, behaviors of masonry under compression and tensile stresses were investigated in detail and determined.

As a result of the analyses, it was determined that tensile stresses were more effective than compression stresses on damage. In LTH analysis, it was observed that the maximum tensile stresses were about 2.00 and 7.64 MPa in the Akhisar and Düzce earthquakes, respectively. The stresses obtained by LTH analyses in the minaret subjected to Düzce earthquake considerably exceeded limit stresses, but any damage has been observed in the minarets for long years. It proves that the LTH method gives exaggerated results compared to NLTH. In NLTH analysis, the maximum tensile stresses were about 0.58 MPa and 2.82 MPa in the Akhisar and Düzce earthquakes, respectively. According to all these findings, it was concluded that a severe earthquake could cause significantly damages in the historical Hafsa Sultan minaret.

After the earthquake in the early 20th century, although the minaret of Muradiye Mosque that is very near the Hafsa Sultan Mosque collapsed, the minaret of the Hafsa Sultan mosque remained steady. It can be explained by the fact that the minaret is separate from the mosque unlike Muradiye minaret and by the iron clamps and vertical bars used in the Hafsa Sultan minaret. Finally, the Hafsa Sultan minaret should be strengthened quickly with a convenient method so that its cultural heritage can be safely handed down to future generations.

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