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Field investigation and seismic analysis of a historical brick masonry minaret damaged during the Van Earthquakes in 2011

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Abstract. The paper presents the field investigations and seismic analyses of a historical masonry brick minaret damaged during October 23 (Erciş) and November 9 (Edremit), 2011 Van earthquakes in Turkey. Ulu Mosque Minaret located on Tebriz Kapı Street in the city centre of Van, Turkey is selected for investigation. Two earthquakes hit the minaret within seventeen days, causing progressive damage. It was seen from the field investigations that the minaret was heavily damaged. To validate the field investigations, three dimensional finite element model of the minaret is constituted by ANSYS software using relievo drawings. Finite element model of the minaret is analyzed under the Van earthquake records to determine the seismic behavior. The displacements, maximum and minimum principal stresses and strains are obtained from the analyses and compared with field observations.

Keywords: earthquake damages; seismic analyses; masonry minarets; Ulu Mosque minaret; Van earthquakes in 2011; field investigations

1. Introduction

Minarets are one of the thin and tall engineering structures. They are distinctive architectural features of Islamic mosques and generally tall spires with onion shaped or conical crowns. Minarets are used for calling out the azan five times each day by a muezzin in order to signal people to come to prayers.

A typical minaret basically consists of three parts such as base, shaft, and gallery (see Fig. 1). Base is reached from hard rock soil to floor. Shaft is a thin and slim body of the minaret and stairs are taken place cylindrically in the shaft to provide the necessary structural support for highly elongated shafts. The gallery is a balcony which encircles the upper section where the muezzins call out to prayer.

In many earthquake-prone or high strong wind areas, many of the minarets are partly or completely damaged after earthquakes. The October 23 and November 9, 2011 Van earthquakes in Turkey also caused many minaret damages in Van and their villages. Therefore, minarets have become of increasing concern in the last decade (Turk and Cosgun 2012, Sezen *et al*. 2008). It can be seen from the literature that there is no enough studies on damaged masonry brick minarets. In order to understand the behaviour of the damaged masonry brick minarets and to determine their

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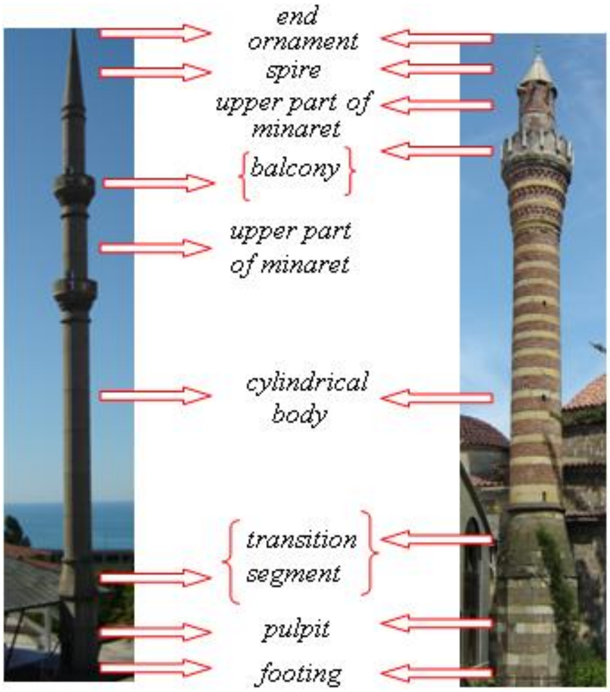


(a) Reinforced concrete minaret (b) Masonry minaret

Fig. 1 Typical reinforced concrete and masonry minarets in Turkey

seismic performances under earthquakes, Ulu Mosque minaret damaged during the Van earthquakes in 2011 is selected as an application in this study. Field investigations, evaluations and seismic analysis results of Ulu Mosque minaret are presented below.

2. Seismological aspects

The two earthquakes occurred in 2011 in Van, Turkey. The first earthquake with the magnitude of M_L=6.7 and M_w=7.2 occurred at local time 13:41 on Sunday, October 23, 2011 in the Erciş township of Van located in the eastern part of Turkey. The epicentre is about 30km to the north of the Van city-centre and its coordinates are reported as 38.68N-43.47E by the Earthquake Department of the Disaster and Emergency Management Presidency (AFAD 2011). The depth of the earthquake is given as 19.02 km. Following the mainshock, approximately 650 aftershocks occurred in the first 2 days (EERC 2011). The aftershocks follow SW-NE trend.

The second earthquake with the magnitude of M_w=5.6 occurred at local time 21:23 on Wednesday, November 9, 2011 in the Edremit township of Van located in the eastern part of Turkey. The epicentre is in the Edremit subprovince, about 16km to the south of the Van city centre. Its coordinates are reported as 38.429N-43.234E by the Kandilli Observatory and Earthquake Research Institute (KOERI 2011). The depth of the earthquake is given as 5 km. This earthquake has a dominantly strike-slip mechanism (KOERI 2011).

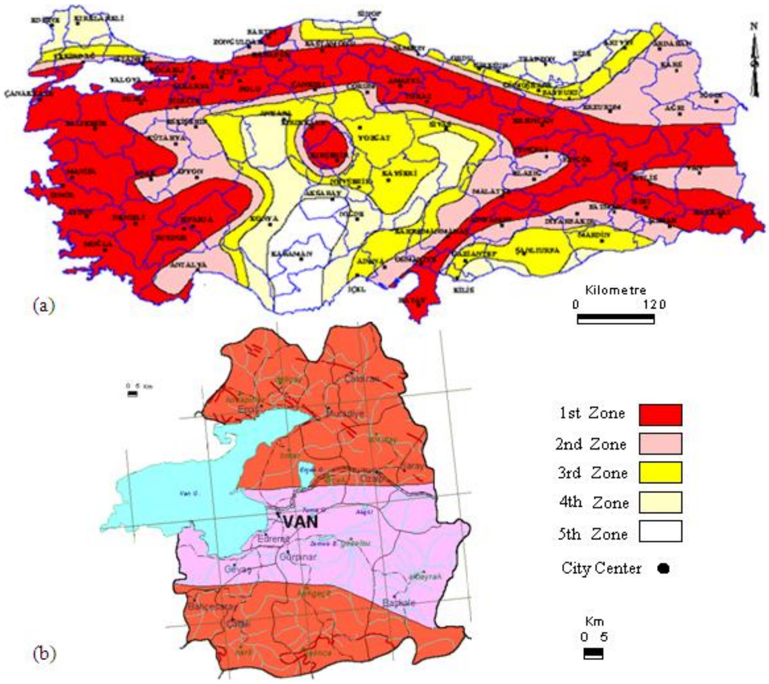


Fig. 2 Seismic zoning map of Turkey (a) and Van (b) (AFAD 2011)

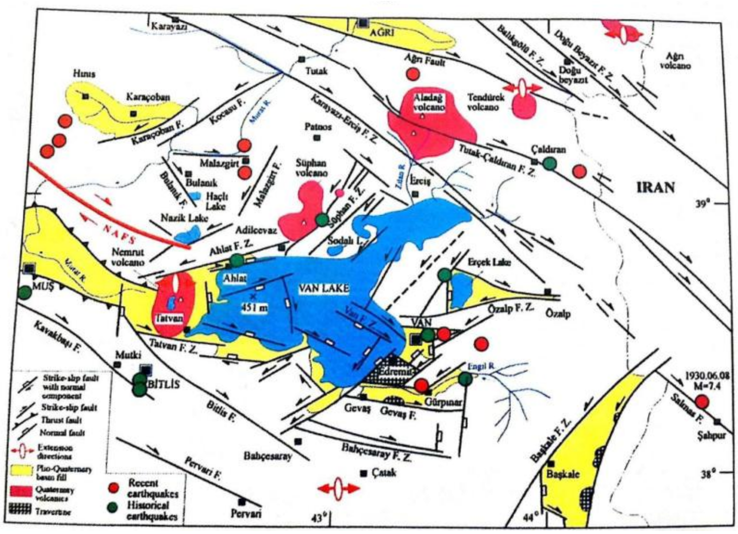


Fig. 3 The regional active fault map of Van (EERC 2011)

According to the latest information data (December 9, 2011), a total of 6284 aftershocks occurred after October 23 and November 9, 2011 earthquakes between 1.7 and 5.8 magnitude. 604 people (61 in the centre, 66 in villages and 477 in Erciş) as a result of first earthquake (October 23 2011) and 40 people because of second earthquake (November 9 2011) have died. 2608 people were injured after first earthquake (AFAD 2011). Many reinforced concrete and masonry buildings damaged and collapsed. A total of 63 reinforced concrete and masonry minarets are heavily damaged or collapsed in the city centre and surrounding villages.

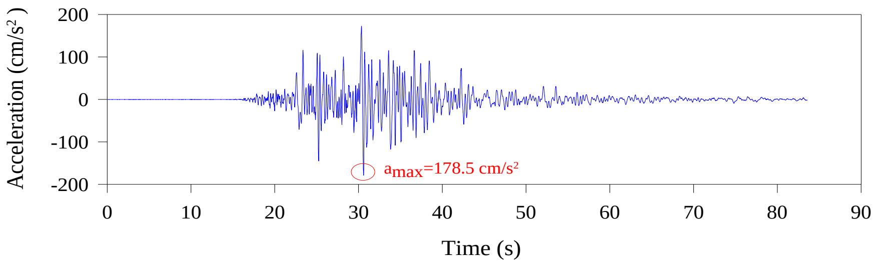
Seismic Zoning Map published by the Ministry of Public Works and Settlement of Turkey in 1996 considering maximum acceleration and the whole country is divided into 5 zones, as shown in Fig. 2(a). The majority of the Van city is at the first degree earthquake zone and the other regions at the second degree earthquake zone (see Fig. 2(b)) (AFAD 2011). The Erciş and Edremit earthquakes occurred on October 23 and November 9 2011, respectively took place on a blind fault, did not occur on a fault previously indicated and discussed in the literature. The regional active fault map is shown in Fig. 3.

3. Strong ground motions

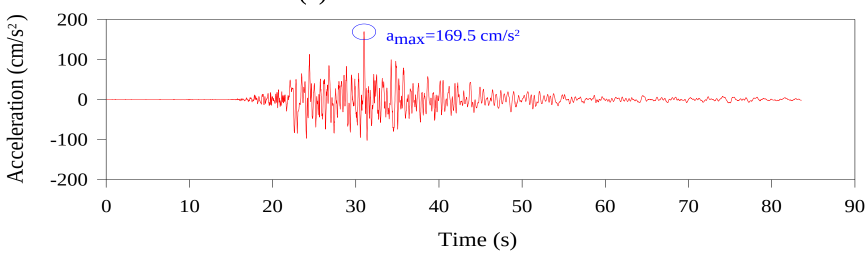
The reported parameters for October 23 and November 9, 2011 Erciş and Edremit earthquakes are given in Table 1. The three components of ground acceleration records for both earthquakes obtained at Muradiye station are given in Figs. 4 and 5. The accelerations were not recorded in the city centre.

Table 1 Parameters of October 23, 2011 Erciş and November 9 2011 Edremit earthquakes (URL-1]

Station Code	Date	Time	Depth (km)	N-S (cm/s^2)	E-W (cm/s^2)	U-D (cm/s^2)	Latitude (N)	Longitude (E)	Region
6503	23/10/2011	13:41	19.02	178.5	169.5	79.5	38.680	43.470	Erciş
6501	09/11/2011	21:23	5.00	148.08	245.90	150.54	38.429	43.234	Edremit

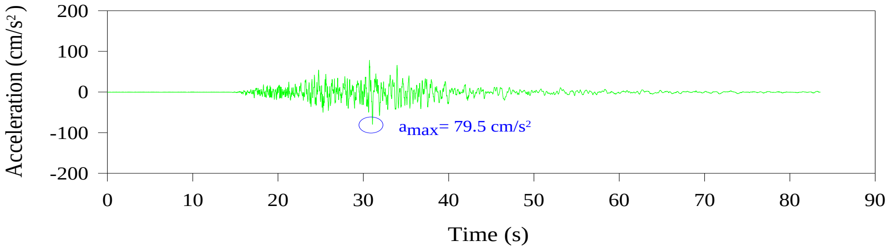


(a) North-South direction



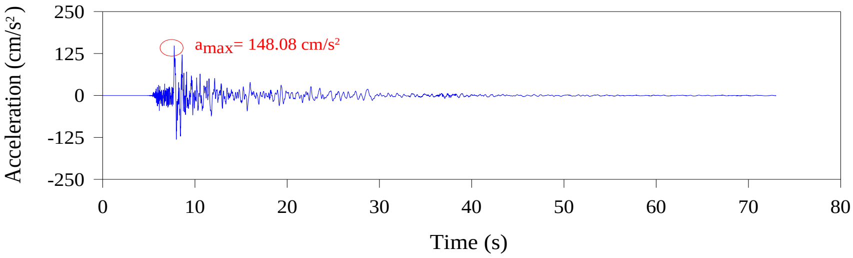
(b) East-West direction

Fig. 4 Three components of ground accelerations of October 23, 2011 Erciş earthquake recorded at Muradiye station. (EERC 2011, KOERI 2011)

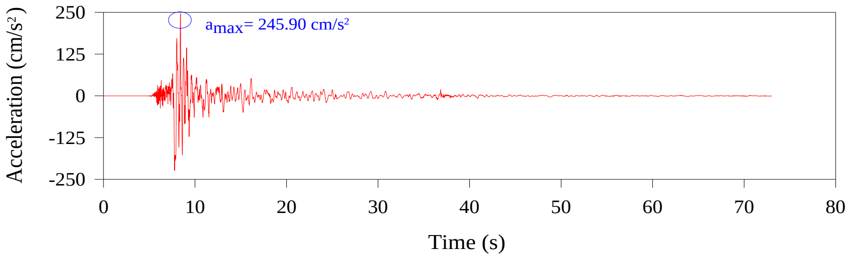


(c) Vertical direction

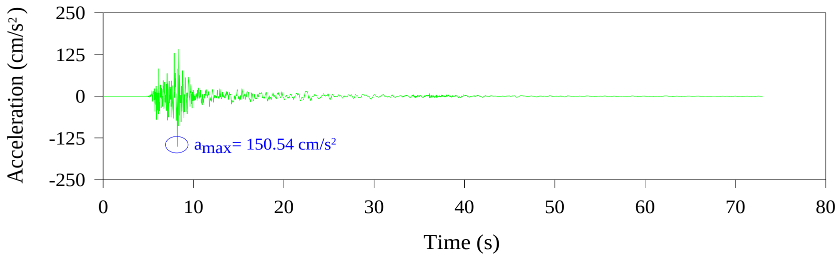
Fig. 4 Continued



(a) North-South direction



(b) East-West direction



(c) Vertical direction

Fig. 5 Three components of ground accelerations of November 9, 2011 Edremit earthquake recorded at Van Central Department of Public Works and Settlement station a) North-South direction, b) East-West direction and c) Vertical direction (EERC 2011, KOERI 2011)

4. Field investigations on the Minarets

The 23 October and 9 November 2011 Erciş and Edremit earthquakes caused significant damage to Van and its vicinity. The two earthquakes hit the minarets within seventeen days, causing progressive damage. A total of 63 reinforced concrete and masonry minarets are heavily damaged or collapsed in the city centre and surrounding villages after both earthquakes. Almost all the minarets are affected in the region. Most of the minarets in the affected villages were not designed and constructed in accordance with Turkish earthquake code (Turkish Earthquake Resistant Design Code 2011). It is seen from the field investigations that the damages in the masonry minarets can be classified into some points such as site effect, location, length of the fault, damage of the transition segment, reduction in cross section, use of cut stone with insufficient strength, material deteriorations, larger mass and stiffness concentrations, failure at the cylindrical body, damage of spire and end ornament, time dependent un-symmetry geometry due to the extra boundary conditions.

4.1 Ulu Mosque Minaret

Ulu Mosque Minaret located on Tebriz Kapı Street in Van city, Turkey. The minaret is located in the north western corner of the mosque.

Because of the fact that there was no inscription about the exact date of construction, the mosque and minaret dated to various periods by researchers. It can conclude from this inscription that this part of the mosque and minaret was constructed between the years of 1703-1704.

The minaret basically consists of three parts such as base, shaft and gallery. Base is reached from hard rock soil to floor. Shaft is a thin and slim body of the minaret and stairs are taken place cylindrically in the shaft to provide the necessary structural support for highly elongated shafts. The gallery is a balcony which encircles the upper section where the muezzins call out to prayer. It is covered by a roof-like canopy and adorned with ornamentation such as decorative bricks and decorated with painted tile, cornices, arches and inscriptions. The base has 1.4 m total height and continues on the upper with brick materials. The cylindrical body has variable cross-section, 12.20 m total height, 4.61 m diameter and 1.0 m wall thickness. There is a stone block, with 0.375 m diameter, in the middle of the minaret. Around the stone block, there are 55 stairs from the floor to the top point, and they have 0.28-0.30 m step height. Each stair has inner and outer radius as 0.375 m and 1.30 m, respectively.

From the field investigations, it is seen that the damages on Ulu Mosque Minaret occurred during the earthquakes. The view of the deteriorations and damages on Ulu Mosque Minaret can be seen in Fig. 7. The minaret is heavily damaged and should be restored.

5. Analyses of Ulu Mosque Minaret

5.1 Material properties

Determination of material properties and boundary conditions that must be taken into account in the finite element analysis is very important for thin and tall structures such as minarets. For this purpose, the bricks samples taken from the minaret were tested in the laboratory conditions to determine the mechanical properties. According to the experimental studies, the compressive strength of the bricks was obtained as 9.875MPa. Some views of the samples and laboratory tests can be seen in Fig. 7.

The selected values of the material properties for the analyses of the minaret are given in Table

2. It can be seen from Table 2 that the cylindrical body of the minaret divided into three groups. The terms of Part 1, Part 2 and Part 3 are used to imply the current situation of the minaret such as less damaged, moderately damaged and fully damaged, respectively.

Fig. 6 The view of the deteriorations and damages on Ulu Mosque Minaret

Fig. 6 Continued

Fig. 7 Some views of the samples and laboratory tests

Table 2 Material properties used in analyses of the minaret

Elements	Material properties		
	Modulus of elasticity (N/m^2)	Poisson ratios (-)	Mass per unit volume (kg/m^3)
Minaret-part 1	0.9E10	0.30	1600
Minaret-part 2	0.6E10	0.30	1600
Minaret-part 3	0.3E10	0.30	1600
Stairs and stone block	0.6E10	0.30	1600
Ground	1.2E10	0.35	2500

5.2 Finite element model and seismic analyses

Three dimensional finite element models of the minaret was developed using ANSYS software (ANSYS 2008). This program can be used for linear and non-linear, static and dynamic analyses of 3D model structures.

Convergence studies about element size were performed and the optimum element sizes were chosen for the finite element models. In the finite element models of the minaret, SOLID186 elements were used which exhibit quadratic displacement behavior. The element had 20 node and three degrees of freedom per node: translations in the nodal x, y, and z directions. In addition, it had the capability of plasticity, elasticity, creep, stress stiffening, large deflection, and large strains. When the structural solid geometry property of SOLID186 element is examined, it can be seen that the elements appear to be made of tetrahedral, pyramid or prism options in the finite element mesh model of the minaret.

The minaret was taken in place rock soil. As initial boundary conditions, all of the degrees of freedom under the footing part of the minaret are selected as fixed. The 3D finite element models of the minaret including concrete block and stairs is shown in Fig. 8. According to the convergence studies, optimum mesh size is chosen as 50cm. Therefore, 49286 SOLID186 elements are used in the finite element model.

A total of 5 natural frequencies of the minaret were obtained with a range between 6.38-25.59 Hz, respectively. When the first five modes are examined, the first two modes of the minaret are lateral modes in the z and x directions, the third mode is a torsional mode and last two modes are lateral modes in the z and x directions as seen in Fig. 9.

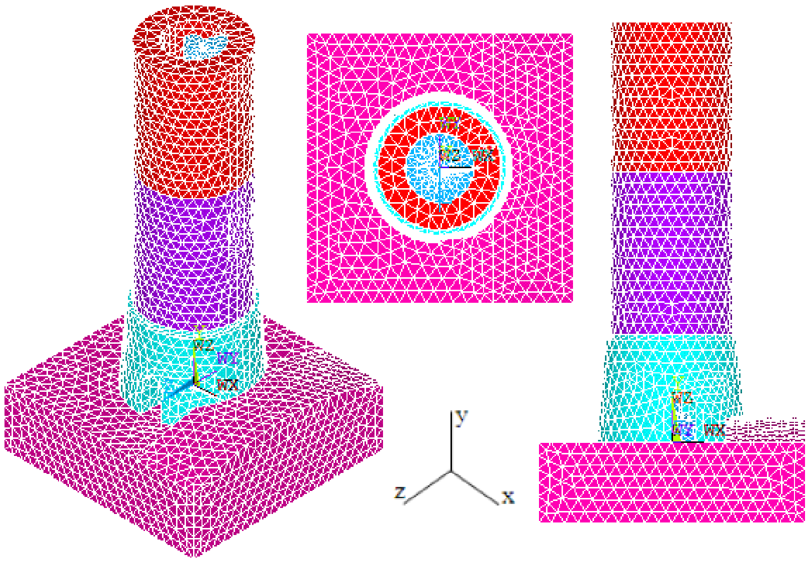


Fig. 8 3D finite element models of the minaret

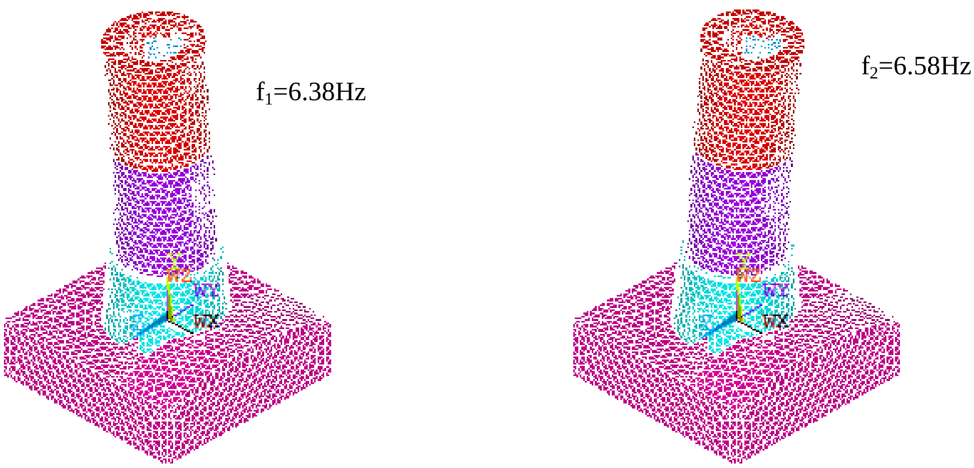


Fig. 9 Natural frequencies and corresponding mode shapes of the minaret

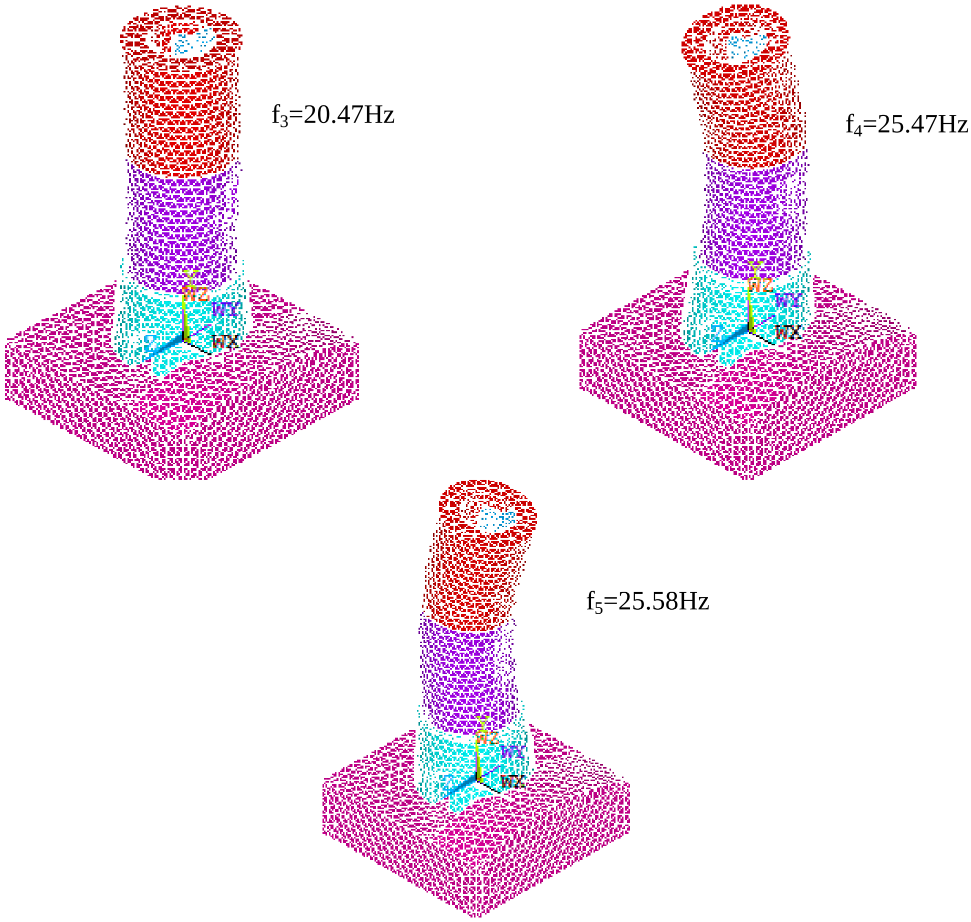


Fig. 9 Continued

Linear transient seismic analyses of the historical masonry minaret were performed using the Van earthquake ground motion. The Newmark method was used in the solution of the equations of motion. Rayleigh damping constants were calculated between the first horizontal mode of the minaret and the fifth mode, assuming a 5% damping ratio. Alpha and Beta coefficients were calculated as 3.206 and 0.0005. Because of the large memory required for the analyses, only the first 6.5 second of the ground motions, which is the effective duration, was taken into account in the calculations.

Fig. 10 points out the contours of maximum horizontal displacement. These displacement contours represent the distribution of the peak values reached by the maximum displacement at each point within the section. It is seen that the displacements increase along the height of the minaret and the maximum displacement (at the top of the minaret) is obtained as 17.64 mm.

The horizontal displacements along to the height of the minaret at the time of maximum response are given in Fig. 11(a). Also, the time histories of the horizontal displacements (with a peak value of 17.64 cm) at the top of the Ulu Mosque historical masonry minaret subjected to the ground motion is presented in Fig. 11(b).

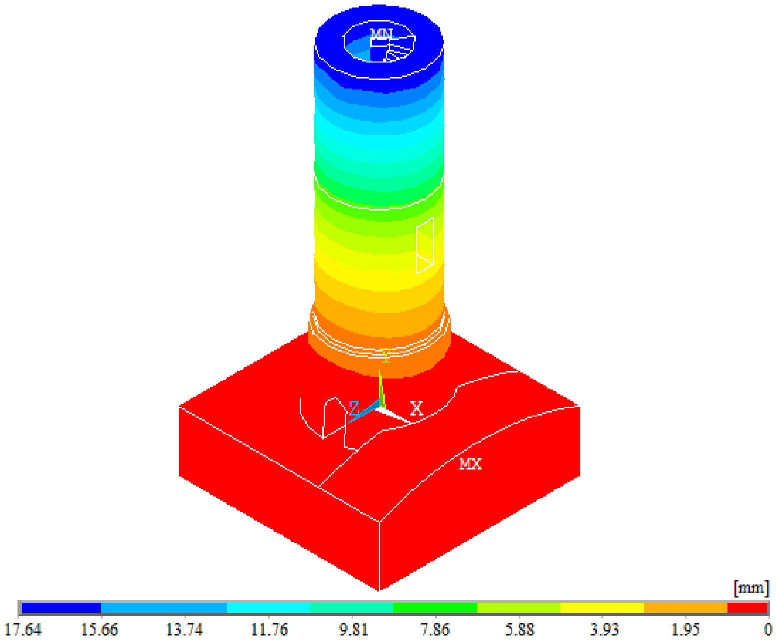
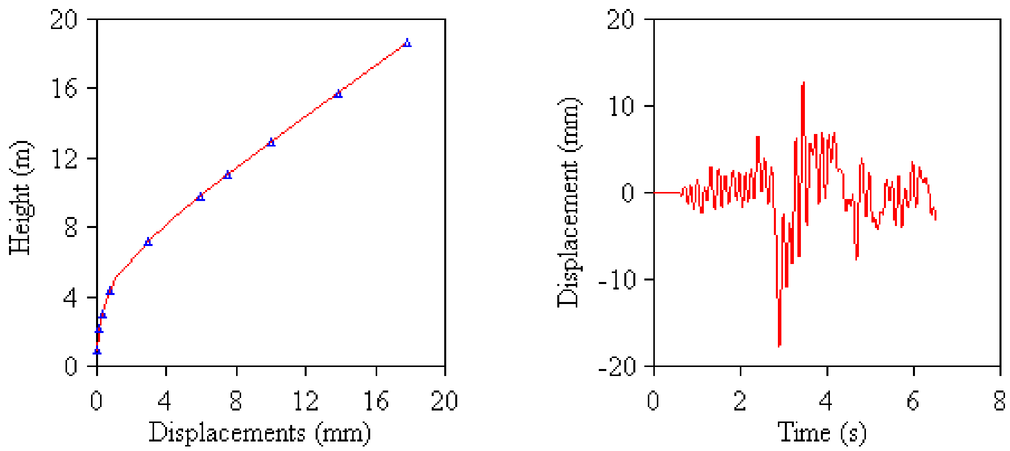


Fig. 10 Maximum displacement contours of the minaret

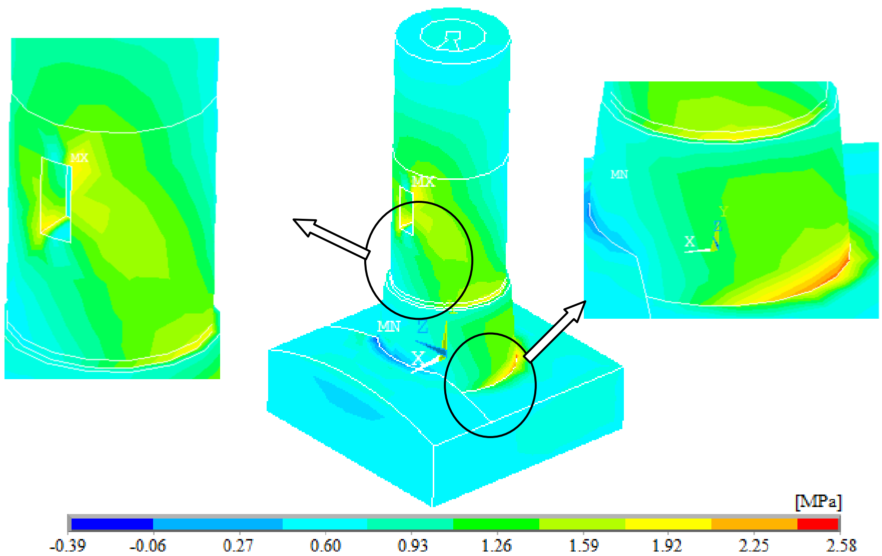


(a) (b)

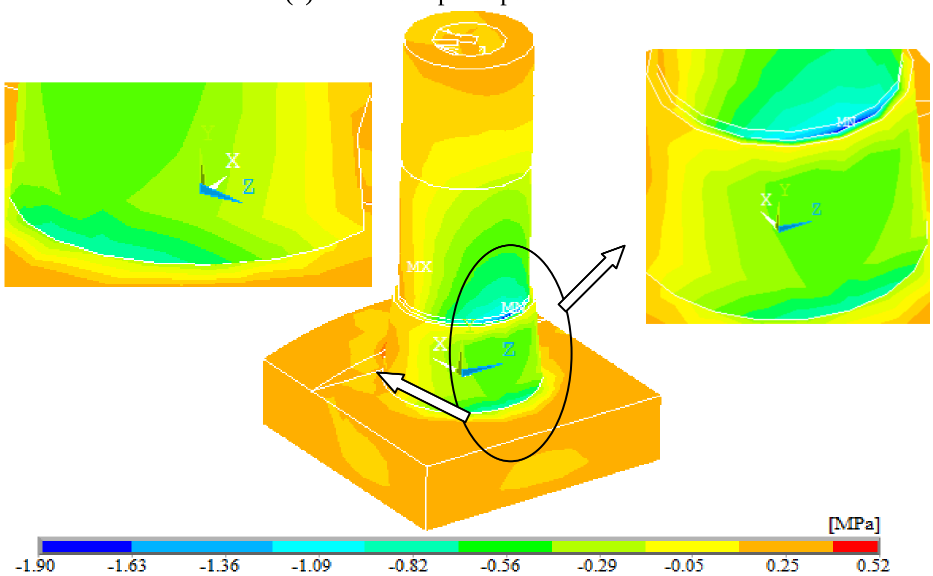
Fig. 11 Variation of the maximum displacements along to the height of the minaret and the time histories of maximum displacements at the top of the minaret

The maximum and minimum principal stresses contours which represent the distribution of the peak values reached by the principal stresses at each point within the section are given in Fig. 12. It is clearly seen from Fig. 12 that maximum and minimum principal stresses are occurred at the region between transition segment and cylindrical body. Also, extra stress distributions are obtained at the spaces such as door and windows. The maximum and minimum principal stresses were occurred as 2.58 MPa and 1.90 MPa, respectively. It can be said that the values of minimum principal stresses (compressive) obtained as 1.90 MPa does not cause any damage, but the values of maximum principal stresses (tensile) obtained as 2.58MPa caused the existing damage on the minaret.

The maximum and minimum elastic strains contours which represent the distribution of the peak values reached by the elastic strains at each point within the section are given in Fig. 13. The maximum and minimum elastic strains were occurred as 0.24E-3 and 0.21E-3, respectively.

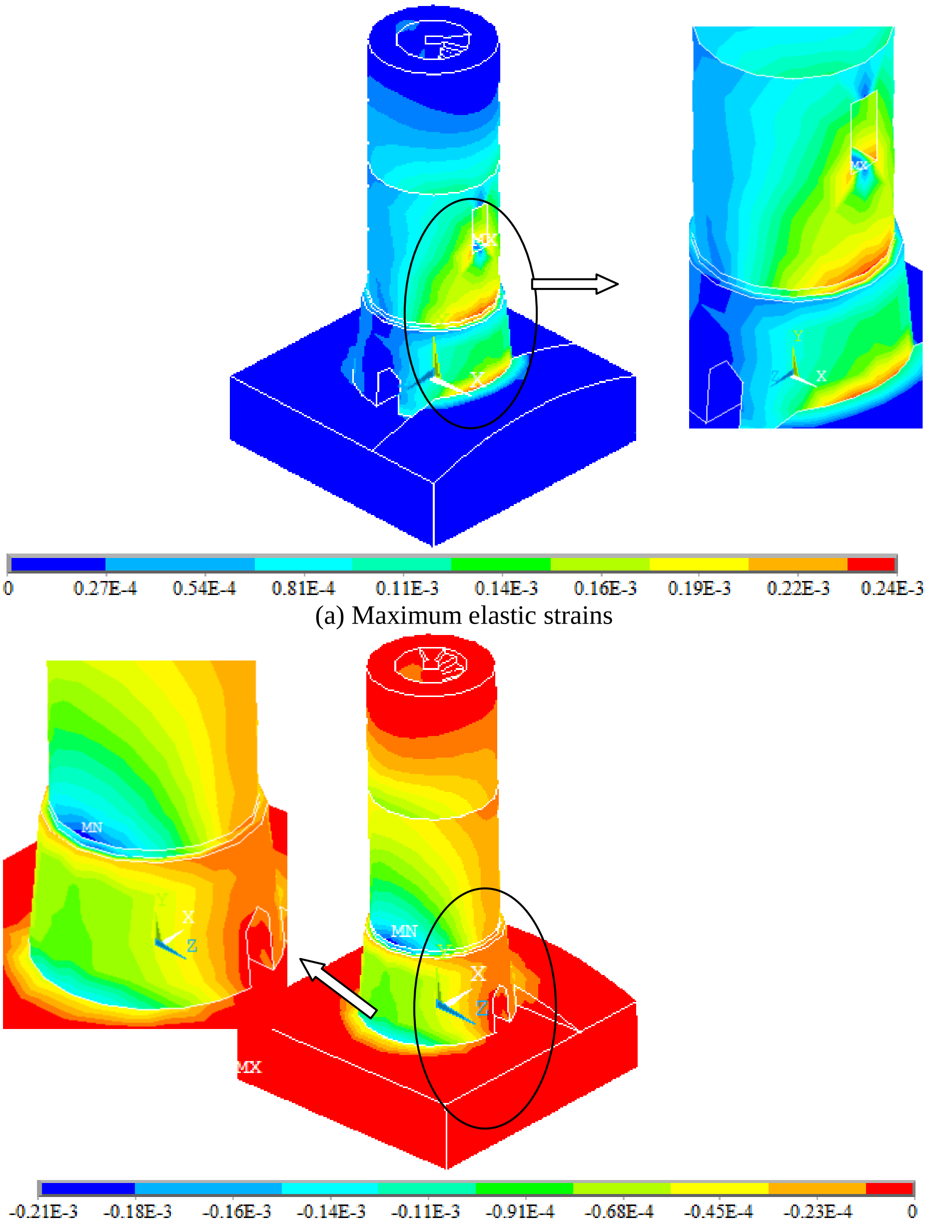


(a) Maximum principal stresses



(b) Minimum principal stresses

Fig. 12 Maximum and minimum principal stress contours of the historical minaret



(b) Minimum elastic strains

Fig. 13 Maximum and minimum elastic strains contours of the historical minaret

6. Conclusions

The paper addresses the field investigations and seismic performance evaluation of Ulu Mosque historical brick masonry minaret damaged during October 23 (Erciş) and November 9 (Edremit), 2011 Van earthquakes in Turkey. Based on the site observations and seismic finite element analyses results, the following conclusions could be drawn:

• A large proportion of non-engineering masonry minarets completely collapsed or damaged heavily in the region.

• Damages in the masonry minarets can be classified into some points such as site effect, location, length of the fault, damage of the transition segment, reduction in cross section, use of cut stone with insufficient strength, material deteriorations, larger mass and stiffness concentrations, failure at the cylindrical body, damage of spire and end ornament, time dependent un-symmetry geometry due to the extra boundary conditions.

• Two earthquakes hit the minarets in seventeen days. All of the collapsed and damaged minarets in the second earthquake have already been damaged in the first earthquake.

• According to the experimental studies, the compressive strength of the bricks used in the minaret was obtained as 9.875 MPa.

• A total of 5 natural frequencies of the minaret were obtained with a range between 6.38-25.59 Hz, respectively. When the first five modes are examined, the first two modes of the minaret are lateral modes in the z and x directions, the third mode is a torsional mode and last two modes are lateral modes in the z and x directions.

• The displacements increase along the height of the minaret and that the maximum displacement (at the top of the minaret) is obtained as 17.64 mm.

• The maximum and minimum principal stresses are occurred at the region between transition segment and cylindrical body. Also, extra stress distributions are obtained at the spaces such as door and windows. The maximum and minimum principal stresses were occurred as 2.58 MPa and 1.90 MPa, respectively. It can be said that the values of compressive stresses obtained as 1.90 MPa does not cause any damage, but the values of tensile stresses obtained as 2.58 MPa caused the existing damage on the minaret.

• The maximum and minimum elastic strains were occurred as 0.24E-3 and 0.21E-3, respectively.

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