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Seismic Assessment of Masonry Minarets under Different Earthquakes

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Abstract: Minarets are tall and slender structures and form important elements of mosques. Most historical minarets are constructed with masonry (brick or stone units), while modern minarets typically use reinforced concrete. Recent earthquakes have shown that the majority of these structures are highly susceptible to seismic excitation leading to a range of structural damage, from minor cracking to complete collapse. In this paper, the seismic response of a representative masonry minaret was investigated using acceleration records of the 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes. All acceleration records were scaled according to the location of the minaret. For this purpose, a representative masonry minaret that is thought to have been built in the city's central part of Elazığ, Turkey was chosen. After the seismic analysis, displacement and stress values obtained on the minaret were presented. It was seen that the displacements were increased along the height of the minaret. Also, the maximum and minimum stress values were obtained between the cylindrical body and transition segment of the minaret in accordance with the damage zones in the past earthquakes.

Key words: Masonry minaret, finite element modeling, seismic response.

Farklı Depremler Altında Yığma Minarelerin Sismik Değerlendirmesi

Öz: Minareler, camilerin önemli yapı elemanları olup ince ve uzun yapılardır. Tarihi minarelerin çoğu yığma malzeme (tuğla veya taş üniteler) ile inşa edilirken, modern minarelerde genellikle betonarme kullanır. Son depremler, bu yapıların çoğunluğunun, çatlaklardan tamamen göçmeye kadar çeşitli yapısal hasarlara yol açan sismik hareketlere karşı oldukça duyarlı olduğunu göstermiştir. Bu çalışmada, temsili bir yığma minarenin sismik davranışı, 1999 Kocaeli, 2003 Bingöl ve 2011 Van depremlerinin ivme kayıtları kullanılarak incelenmiştir. Kullanılan tüm ivme kayıtları minarenin konumuna göre ölçeklendirilmiştir. Bu amaçla Elazığ şehir merkezinde inşa edildiği düşünülen temsili bir yığma minare dikkate alınmıştır. Sismik analizin ardından minare üzerinde elde edilen deplasman ve gerilme değerleri elde edilmiştir. Minare yüksekliği boyunca yer değiştirmelerin arttığı görülmüştür. Ayrıca geçmiş depremlerdeki hasar bölgelerine benzer şekilde minarenin silindirik gövdesi ile geçiş bölümü arasında maksimum ve minimum gerilme değerleri elde edilmiştir.

Anahtar kelimeler: Yığma minare, sonlu elemanlar modeli, sismik tepki.

1. Giriş

Minarets may be described as high towers. They are the characteristic architectural feature of the mosques, which are principally used for the call to prayer (adhan). Nowadays, minarets are no longer used for this function because of the use of loudspeakers, but they are still constructed as one of the indispensable architectural components of mosques [1, 2]. They are tall and slender engineering structures that are constructed separately or contiguous to the mosque structures. The first known minaret was constructed in 710 CE in Tunisia [3]. In the early periods of minarets, these structures did not have a specific form and were constructed using bricks, stones, and wood [4]. Also, it is accepted that the Seljuks built the earliest minarets in Anatolia, Turkey [5]. There are many masonry minarets in the world that have been built from past to present. Although the architectural characteristics of the minarets may vary according to the time and region they are built, most historical masonry minarets are constructed using brick or stone units. Classical Ottoman minarets are generally stone blocks or brick masonry, while most of the contemporary ones are usually reinforced concrete (RC) [6]. However, masonry minaret construction is still common in rural regions. As it is known from the past, the most important external effects that damage minarets are earthquakes. Seismicity is significantly high in Turkey where the African, Arabian and Eurasian plates converge. The westward motion of the Anatolian plate is accommodated by the East and North Anatolian faults [7]. During the last two decades, several destructive earthquakes like 1992 Erzincan, 1999 Kocaeli and Düzce, 2003 Bingöl, 2010 Elazığ-Kovancılar, 2011 Van and 2020 Elazığ-Sivrice have occurred on the North and East Anatolian faults. Several studies have focussed on assessing the performance of structures during these earthquakes [8–16]. In Turkey, there are no guidelines and regulations for slender masonry structures (minarets,

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towers etc.). Due to their height, slim geometry and characteristical architecture, masonry minarets are vulnerable to seismic loading evidenced by the fact that a large majority of minarets were damaged or collapsed during the past earthquakes. 23 October 2011 (Mw=7.2) and 9 November 2011 (Mw=5.6) Van earthquakes resulted in heavily damaged or collapsed 63 masonry and RC minarets [17]. Significant earthquakes struck Elazığ and its surroundings in the past due to the seismic activity in the region (Fig. 1).

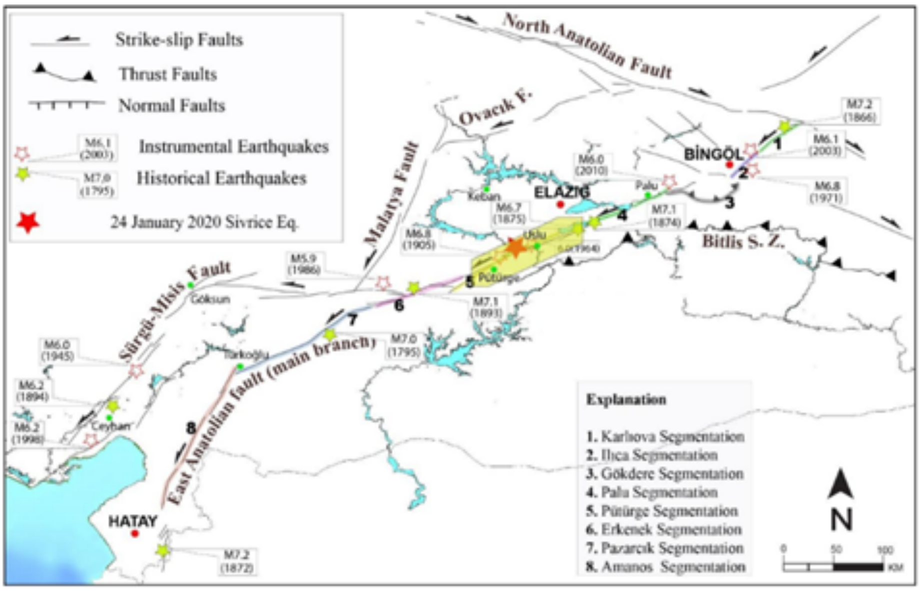


Figure 1. East Anatolian fault (historical and instrumental seismicity) [18].

Some studies have been carried out for seismic assessment of masonry and historical structures in the literature. However, the seismic behavior and performance of masonry minarets and towers are limited. Some of them can be listed as follows. Sezen et al. [19] investigated the damages and vulnerabilities of 64 reinforced concrete and masonry minarets after the 1999 Düzce and Kocaeli earthquakes. Erkek et al. [20] evaluated the seismic behavior of the historical Malatya Grand Mosque according to the Turkish Earthquake Code 2007. Oliveira et al. evaluated the seismic behavior of historical minarets which are constructed of natural block stone in Istanbul by using the finite element method and ambient vibration approach. Altunişik [21] evaluated the dynamic behavior of a masonry minaret before/after FRP (fiber-reinforced polymer) composite strengthening. For this purpose, the 1992 Erzincan earthquake was used to analyze and investigate the analytical model of the minaret. Coşgun et al. [22] studied the seismic behavior of a historical Dolmabahce mosque's minaret in Istanbul and presented a strengthening FRP procedure for the minaret. Pekgökgöz et al. [2] investigated the dynamic modulus of elasticity of the building stone of the Şanlıurfa historical Grand Mosque minaret. Measurements of the minaret were made by direct and semi-direct method. Hejazi et al. [23] assessed the structural analysis of a historical masonry minaret in Isfahan under temperature, wind, and earthquake loads. The analyses were studied for two different cases (the outer shell and the complete minaret) to investigate the effect of the central column and spiral staircase. Nohutcu et al. [24] investigated the damage and collapse mechanism in historical masonry minarets subjected to seismic loads. Hafsa Sultan minaret in the city of Manisa was selected as a numerical example Ercan et al. [25] analyzed a masonry minaret in Izmir, Turkey using linear and nonlinear time history analysis with two different acceleration records. Döven et al. [26] investigated the dynamic behavior of the Yeşil Mosque's minaret in Kütahya, Turkey in the case of closed and open balconies and compared them. For numerical analysis, ABAQUS finite element software was used. Hökelekli et al. [27] evaluated the seismic damage behaviors of stone masonry minarets with soil-structure interaction under different soil types. Türkeli [28] evaluated the historical Iskenderpaşa Mosque's masonry minaret under seismic and wind effects. For seismic effect, on 17 August 1999 Kocaeli and 12 November 1999 Düzce earthquakes were considered and top joint displacements and stress distributions were acquired. Yurdakul et al. [29] carried out a study to investigate the seismic performance of a historical minaret in Bayburt, Turkey. For this purpose, three acceleration records (1992 Erzincan, 1999 Kocaeli-Duzce, and 2011 Van-Ercis) were applied to evaluate the seismic behavior of the historical minaret.

Usta [4] studied the seismic assessment of historical masonry minarets which were placed in Antalya, Turkey. Time history analysis was performed to evaluate the earthquake performance of the minarets. Günaydın et al. [30]

presented a structural performance assessment of a historical masonry clock tower. For this purpose, a nonlinear time-history analysis was carried out and the seismic performance of the tower was evaluated. Scamardo et al. [31] evaluated the seismic behavior of a historical masonry tower located in Northern Italy. It is important to evaluate the seismic behavior of the minarets because there are no guidelines or code requirements for the design of masonry minarets in Turkey.

The aim of this study is to investigate the dynamic response of a representative masonry minaret which is thought to have been built in the city centre of Elazığ. For this purpose, three dimensional (3D) masonry minaret with typical geometry and material is modeled to study its dynamic response using ANSYS finite element software. To simulate seismic excitation, 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquake acceleration records which were scaled according to the location of the minaret were considered. By performing the seismic analysis, stress values and displacement obtained on the minaret were presented.

2. Descriptions of the Representative Minaret

Minarets are interesting structures due to their vulnerability to horizontal loads and their typological characteristics. They are the main part of the mosques and are mostly constructed near or attached to the mosques. Due to their slender geometry, masonry minarets are accepted as the most vulnerable structures to earthquakes. It is believed that the square tower was abandoned for the octagonal or cylindrical minaret during the Ottoman period [5]. In the Ottoman period, slender cylindrical and polygonal shafts with conical caps constituted the specific form of Turkish minarets [32]. Although its style (shape, height and physical geometry) varies according to the region and the period it is built, the basic form of the minaret consists of a base, shaft, and gallery. In Turkish mosque architecture, minarets are frequently placed on two sides of the mosques symmetrically. Every mosque has a minimum of one minaret. The number of minarets may vary depending on the significance of the mosque. Historical masonry minarets were generally constructed using stone or brick units. In Turkey, the stone units were largely used to construct historical masonry minarets. A minaret may either have an independent foundation or the base of the minaret may be attached to the roof of the mosque [33]. Depending on the number of balconies, masonry minaret height varies generally between 25 m and 70 m [34]. There may be one or more balconies at the minaret. If the minarets have balconies or balconies, these balconies cause concentrated mass along the minaret's height and they affect the seismic structural response of the minaret. A typical minaret generally consists of eight parts or components (Fig. 2).

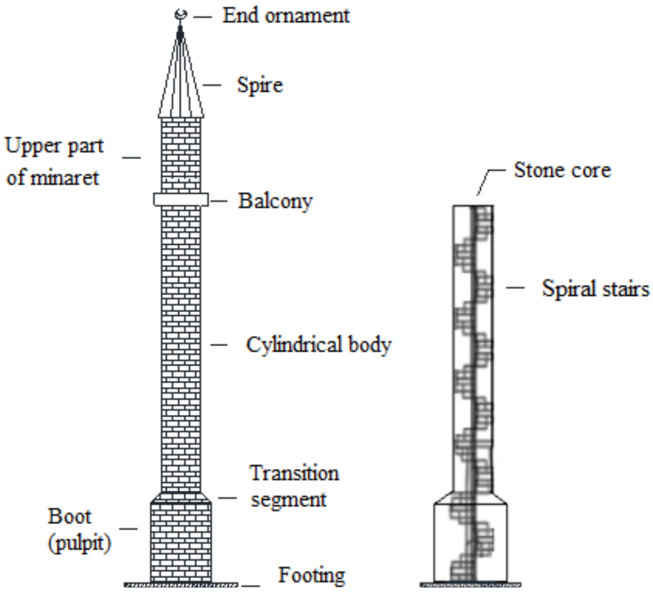


Figure 2. Typical masonry minaret.

These components are the footing (base), boot, transition segment, cylindrical or polygonal body, balcony, upper part of the minaret, spire and end ornament. Also, there is a stone core surrounded by a stone spiral stairway from the base up to the balcony level within the shaft. Stone core and stairs offer the required structural support to the shaft. The spiral stone stairways as well as the stone core end at the balcony level. The cross-section and geometrical properties of the masonry minaret are given in Figure 3. In the middle of the minaret, there is a 0.3 m diameter stone block within the shaft. The stone block is surrounded by spiral stone stairways with 0.25 m step height from the base up to the balcony.

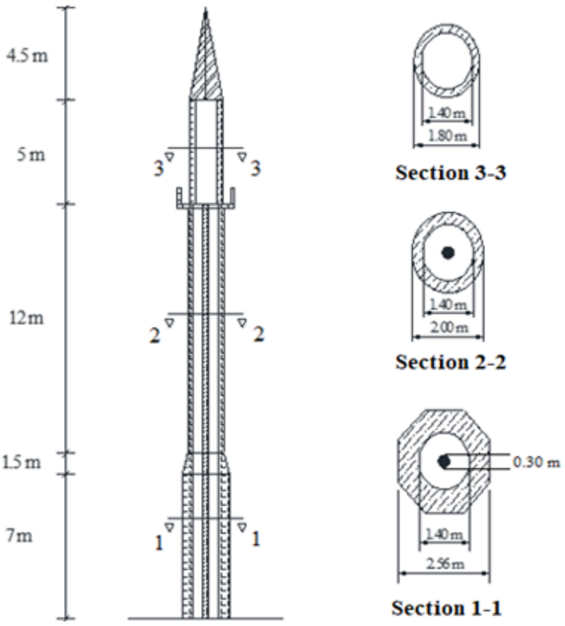


Figure 3. Cross-section and geometrical properties of the representative masonry minaret.

3. Finite Element Modeling of the Minaret

Modeling strategies of masonry structures, depending on the level of accuracy and the simplicity desired, had been divided into three groups (Figure 4). These approaches are detailed micro modeling, simplified micro modeling and macro modeling. Micro and macro models have different application fields therefore one modelling strategy cannot be preferred over the other [35, 38].

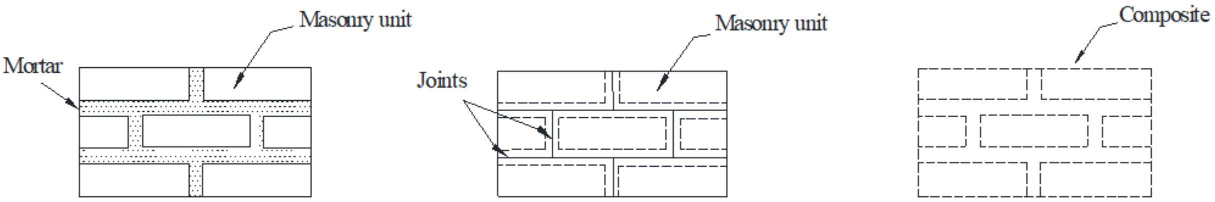


Figure 4. Modeling strategies for masonry structures [35,38].

Macro modeling is the most computationally efficient and modeling strategy, although accuracy may be sacrificed relative to micro- and simplified micro-modeling. However, given the high variability in the behavior of historical masonry constituents (stone/brick and mortar), the accuracy of micro-modeling can indeed suffer from the compounding effect of uncertainty propagation. In such cases, taking the macro-modeling approach using averaged properties can be beneficial. Moreover, given its low computational effort and sufficient validation of observational data, macro-modelling strategy is generally preferred in past studies [36–40] In this study, a representative masonry minaret with height of 30 m was developed using the macro-modelling approach in ANSYS. 3D solid finite elements (SOLID186) were considered for numerical modelling of the minaret. The element has twenty nodes and three degrees of freedom at each node, translations in the nodal x, y, and z directions. Figure 5 shows the geometry of the SOLID186 element.

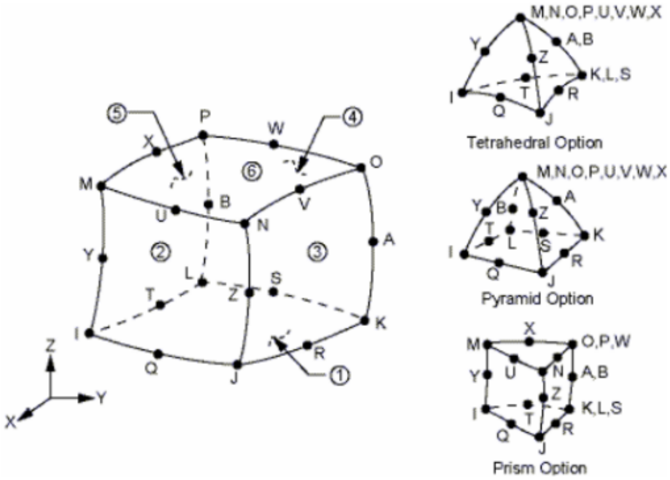


Figure 5. The geometry of the SOLID186 element [41].

The 3D finite element mesh model of the minaret and stone core with spiral stairs is given in Figure 6. The model consists of 14058 nodal points and 9673 elements. In this figure, one nodal point is selected at the top of the minaret for time history displacement graphs. It was assumed that the minaret is located on the rock soil and all degrees of freedom at the base of the minaret were selected as fixed. Linear elastic material behavior was assumed for the minaret model. Material properties used for the finite element model of the minaret were taken from the literature [34, 42]. Poisson's ratio, elasticity modulus, and unit weight of the masonry material used in the representative minaret were taken as 0.20, 10000 MPa and 2.2 t/m^3, respectively. Also, the compressive and tensile strength of the masonry material was taken as 16.9 and 0.9 MPa, respectively.

These values belong to the limestone masonry which is frequently used in the construction of the masonry minarets in Turkey and determined experimentally [43].

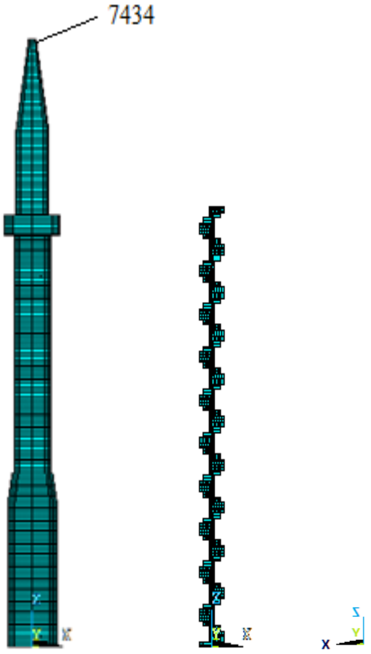
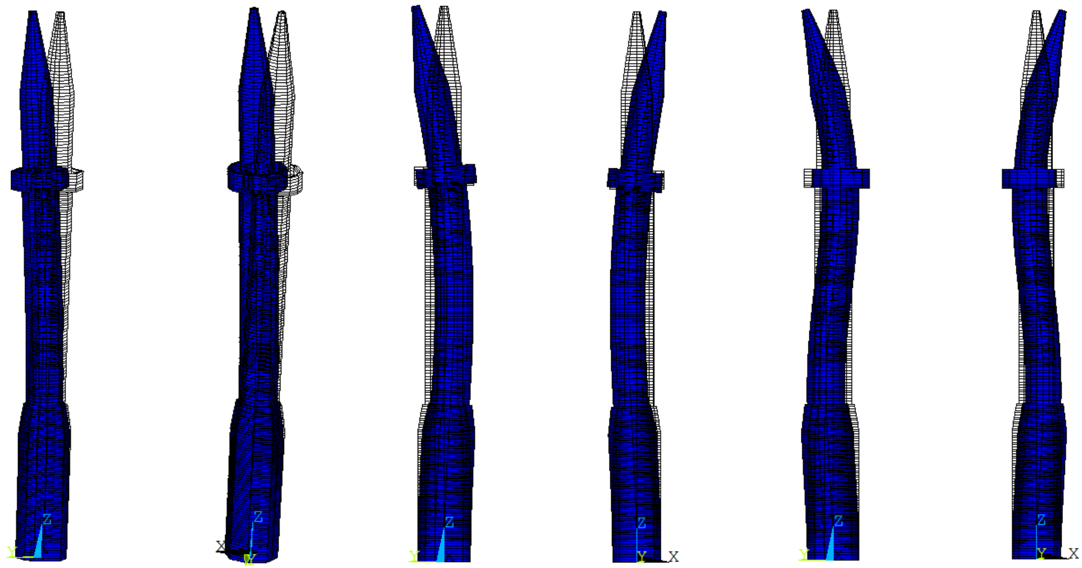


Figure 6. 3D finite element mesh model of the representative masonry minaret with stone block and spiral stairs.

4. Dynamic Analysis of the Masonry Minaret

4.1. Modal analysis

Minarets are generally slender and tall structures with low bending strength and they make large displacements under lateral loads such as earthquakes and wind. Past seismic events have shown that these tall structures are particularly vulnerable to earthquakes. They can easily collapse in the case of dynamic resonance. To define the dynamic characteristics of the masonry minaret before seismic analyses, modal analysis was performed. Mass participation ratios, mode shapes and free vibration periods of the investigated structure were obtained in the modal analysis. The damping ratio was taken into account as 5% for the Rayleigh damping coefficients in the analysis [4, 34, 44-45]. Dynamic characteristics of the minaret were calculated for the first 30 modes. The sum of the calculated effective mass participation ratios was found to be more than 90% of the total mass of the minaret for 30 modes. The first two modes of the minaret have similar frequencies because of the nearly circular symmetric shape of the minaret. The first six mode shapes and frequencies of the minaret are presented in Fig. 7.

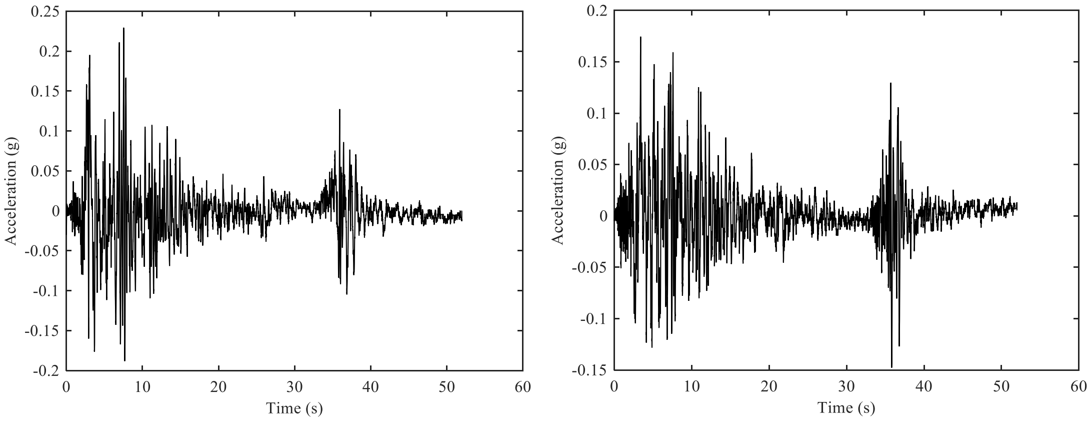


1st mode (f_1 = 1.514 Hz) 2nd mode (f_2 = 1.545 Hz) 3rd mode (f_3 = 6.544 Hz) 4th mode (f_4 = 6.703 Hz) 5th mode (f_5 = 13.763Hz) 6th mode (f_6 = 14.163Hz)

Figure 7. First six modes of the minaret.

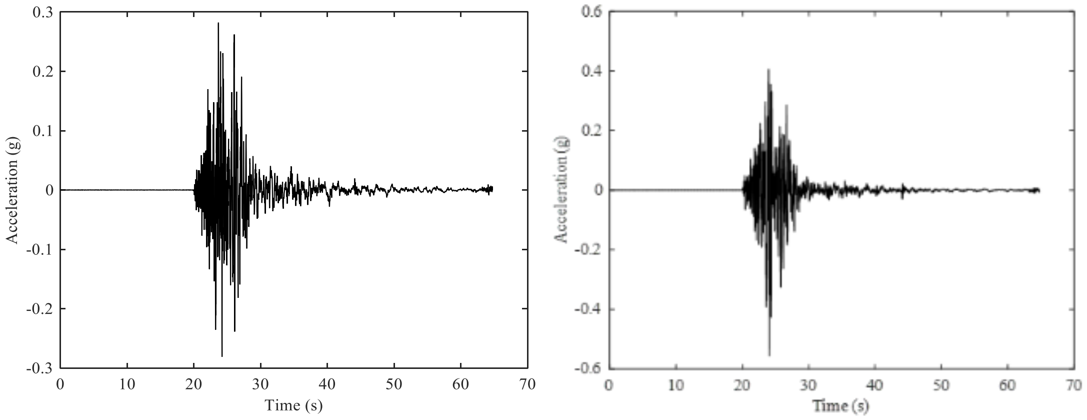
4.2. Seismic analysis

In this study, three different strong ground motions (1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes' acceleration records) were considered to evaluate the dynamic analyses of the masonry minaret. According to the location of the minaret, these acceleration records were scaled and applied to the masonry minaret in two horizontal (x and y) directions. The earthquake records were scaled using Seismomatch software [46]. The earthquake level of the seismic ground motion was chosen as DD-2 which represents a 10% probability of exceedance in 50 years (475 years return period) [47]. East-west (E-W) and north-south (N-S) components of these records were given in Figs. 8-10. HHT-α direct integration approach was considered for the time history analysis. Acceleration records of 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes are 52 s, 64.5 s and 83.5 s for durations, respectively. In the dynamic analysis, these records time of all earthquakes were used without shortening.



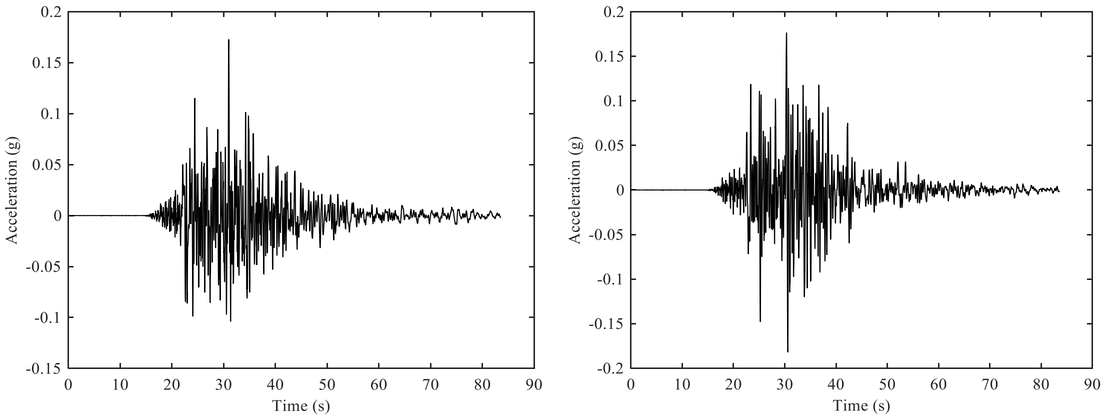
a) (E-W) component b) (N-S) component

Figure 8. Acceleration records of 1999 Kocaeli earthquake



a) (E-W) component b) (N-S) component

Figure 9. Acceleration records of 2003 Bingöl earthquake

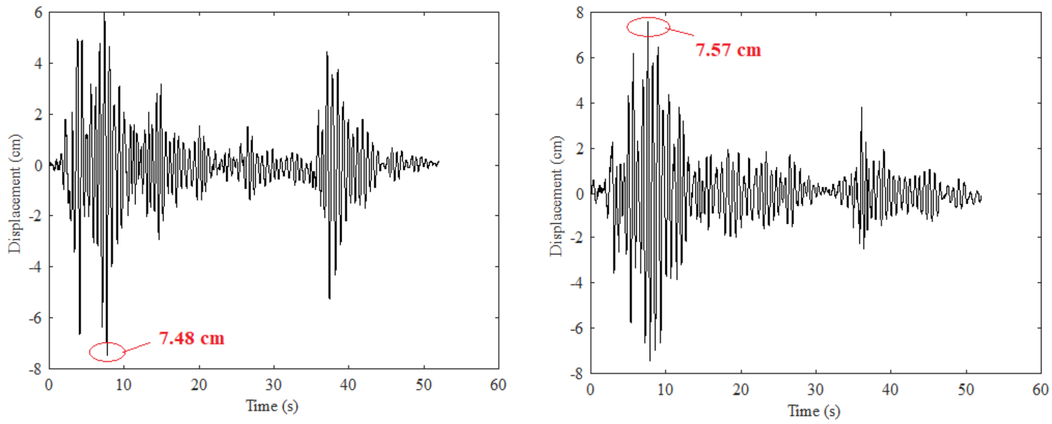


a) (E-W) component b) (N-S) component

Figure 10. Acceleration records of 2011 Van earthquake.

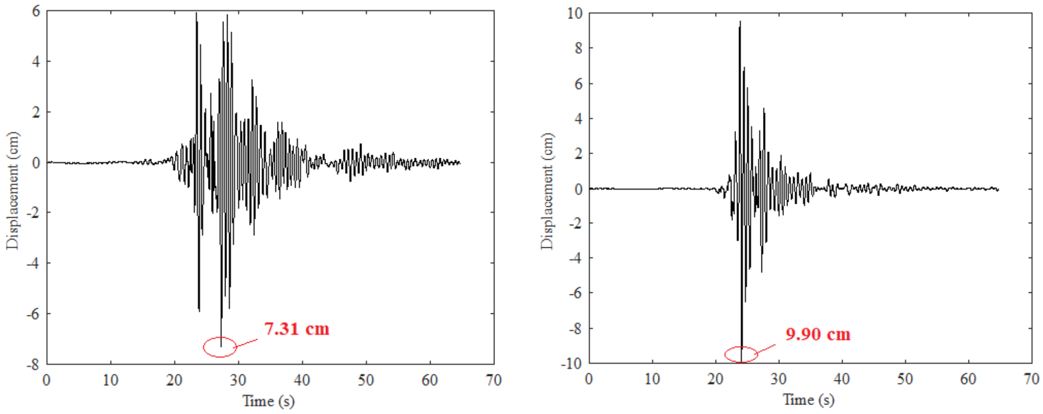
After the dynamic analyses, the horizontal displacements of the top of the minaret (nodal point 7434) in x and y directions were obtained for 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes. The time histories of the displacement in x and y direction subjected to the Kocaeli, Bingöl and Van earthquakes were given in Figs.

11-13. For 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes, absolute displacement values of the nodal point 7434 in x and y directions are 7.48 cm and 7.57 cm, 7.31 cm and 9.90 cm, 7.60 cm and 7.89 cm, respectively. When the time history graphs of displacement were examined for selected earthquake records, the maximum absolute displacement values of the minaret in the x and y directions were obtained from the 2011 Van and 2003 Bingöl earthquake acceleration records, respectively.



a) x direction b) y direction

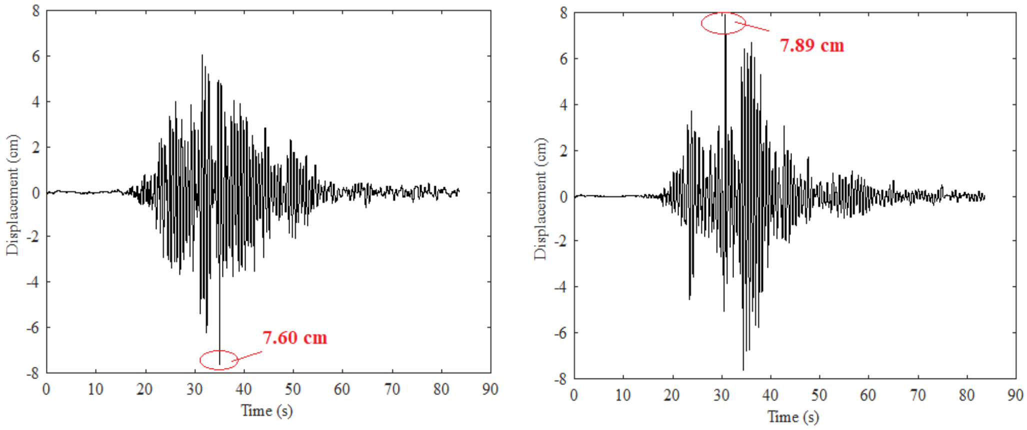
Figure 11. Horizontal displacement time history graphs at the top of the minaret subjected to 1999 Kocaeli earthquake.



a) x direction b) y direction

Figure 12. Horizontal displacement time history graphs at the top of the minaret subjected to 2003 Bingöl earthquake.

Also, six nodal points were selected on the masonry minaret and the absolute maximum horizontal displacement of these selected points was obtained after the dynamic analyses for selected earthquakes. Tables 1-3 show the maximum horizontal displacement (in x and y directions) values of the selected nodal points over the masonry minaret. The displacements are quite small up to the relatively more rigid boot level. When the horizontal displacements were examined over the height of the minaret, the displacements started to increase above the transition segment (8 m high) for all investigated earthquakes. However, there are two inflection points (slope of the graph changes) at the transition segment and balcony level in Fig. 14. The absolute maximum horizontal displacement distribution over the height of the minaret model for investigated earthquakes is given in x and y directions in Fig. 14.



a) x direction b) y direction

Figure 13. Horizontal displacement time history graphs at the top of the minaret subjected to 2011 Van earthquake.

Table 1. Displacements for selected nodal points in x and y directions for 1999 Kocaeli earthquake.

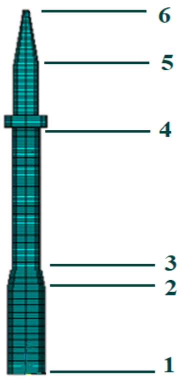
	**Location**	**Height (m)**	**Displacement (cm) x direction**	**Displacement (cm) y direction**
	1	0	0	0
	2	7	0.31	0.38
	3	8.5	0.45	0.52
	4	20.5	3.39	3.41
	5	25.5	5.66	5.71
	6	30	7.48	7.57

Table 2. Displacements for selected nodal points in x and y directions for 2003 Bingöl earthquake.

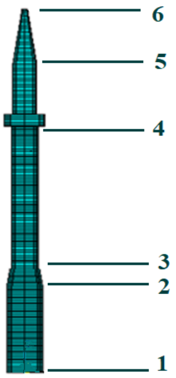
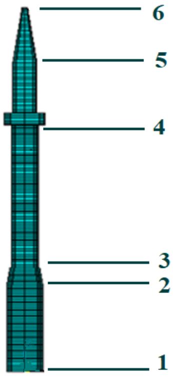
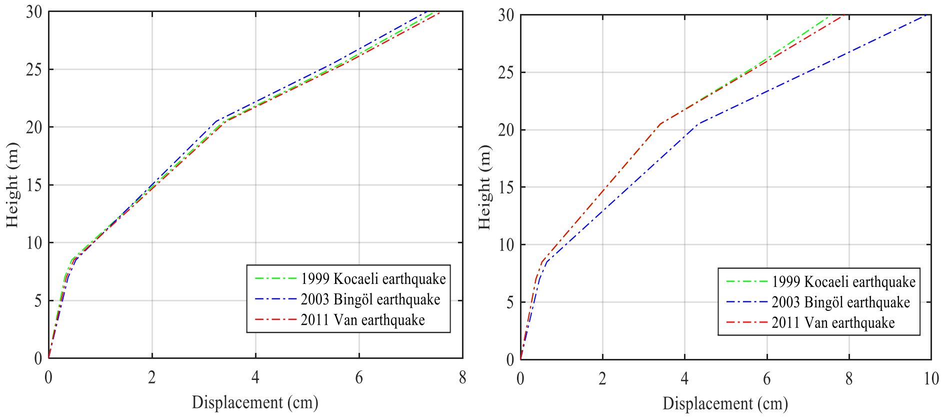
	**Location**	**Height (m)**	**Displacement (cm) x direction**	**Displacement (cm) y direction**
	1	0	0	0
	2	7	0.38	0.46
	3	8.5	0.53	0.64
	4	20.5	3.24	4.33
	5	25.5	5.49	7.27
	6	30	7.31	9.90

Table 3. Displacements for selected nodal points in x and y directions for 2011 Van earthquake.

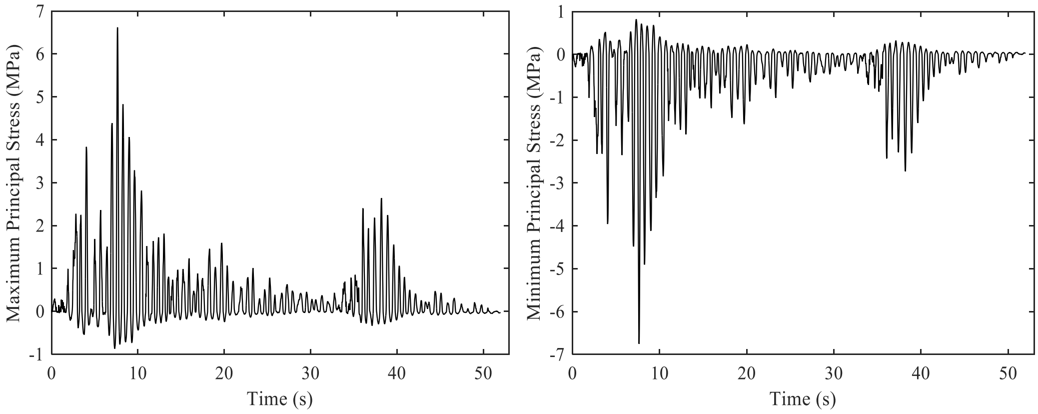
	Location	Height (m)	Displacement (cm) x direction	Displacement (cm) y direction
	1	0	0	0
	2	7	0.34	0.37
	3	8.5	0.49	0.52
	4	20.5	3.43	3.40
	5	25.5	5.73	5.79
	6	30	7.60	7.89



a) x direction b) y direction

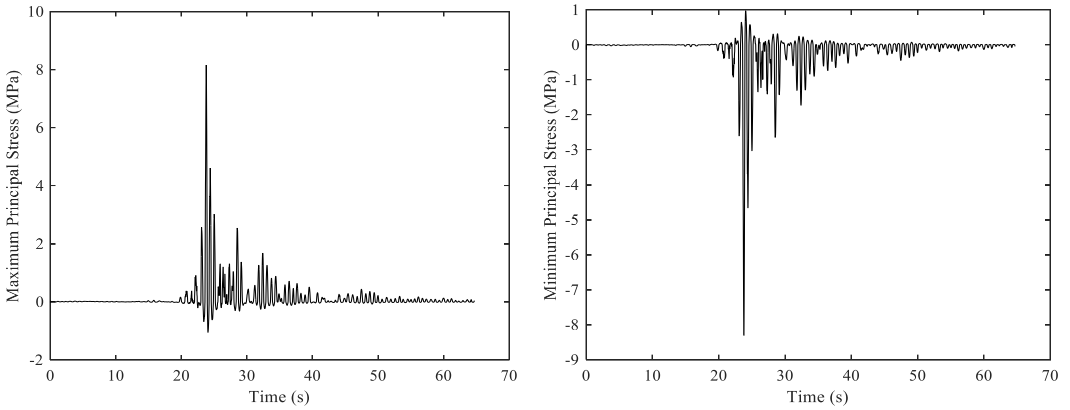
Figure 14. Absolute maximum horizontal displacement distribution along the height of the minaret.

The time history graphs of the maximum and minimum principal stresses of the minaret subjected to 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes are given in Figs. 15-17. The absolute maximum values of the maximum and minimum principal stresses for 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes were obtained at 6.62 MPa and 6.75 MPa, 8.16 MPa and 8.30 MPa, 7.59 MPa and 7.95 MPa, respectively. Maximum and minimum stress values have occurred for 2003 Bingöl earthquake. The obtained minimum stress on the masonry minaret is below the compressive strength of the masonry material, but the maximum stress is above the tensile strength of the masonry material. For this reason, possible cracks and damages can occur in the regions where the tensile strength exceeds.



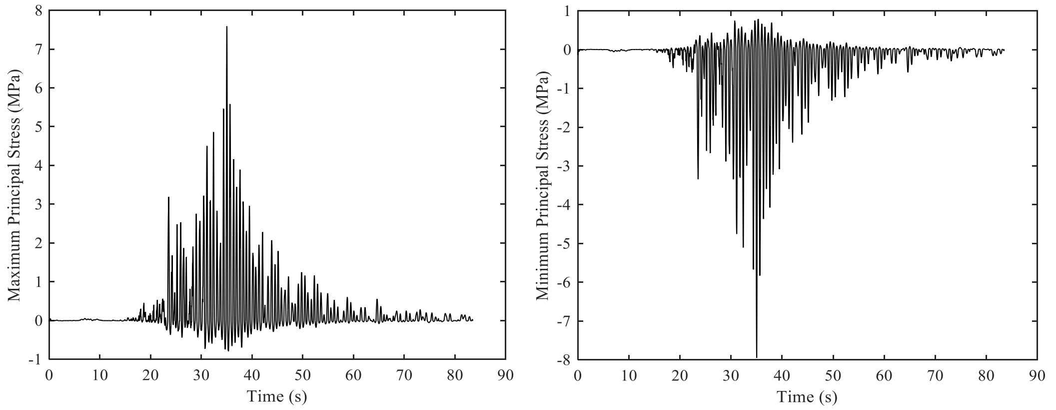
a) Maximum principal stress b) Minimum principal stress

Figure 15. Time history of the maximum and minimum principal stresses for 1999 Kocaeli earthquake.



a) Maximum principal stress
b) Minimum principal stress

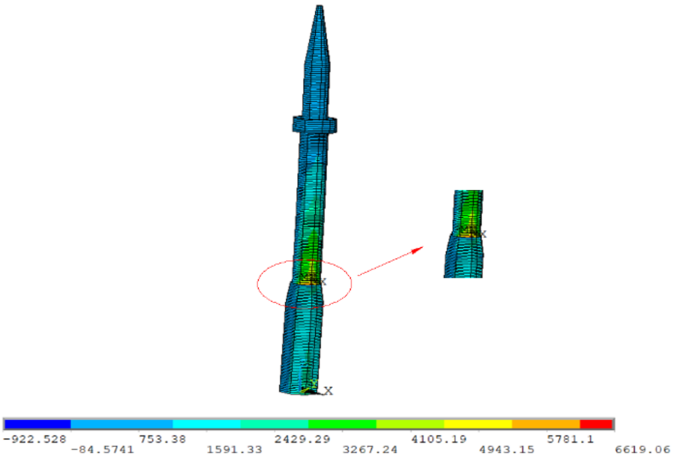
Figure 16. Time history of the maximum and minimum principal stresses for 2003 Bingöl earthquake.



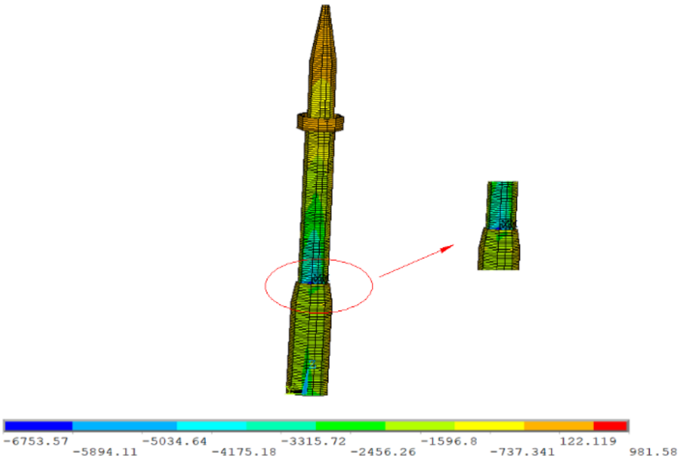
a) Maximum principal stress
b) Minimum principal stress

Figure 17. Time history of the maximum and minimum principal stresses for 2011 Van earthquake.

The maximum and minimum principal stress contours of the minaret for 1999 Kocaeli, 2003 Bingöl, 2011 Van earthquakes are given in Figs. 18-20, respectively. The distribution of the stress over the minaret was described by these stress contours. After the dynamic analyses, it was seen that the maximum and minimum principal stresses occurred in the region between the cylindrical body and transition segment. Obtained potential damage zones from the analysis are compatible with the minaret failures observed during the past earthquakes. When the post-earthquake evaluations and analysis results of masonry minarets are investigated, it is seen that most of these structures failed at the bottom part of the cylindrical body, just above the transition segment [4, 21, 22]. The most vulnerable section of the minaret is above the transition segment.

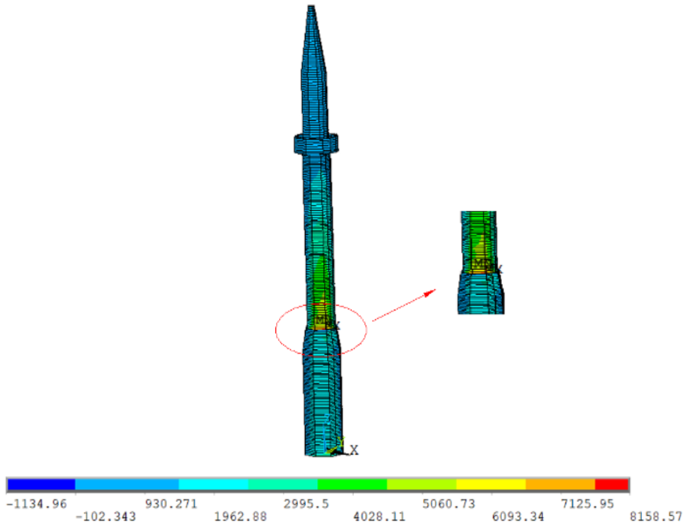


a) Maximum principal stress contours

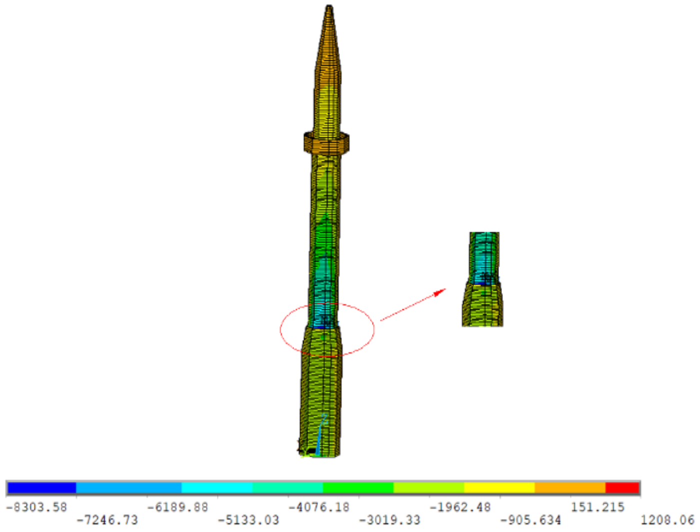


b) Minimum principal stress contours

Figure 18. Maximum and minimum principal stress contours of the minaret for 1999 Kocaeli earthquake (in kPA).

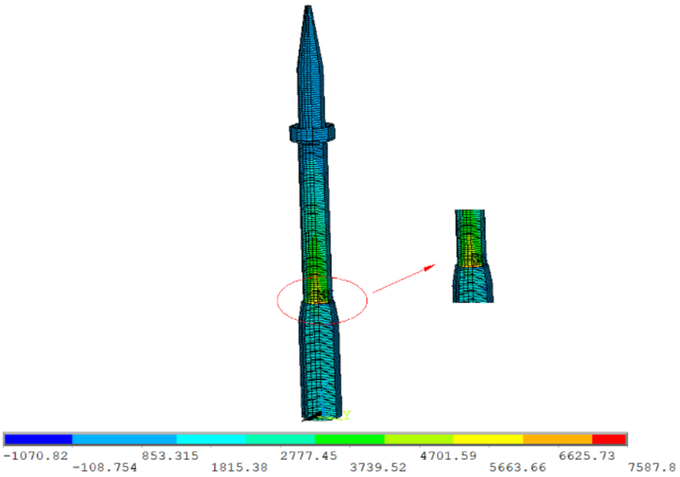


a) Maximum principal stress contours

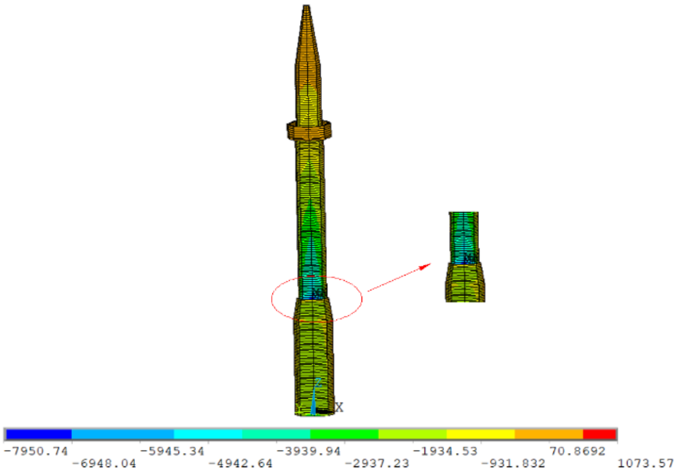


b) Minimum principal stress contours

Figure 19. Maximum and minimum principal stress contours of the minaret for 2003 Bingöl earthquake (in kPA).



a) Maximum principal stress contours



b) Minimum principal stress contours

Figure 20. Maximum and minimum principal stress contours of the minaret for 2011 Van earthquake (in kPA).

5. Conclusions

Minarets have specific role in mosque architecture despite the loss of main function. In this paper, the dynamic response of the masonry minaret presents. For this purpose, a representative masonry minaret located in Elazığ, Turkey with a height of 30 m was considered as a case study. Firstly, the structural model was constructed using solid elements with ANSYS software, and then dynamic analysis was performed using the same software. For dynamic analysis, 1999 Kocaeli, 2003 Bingöl and 2011 Van earthquakes were considered and applied to the minaret two horizontal directions. In the dynamic analyses, it can be seen that the acquired displacements increase with the height of the minaret. Also, the absolute maximum displacement occurred at the top of the minaret in x and y directions for 2011 Van and 2003 Bingöl earthquakes, respectively. Maximum and minimum principal stresses obtained from the dynamic analyses concentrated in the region between the cylindrical body and the transition segment. Therefore, it can be said that the most vulnerable part of the minaret is right above the transition segment. Also, maximum and minimum stresses values were occurred for 2003 Bingöl earthquake. For all earthquakes used in the analysis, the minimum stress on the masonry minaret is below the compressive strength of the masonry material, but the maximum stress is above the tensile strength of the masonry material. For this reason, it is likely that possible cracks and damages due to earthquakes may occur in the region between the cylindrical body and the transition segment. Finally, the obtained results in this paper comprise one representative masonry minaret but the main findings may be generally applied to other masonry minarets. In future studies, proper and applicable retrofit methods can be investigated to increase minarets earthquake resistant by using the nonlinear material models for dynamic analyses.

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