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Earthquake behavior of M1 minaret of historical Sultan Ahmed Mosque (Blue Mosque)

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Abstract. Minarets are almost the inevitable part of Mosques in Islam and according to some, from a philosophical point of view, today they symbolize the spiritual elevation of man towards God. Due to slenderness, minarets are susceptible to earthquakes and wind loads. They are mostly built in a masonry style by using cut limestone blocks or occasionally by using bricks. In this study, one minaret (M1 Minaret) of one of the charmest mosques of Turkey, Sultan Ahmed Mosque, popularly known as Blue Mosque, built between 1609 and 1616 on the order of Sultan Ahmed by the architect Mehmet Agha is investigated under some registered earthquake loads. According to historical records, a great earthquake hit Istanbul and/or its close proximity approximately every 250 years. Ottomans tackled with the problem of building earthquake resistant, slender minarets by starting to use forged iron connectors with lead as a filler to fix them to the upper and lower and to adjacent stones instead of using traditional mortar only. Thus, the discrete stones are able to transfer tensile forces in some sense. This study investigates the contribution of lead to the energy absorption capacity of the minaret under extensive earthquakes occurred in the region. By using the software ANSYS/LS-DYNA in modelling and investigating the minaret nonlinearly, it is found out that under very big recorded earthquakes, the connectors of vertical cast iron-lead mechanism play very important role and help to keep the structure safe.

Keywords: historical masonry structures; finite element analysis; discrete element method; earthquake analysis; earthquake resistant structures

1. Introduction

Sultan Ahmed Mosque is the second greatest and artistic imperial mosque in Istanbul and also is popularly known as Blue Mosque and visited by hundreds of thousands of tourists yearly (Fig. 1). It is the only historical mosque that has six minarets. Four of the minarets have three balconies while two of them have two balconies. Actually minarets are towers traditionally used by a crier (muezzin) to call the faithful to pray five times each day when there were no loudspeakers. The crier climbed up the stairs inside the minarets to reach balcony of it and on the balcony of minaret, he called out the adhan (call to prayer). Today, calls to pray are usually done in the prayer hall through a loudspeaker, and minarets serve as cultural symbols of Islam. But still the loudspeakers

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Fig. 1 Landscape view of Sultan Ahmed Mosque (Blue Mosque)

(a) Gaps between the Stones of M1 minaret above the second balcony

(b) Huge gaps between the cut Stones just below the upper most balcony (Inside view)

(c) The photo just below the second balcony after dismantling the Stones of the second balcony and the part above the second balcony

Fig. 2 Gaps and dismantled view of M1 minaret

are installed on the balcony of the minaret.

Due to their great importance to be the historical and cultural heritages and their slender structural systems, the behavior of minarets has been investigated by many researches. However, lack of detailed information and the absence of technical drawings make it difficult to create appropriate models and investigate the structural behavior under extreme conditions. Currently, M1 minaret of Sultan Ahmed, of which the behavior under earthquake loadings was investigated in this paper, is under restoration and the stones of the second balcony and the part above it were dismantled due to the gaps between the cut stones above the second balcony (Fig. 2). The first author of this study is among the consultancy committee of the restoration studies of M1 minaret of Sultan Ahmed Mosque (Blue Mosque). Without a consultancy committee consisting of an expert civil engineer, an expert architect (restorator), art historian and an expert chemist of construction chemicals on historical structures, it is impossible to fully evaluate and understand the historical structures and treat them correctly. The main tendency is to keep them as they are with their original strength level, architectural specifications and ornaments such as the carvings on the outer faces of the minarets of Sultan Ahmed Mosque (Fig. 3). If there is no structural damage either due to the detrimental effects of the external environment, for example the harmful effects of polluted air and the cycle of freeze-thaw, wetting-drying and big earthquakes, or if the structural system is not too weak against horizontal and vertical loads, it is not desired to treat or to strengthen a historical structure.

It is written in Kuşüzümü (2010) that in the minarets of mosques of Istanbul, after the use of spare stairs, fill rate was increased until 80%. Also forged iron bars (zıvana) and iron clamps (kenet) were used to connect the stones in the vertical and horizontal planes, Thus Ottomans achieved to construct tall minarets which are earthquake resistant. Schematic representations of a part of minaret body without and with spare stairs are shown in Fig. 4.

Forged iron connectors with lead to fix them to the upper and lower and to adjacent stones instead of using traditional mortar only were used to make the structure withstand against tensile loads occurred due to earthquake loads. However, as time goes by, due to the detrimental external effects, the forged irons get corroded and due to corrosion they expand, as well. Hence the cracks occur in the stones around them (Fig. 5). Sometimes the lead between the forged iron and the stones can compensate the expansion of the corroded forged iron and in this case, there may be no cracks in the stones. Yet, in M1 minaret, corrosion level of the forged irons were high and hence especially the upper part of the minaret becomes weaker against the wind loads and for this reason

Fig. 3 Stone carvings on the outer face of the M1 minaret and some deterioration of the cut stones

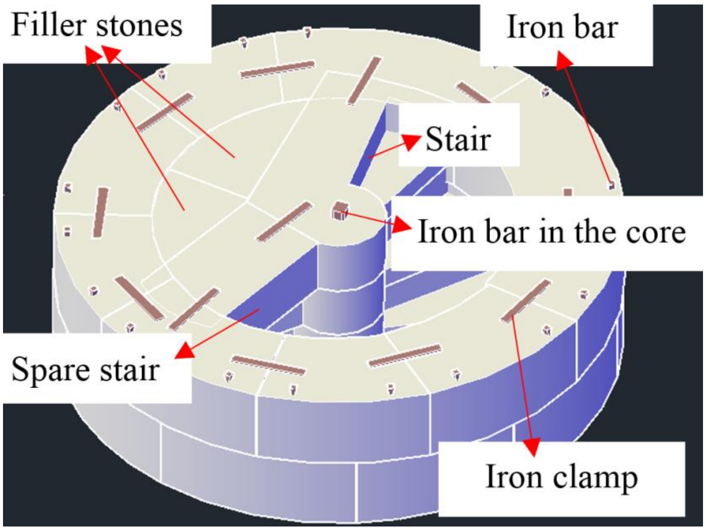


Fig. 4 Schematic presentations of a part of M1 minaret just above the upper most balcony

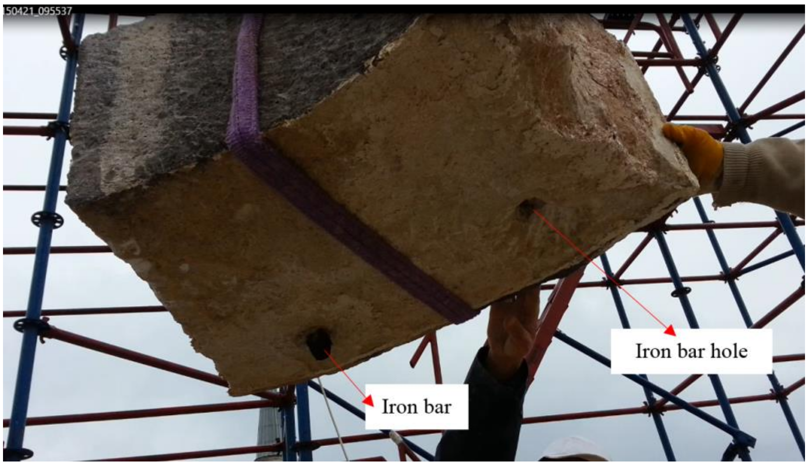


Fig. 5 Corroded vertical iron bars

there were gaps between the stones of M1 minaret as can be seen in Fig. 2. One of the reasons of these gaps is the expansion of the iron bars due to metal corrosion. The stones of the M1 minaret were dismantled until the second (uppermost) balcony but still the forged iron bars were corroded in advanced level. Hence, it is necessary to investigate whether or not the iron bars are effective against the earthquake loads, whether or not they damp the mechanical energy stored in the structure due to earthquakes to decide on dismantling the stones below the second balcony and to put them back to their original places by using new steel with lead filler. This decision is very important because as it is known the restoration studies are very costly. Also, according to the result of this study, there may be some comments on the reasons of collapses of old masonry minarets. Because, the reason may be the corroded iron bars.

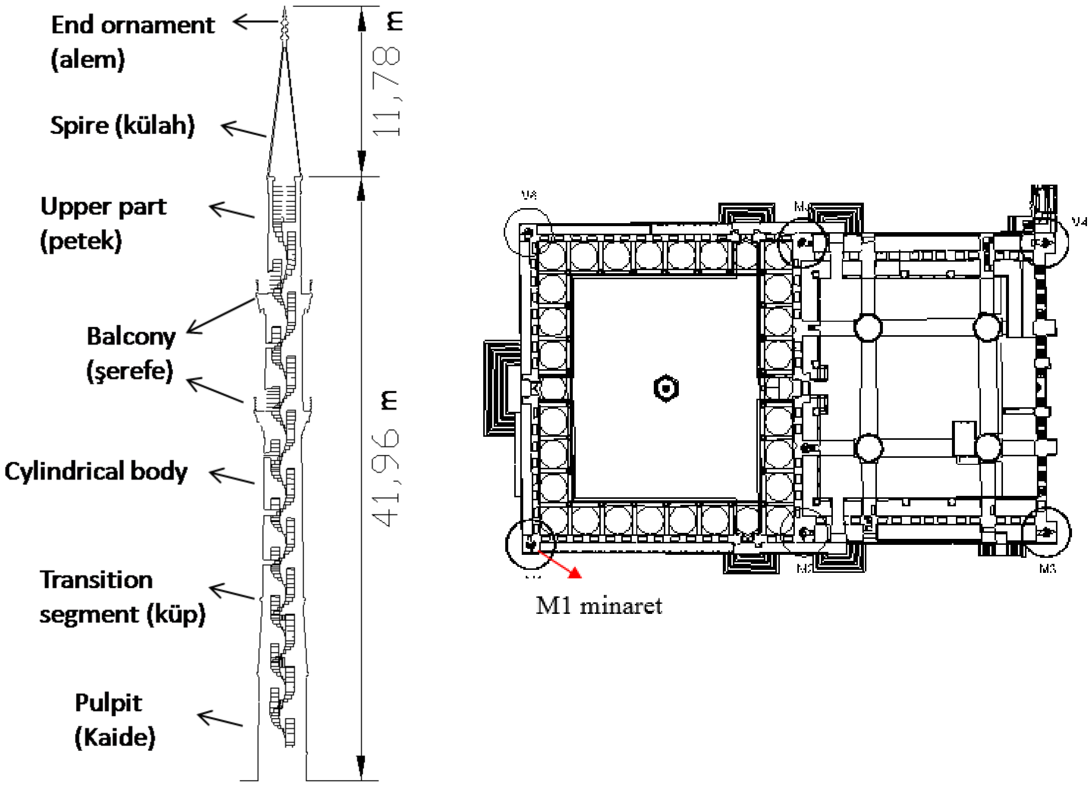
According to the Ottoman Archives of the Prime Ministry of Turkey, the parts above the uppermost balcony of the three minarets of Sultan Ahmed Mosque collapsed during the 1766 great earthquake which was greater than the 1509 earthquake (IM Architecture, 2012).

The general aim of this study is to investigate the contribution of vertical connectors to the earthquake resistance of the M1 minaret. Finite-discrete element method (FEM/DEM) is used to model the separation and rocking of individual stone blocks as well as the frictional behavior of the interfaces. Finite-discrete element method considers the structures as a collection of individual (discrete) elements (Cundall and Hart 1992, Lemos 1997, Sincraian 2001). In this method, each separate block moves independently and interacts with the adjacent elements by transferring loads, producing displacement fields and contact forces. The FEM/DEM method is inherently superior to the classical FEM approaches in modeling masonry structures (Dimitri *et al*. 2011, Baraldi 2015). Therefore, utilizing the finite-discrete element method on the simulation of masonry structures provides a way to obtain more realistic results which can be used in the decision process of retrofitting and restoration. Although, there are studies dealing with the dynamic behavior of masonry structures, strengthening of masonry minarets and masonry structures either by considering the walls of it, as a continuous homogeneous media (Pekgökgöz *et al*. 2013, Oliveira *et al*. 2012, Turk and Cosgun 2012, Turk 2013, Bayraktar *et al*. 2010, Dogangun and Sezen 2012, Ç akti *et al*. 2013, Cakti *et al*. 2014, Haciefendioglu and Birinci 2001) or as discrete stone elements (Bakeer 2009, Smoljanovic *et al*. 2015, DeJong and Vibert 2012, Tóth *et al*. 2009, Smoljanović *et al*. 2013), there are no studies considering the damping effect of lead filler between the forged irons and stones. As far as the authors know, this study is the first one investigating the efficiency of the connectors of vertical cast iron-lead mechanism on the dynamic behavior of the minarets under the earthquake loads.

2. Construction technique and geometric properties of the minaret

Classical Ottoman minarets essentially consists of a masonry wall and an inner core surrounded by a helicoidal stairway going up in the counter clockwise direction. This stairway is made of steps spanning from the inner core to the wall. The basic elements of the minaret are as follows: Footing, pulpit (*kaide*), transition zone (*küp*), cylindrical or polygonal lower part of the minaret body, stairs, balcony (*şerefe*), upper part of the minaret body (*petek*), spire or cap (*külah*) and end ornament (*alem*) (Fig. 6). Spire is usually a 3-D timber structure covered by 2-mm-thick lead sheets. There are two balconies of M1 Minaret of the Sultan Ahmed Mosque. Above the upper balcony, the helicoidal stairway goes up a few meters as well as the stone core in M1 Minaret. To support the spire, a wooden vertical cylindrical column with a diameter slightly smaller than the diameter of the stone core is used. This wooden column is put into a hole which is located a few meters below the top cylindrical body and extended towards the ornament.

In order to obtain earthquake resistant slender minarets, cut stones are connected with each other by anchoring the forged iron bars to the stones which are put one onto the other. Forged iron bar connectors (zıvana) are placed into the hole of the upper stone and the gap between stone and the iron bar is filled with melted lead. Subsequently, this stone with the iron bar is put onto the lower stone just in the position that the iron bar is plugged into the hole of the lower one. After that, by means of a thin channel cut beforehand, melted lead is filled into the hole in the lower cut stone. It is easy to connect the cut stones which are in the same level. *U* shaped clamps (kenet) are placed into the holes of adjacent cut stones and subsequently melted lead is poured into the gap between the legs of clamp and the hole of stones. Thus the discrete stones can withstand tensile forces. In summary, iron bars with lead as filler are used to connect stones in the vertical directions



(a) Component description (b) Plan view

Fig. 6 Geometrical representation of the M1 minaret

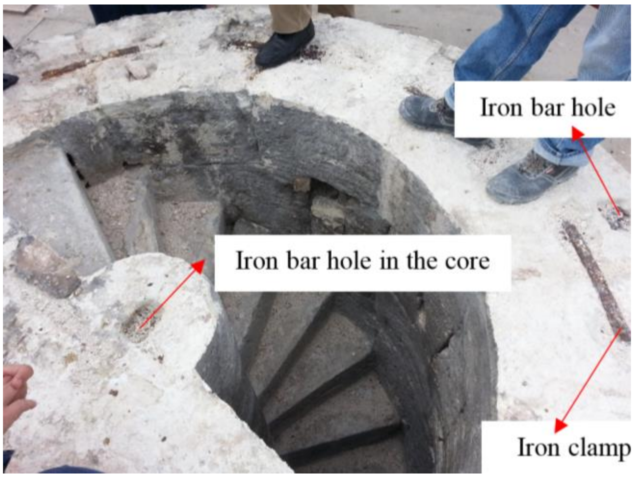


Fig. 7 Iron clamps and holes of the vertical iron bars and core with iron bar hole

and iron clamps with lead as filler are used to connect the stones in the horizontal directions. Detailed representive picture taken on the site is given in Fig. 7.

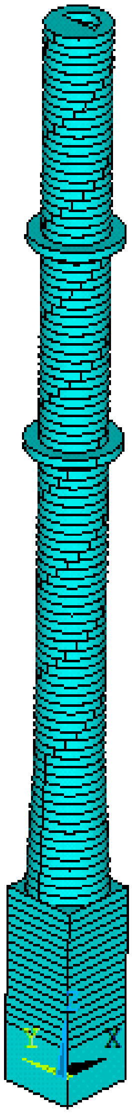
Fig. 8 Usual joints (zero joints) below the upper most balcony (Inside view)

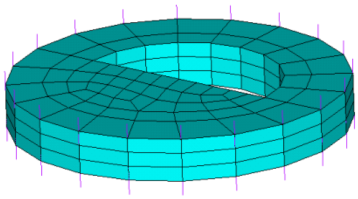
Actually, there must be zero joints between the cut stones of a minaret. However, formerly, it was very difficult to have cut-stones with smooth and level surfaces. Hence, not to allow the rain water going between the stones and causing corrosion, a special mortar called Khorasan (Horasan) mortar was used between the stones. The thickness of this mortar changes from zero to 10 mm according to the smoothness and levelness of the surfaces of the cut-stones. Thus, it can be stated that the contribution of the mortar to the tensile strength is insignificant in most cases. In Fig. 8, the interface of the separate blocks comprises the outer walls can be seen clearly. The mortar is only applied locally (e.g., to fill the gaps in the interface).

3. Finite-discrete element model of the Sultan Ahmed Minaret

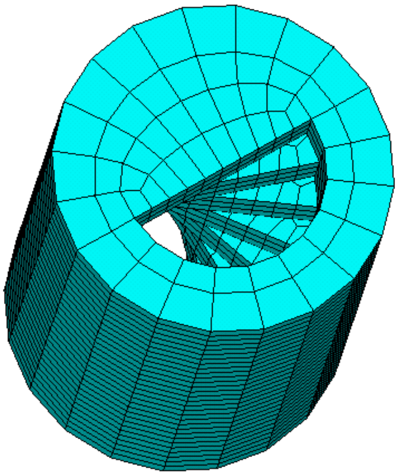
The finite element model of the minaret was created by the help of the technical drawings, which had been prepared during the restoration processes. The geometry of the structure is further simplified in order to reduce the finite element number and improve the efficiency of the finite-discrete element analysis. The minaret was discretized into 112 separate hollow cylindrical blocks with the height of 0.36 cm. The geometry and the FE mesh of the discrete blocks and the entire structure are shown in Fig. 9.

At the interface of the each interacting block, frictional contact behavior was defined. Law of Coulomb friction was adopted. Furthermore, the interfaces were modeled so that the joints have no tension or cohesion. The picture of an interface between separate blocks taken during the restoration processes also supports that the contribution of the mortar at the interfaces to the





(b) Hollow cylinder section with vertical lead connectors and FE mesh of units



(a) Discrete element model

(c) View of the helicoidal stairs

Fig. 9 Finite-discrete element model of the minaret

structural behavior is limited and local (Fig. 8). In many cases, it has been found out that the tensile strength of the mortar is around 0.3-1 MPa, which can be exceeded even under moderate earthquakes or horizontal loads produced by winds (Ural ve Fırat 2015, Bolhassani *et al*. 2015). Hence, it is assumed that the contribution of mortar is negligible. Therefore, the external loads are solely resisted by the self-weight of the structure, the friction between the discrete elements and the vertical iron bars connected to the stones by means of lead.

The isoparametric eight-node 3D brick elements were used in the FEM to model the outer wall and the inner stairs of the minaret. The lead bars which connect two masonry blocks vertically were modeled by truss elements. Those elements carry axial load only and have uniform properties along its longitudinal axis. The material properties of the brick elements (limestones) are assumed to be linear referring to the studies which showed that the maximum compressive stresses does not exceed 8 MPa (Altunisik 2011). The average compressive strength of the masonry units like limestone used in this historical structure is around 16-17 MPa (Bayraktar *et al*. 2011, Clementel *et al*. 2015). An elastic perfectly plastic material model has been adopted for the vertical connectors. In fact, modeling of anchorage of vertical connectors to the masonry units is a challenging task. However, it was assumed that the failure of the connectors is to be led by the failure of the lead filler. Thus, the lead material properties have been used for vertical bars. Crushing of the stone units around the connectors could be expected in some cases. However, this is out of scope of this paper and further investigation is required. The yield stress and the strain of the lead was taken as 18 MPa, 0.1%, respectively. The elastic modulus of the brick material was taken as 9 GPa. Density of masonry blocks was assumed to be 2000 kg/m^2. The density of the masonry units are generally more accurate than compressive strength or yield strain/stress of the materials due to straightforward measurement of the density (Bakeer 2009).

Rayleigh damping is used as the damping model. In general, it is difficult to specify a damping model for the finite-discrete element models since in real-life structures, especially for the ones, which have both material and geometric nonlinearities, damping mechanism could be rather complicated (DeJong 2009). In this study, a mass proportional damping which approximately corresponds to 2% of the critical damping is applied. The coefficient of mass proportional damping ($\alpha = 2\omega\zeta$) was computed by considering the first circular mode which has been obtained by modal analysis. The first circular mode which results in $\alpha = 0.22$, was calculated as 0.85 Hz.

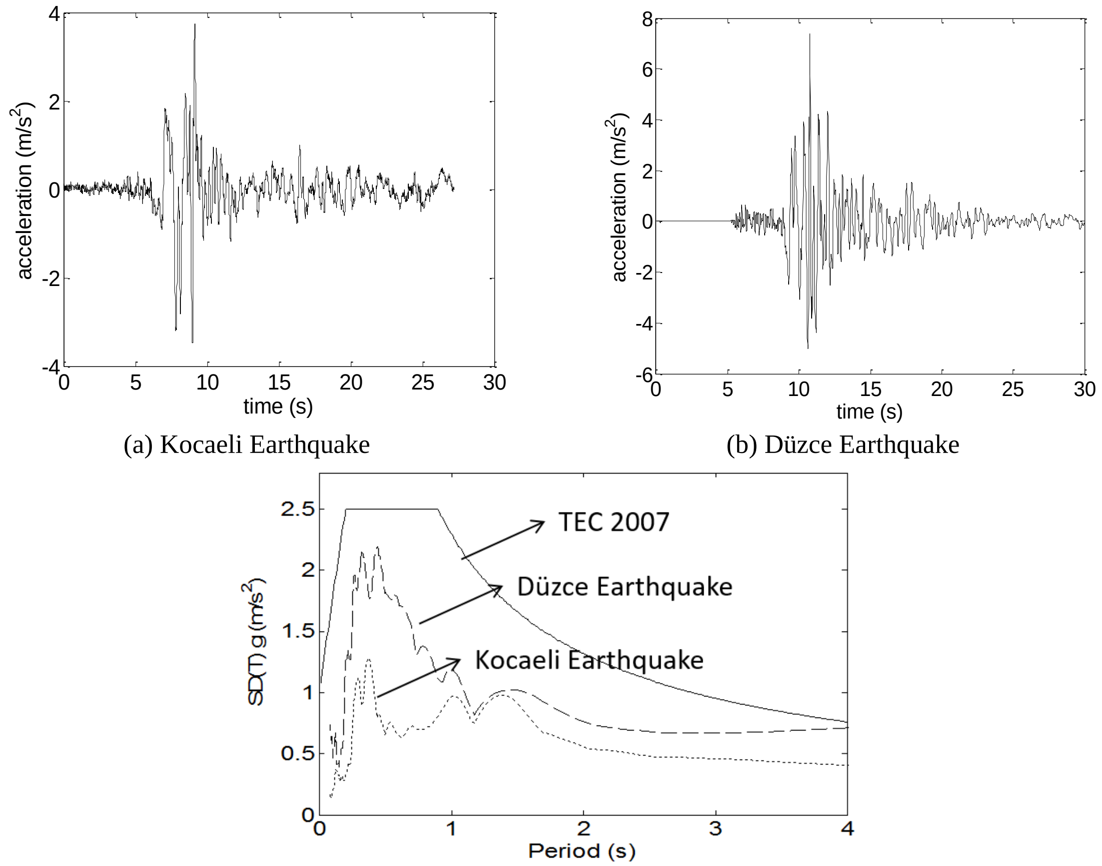
ANSYS/LS-DYNA (2008) defines the coefficient of friction depending on the relative velocity of the interacting masonry units and a decay coefficient which smooths the transition of static to dynamic friction coefficient. In this study, static and dynamic coefficients of friction are taken as 0.6 after surveying studies in the literature (Smoljanović 2013, Casapulla and Portioli 2015).

As mentioned in the first section, the spire is a 3-D timber structure covered by 2-mm-thick lead sheets. It may be assumed that the rigidity of the spire is low in comparison to the masonry stone units and its contribution to the global structural response is relatively insignificant. In addition, modeling of the spire is computationally inefficient due to the increasing number of finite elements. Besides, it may cause local damage and/or overturning of the masonry units at the top of the minaret. Hence, the spire of the minaret was not taken into account in finite-discrete model. However, the weight of the spire which is estimated to be 20-30 kN was added up to the top masonry annular cylindrical ring unit.

The minaret was subjected to two earthquake motions which are the strongest earthquakes that hit the Marmara region one after the other within a few months. The properties of the earthquake records are given in Table 1. Both time history signals are shown in Fig. 10 as retrieved from Prime Ministry Disaster and Emergency Management Authority. Earthquake spectra for registered time histories are also given together with the design spectrum which is proposed in Turkish

Table 1 Properties of earthquake records

Earthquake	Station	Date	Components	Magnitude (M_s)	Peak ground acceleration (m/s^2)
Kocaeli	Düzce	17/08/1999	NS	7.4	3.73
Düzce	Bolu	12/11/1999	NS	7.2	7.44



(a) Kocaeli Earthquake

(b) Düzce Earthquake

(c) Earthquake Spectra

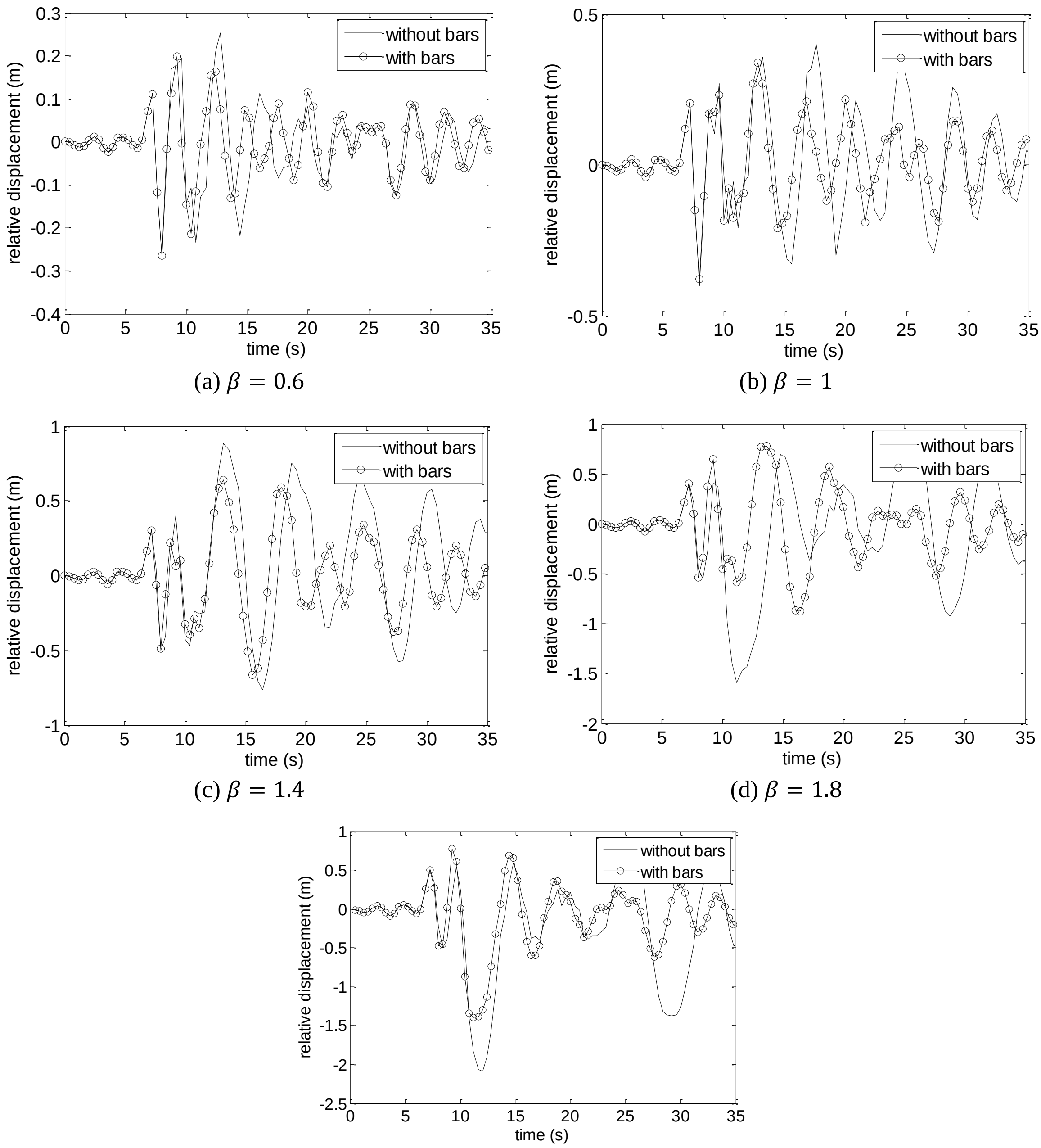
Fig. 10 Acceleration time histories and comparison between the design response spectrum and the spectra of recorded earthquakes

Earthquake Code (TEC) (TEC 2007) for the soft soil and 5% damping ratio. As can be observed, the earthquakes used in the analysis seem unconservative in comparison to the design spectrum. However, multiplication factors have been used to increase the intensity of the earthquakes in the numerical analysis cases.

4. Numerical results

4.1 Dynamic analysis under earthquake loadings

Dynamic analysis of the minaret was conducted using two aforementioned earthquake time history records. The earthquake motions were applied under the footing part of the minaret as acceleration time history signals. The analysis was carried out for various intensities of the earthquakes in order to observe the response of the minaret under the influence of moderate to large amplitudes. In that way, it was aimed to demonstrate the contribution of vertical lead



(a) $\beta = 0.6$

(b) $\beta = 1$

(c) $\beta = 1.4$

(d) $\beta = 1.8$

(e) $\beta = 2.2$

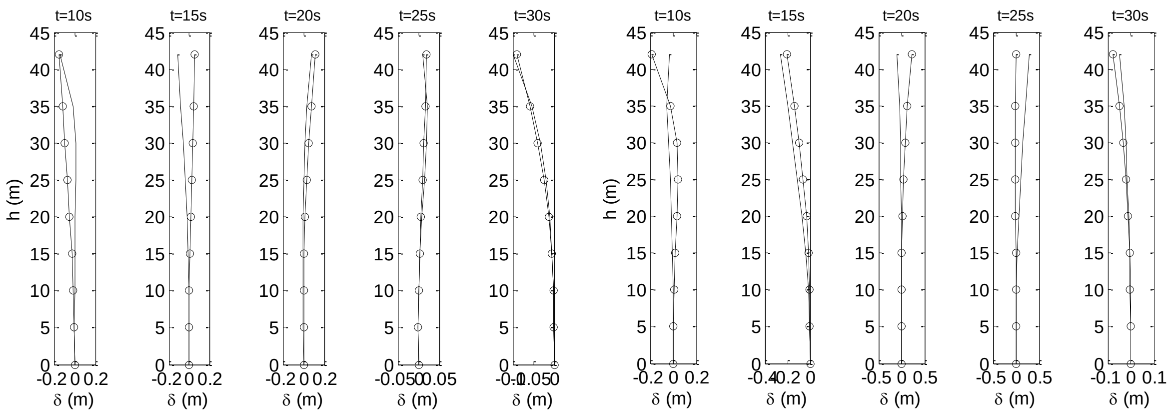
Fig. 11 Comparison of top relative displacement of the minaret with and without lead bars under Kocaeli earthquake motion

connectors to the overall structural behavior. The intensity of the earthquakes was increased gradually by multiplying the acceleration values by constant amplification factors (β) until collapse of the minaret is occurred due to the overturning of individual discrete elements. The multiplication factors (β) used to scale the time histories were adopted as 0.6, 1, 1.4, 1.8 and 2.2. The multiplication factor $\beta = 1$ corresponds to the earthquake itself as recorded.

At first, the dynamic analysis of the minaret was performed under the Kocaeli earthquake motion. The top displacements relative to the ground was recorded and plotted in Fig. 11. It can be observed from the figure that differences in relative top displacements between the minarets *w/* and *w/o* lead bars increases with increase in the multiplication factor β. In other words, difference in relative top displacement of minaret *w/* and *w/o* bars increases depending on the magnitude of the earthquake motion. This result clearly highlights the contribution of the vertical lead connectors on decreasing the vibration amplitude. Number of cycles in the displacement histories is also higher for the minaret *w/* bars (rocking period of the minaret is low) for increasing values of β. That is to say, rigidity of the minaret is increased.

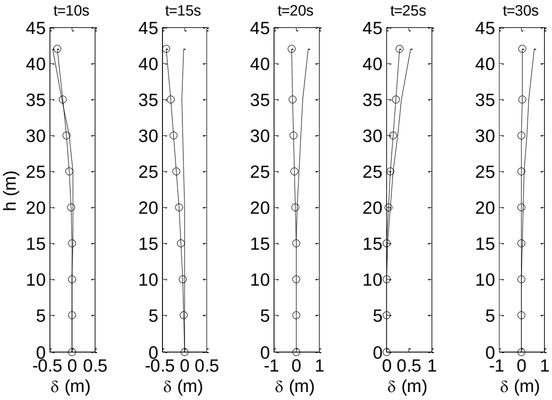
Besides, as the intensity of the earthquake load is increased, the amplitude of the minaret's response increases in both cases. However, the damping effect of the lead bars on the horizontal displacements of the minaret becomes more obvious. As it is apparent in Fig. 11(c), (d) and (e), the differences in the amplitudes of the top relative displacements are prominent. By the way, it should be noted that the displacement cycles are decreased and the displacement amplitudes together with the rocking period of the minaret increased under higher earthquake load intensities. However, the rocking period of the minaret with vertical lead bars is still lower than the minaret without vertical bars. This means that the stiffness and the earthquake resistance of the minaret is improved for the minaret *w/* vertical connectors. Nevertheless, it can clearly be observed from Fig. 11(d) and (e) that the amplitude of the response of the minaret with lead bars is rapidly decaying after the earthquake loads expires at time 27s. After that time, the free vibration takes place in which the lateral displacements are to be damped out quickly for the minaret *w/* lead bars. Yet, this is not true for the minaret *w/o* lead bars since the exponential decaying of the displacement amplitudes are not observed in this case. Adversely, the displacement amplitudes keep increasing.

The displacements along the minaret height at specific time values are given in Fig. 12. Similar results can be deducted from this figure. For lower magnitudes, the response of the minaret *w/* and *w/o* bars does not differ significantly. However, discrepancies in the displacement response are getting higher in the case of high intensity earthquake loading. This is especially more obvious

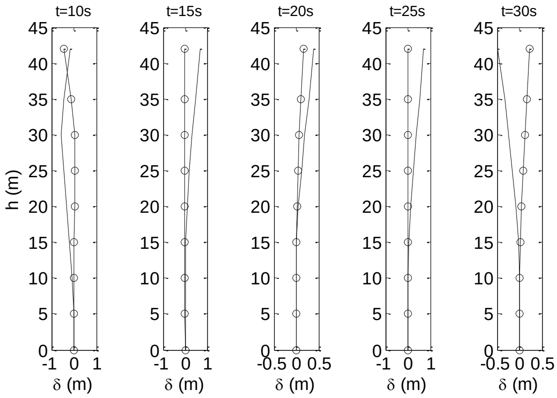


(a) $\beta = 0.6$ (b) $\beta = 1$

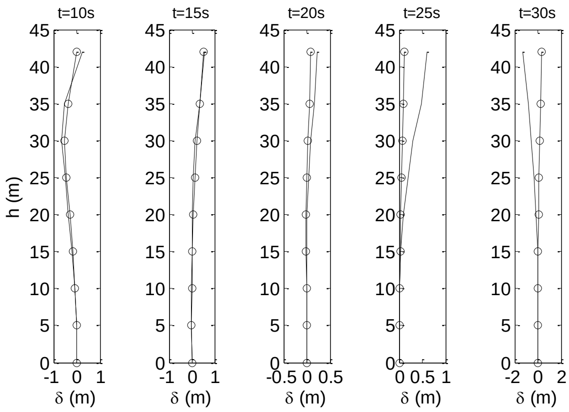
Fig. 12 Horizontal displacements along the minaret at specific time values (continuous and dashed lines correspond to the *w/o* and *w/* bars, respectively)



(c) $\beta = 1.4$

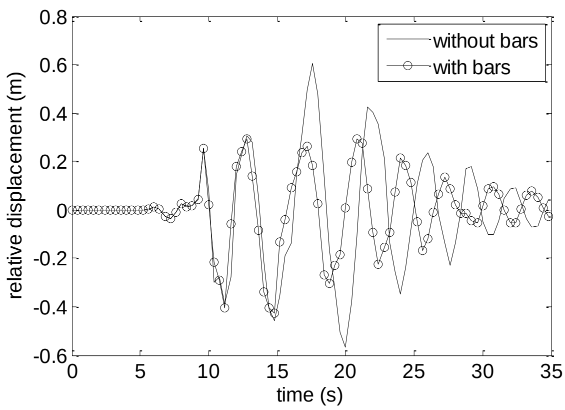


(d) $\beta = 1.8$

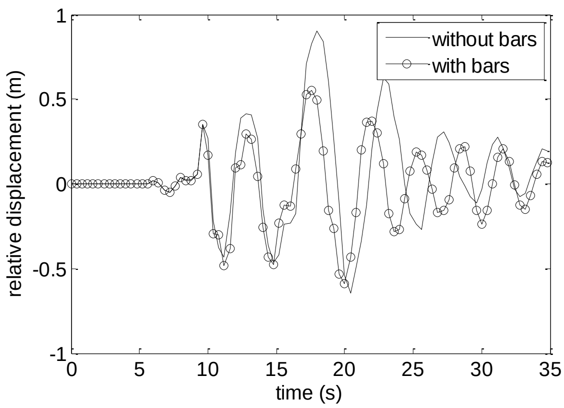


(e) $\beta = 2.2$

Fig. 13 Continued

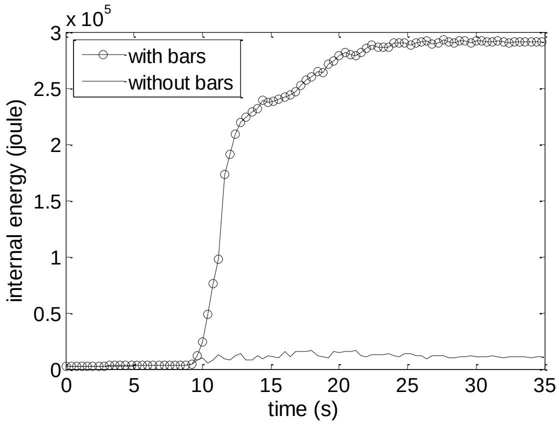


(a) $\beta = 1$

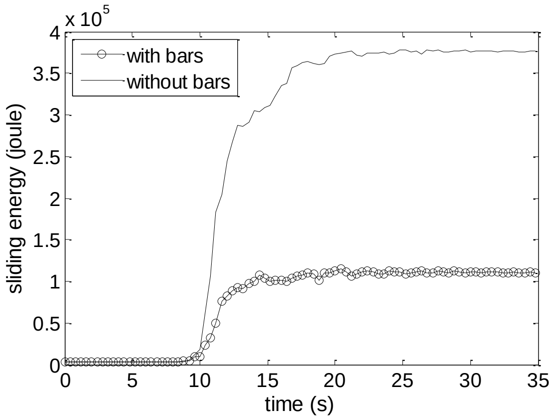


(b) $\beta = 1.4$

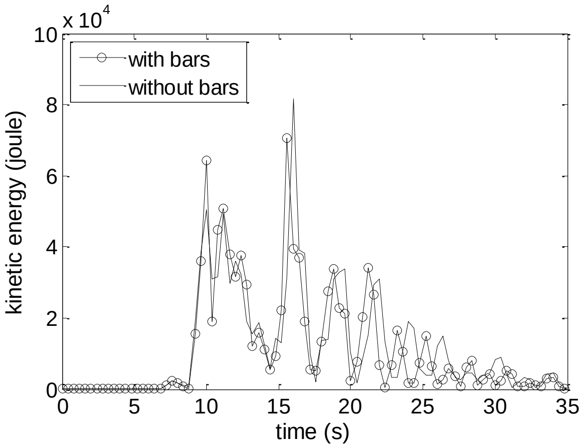
Fig. 14 Comparison of top relative displacement of the minaret with and without lead bars under Düzce earthquake motion



(a) Internal energy



(b) Sliding energy



(c) Kinetic energy

Fig. 15 Energy graphs with respect to time for $\beta = 1.4$ (Düzce earthquake)

when the minaret goes through the free vibration state after which the earthquake loading ceases at 25th and 30th seconds.

The seismic analysis results of the M1 minaret under the Düzce earthquake are similar to the previous case. The relative top displacements given in Fig. 13 demonstrate that the contribution of vertical connectors to the global structural behavior is significant under the strong earthquakes. Due to the analogy of the results with previous case, the analysis was solely carried out for $\beta = 1$ and $\beta = 1.4$. The relative maximum top displacements are around 0.35 and 0.60 m for *w/* and *w/o* lead bars when $\beta = 1$. Nevertheless, the maximum relative top displacements for the minaret *w/* and *w/o* bars become 0.58 and 0.90 m when β is 1.4. The use of lead bars reduces the relative top displacements approximately 35%-42%. Although the minarets *w/* and *w/o* bars respond similarly in the first fifteen seconds, the damping effect of the connectors becomes obvious as the loading continues. Hence, it can be said that the vertical connectors decrease the horizontal displacement amplitudes and enhance the earthquake resistance.

In addition to the horizontal displacements, the total kinetic energy, internal energy (consists of the elastic strain energy, the plastic strain energy due to the lead connectors) and the sliding energy (the work done by frictional forces between the annular cylindrical ring units) of the minaret are given in Fig. 14 for $\beta = 1.4$. The energy graphs are useful for understanding the contribution of different parts of the structures to the global behavior. The total kinetic energy of the minaret w/ and w/o bars does not differ significantly with the lower values of β, namely for the low intensities of the earthquake motion. However, the distinction is substantial for the internal and sliding energies. The internal energy contains plastic works, therefore it indicates the mechanical energy loss or energy dissipation. This value is considerably high for the minaret with bars in comparison to the minaret without bars. The difference between internal energies for both structure is around $2.7\ 10^5$ joule. This arises from energy dissipation capability of the lead bars, which is undoubtedly very high after a certain time for $\beta = 1.4$. As opposed to the internal energy, the sliding energy between the annular circular rings for the minaret without bars is higher than the sliding energy between the annular circular rings with lead bars. The difference ($\approx 2.7\ 10^5$ joule) in the sliding energies is close to the difference in the internal energies of the structure *w/* and *w/o* lead bars. This indicates that the earthquake energy is dissipated by the friction between the annular cylindrical rings in the minaret without lead bars. Adversely, when the lead bars are included, the earthquake energy is dissipated by lead bars which causes considerable increase in the mechanical energy loss or energy dissipation.

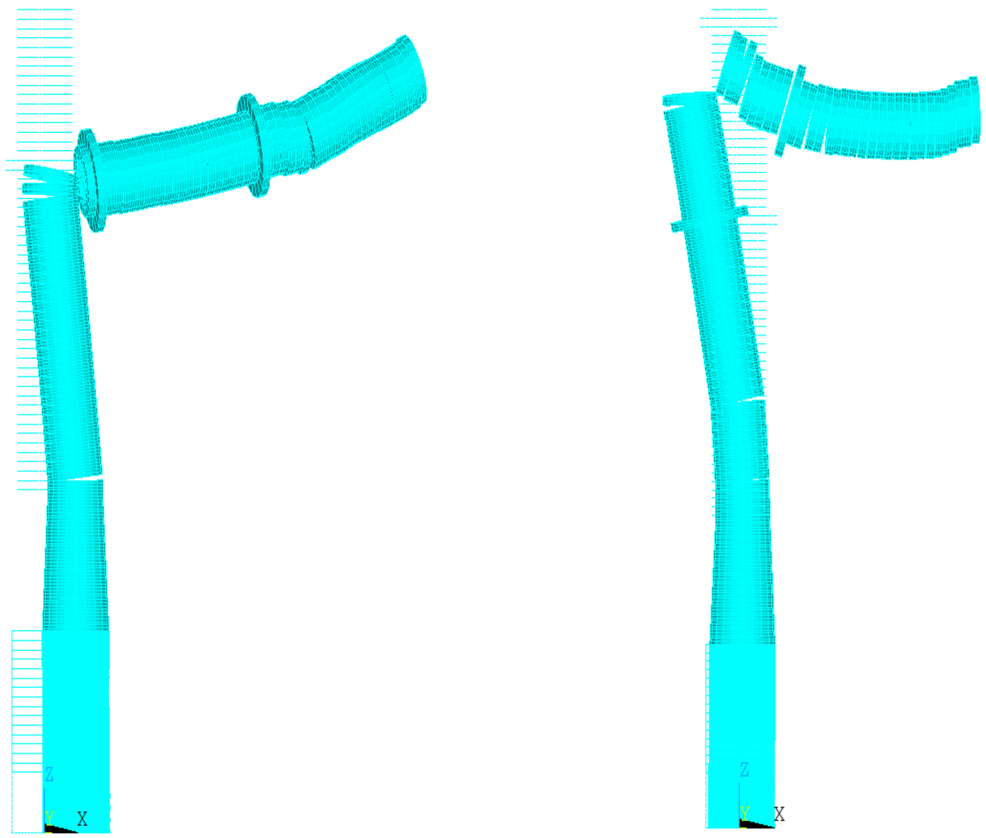
4.2 Collapse mechanism of the M1 minaret

In this section, the effect of the vertical lead bars (connectors) on the earthquake resistance of the M1 minaret of the Sultan Ahmed Mosque is investigated under the earthquake motion, which is intense enough to cause the collapse of the minaret without vertical lead bars. In fact, actual collapse mechanism might be rather complicated and depends on various values of structural variables such as structural and contact damping, material properties, defects in the geometry, discrete element shapes and so on. The effect of the those parameters on the collapse behavior is out of the scope of this work and requires a comprehensive study.

The intensity of both earthquakes applied on the minaret was increased until the collapse of the minaret w/o vertical lead bars occurs. In this case, displacement time-histories are compared and the contribution of the lead bars are presented. For the extreme earthquake loadings in which the minaret collapses, β is taken as 3.5 and 3 for the Kocaeli and the Düzce earthqukes, respectively. The collapse of the minaret under the loadings of specified earthquakes can be seen in Fig. 15. The collapse occurs due to the overturning of the cylindirical elements located right below the first balcony in the Kocaeli earthquake loading case. Collapse mechanism is similar to the previous case, however, overturning occurs between the lower and upper balconies for the Düzce earthquake loading case.

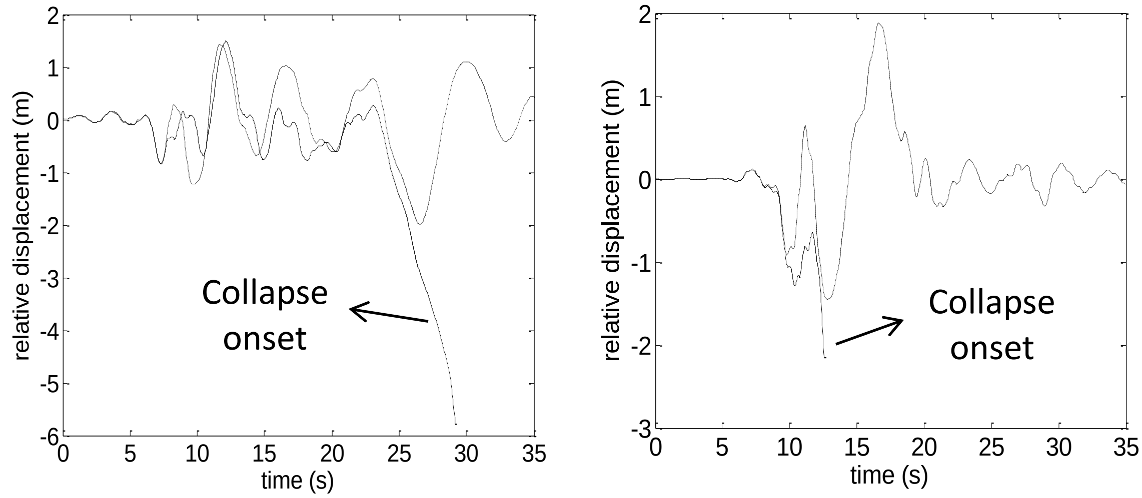
The top displacements relative to the ground for both earthquakes are given in Fig. 15. The collapse of the minaret starts at around 27th second of the loading. This corresponds to time that the earthquake loading ends up and the free vibration starts. However, for the minaret with vertical lead connectors, the amplitudes of the lateral displacements is decreased and the collapse is prevented. In the Düzce earthquake loading case, the minaret loses its stability at the time in which ground acceleration reaches its peak value. Similarly, the effect of vertical lead connectors on preventing the overturning of the elements is obvious.

In order to illustrate the results clearly in the collapse case, the internal energy (consists of the elastic and the plastic strain energy due to lead connectors), the kinetic energy and the sliding energy graphs are plotted with respect to time in Fig. 17 for both earthquakes. The kinetic energy



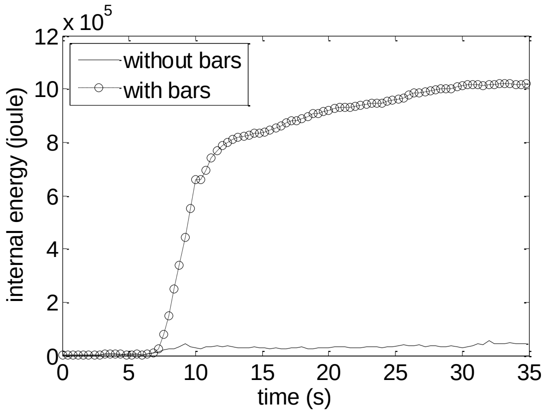
(a) Kocaeli Earthquake (b) Düzce Earthquake

Fig. 16 Collapse of the M1 minaret

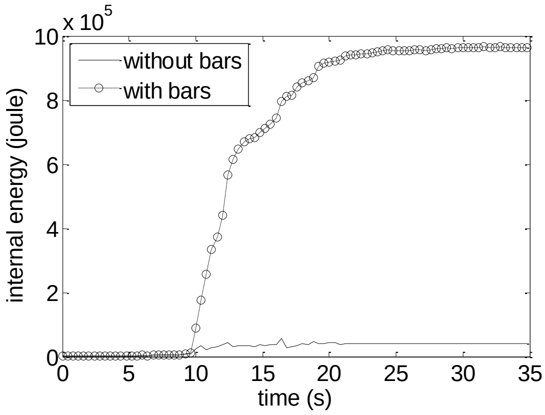


(a) Kocaeli Earthquake (b) Düzce Earthquake

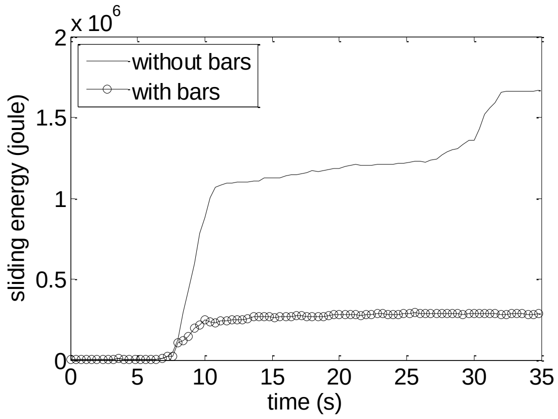
Fig. 17 Relative top displacements (continuous and dashed lines correspond to the *w/o* and *w/* bars, respectively)



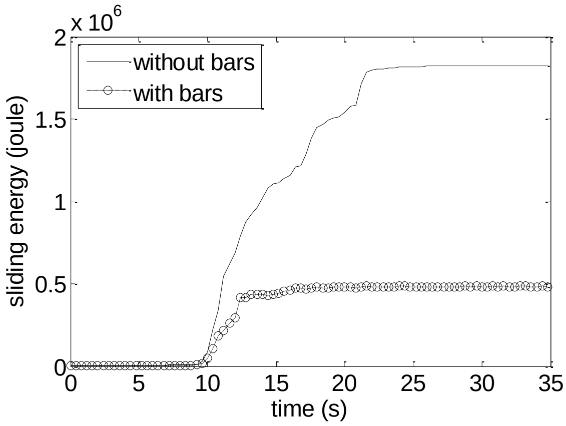
(a) Internal energy for Kocaeli Eartquake



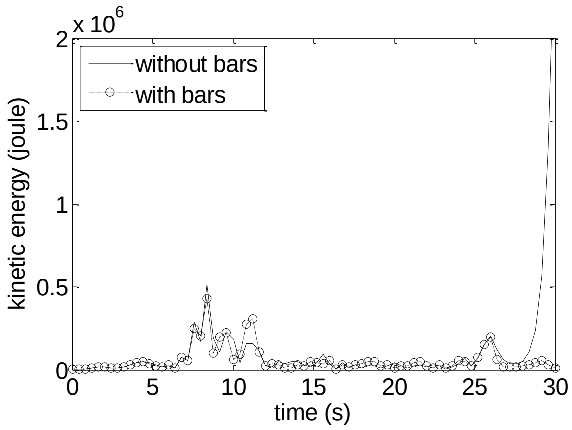
(b) Internal energy for Düzce Eartquake



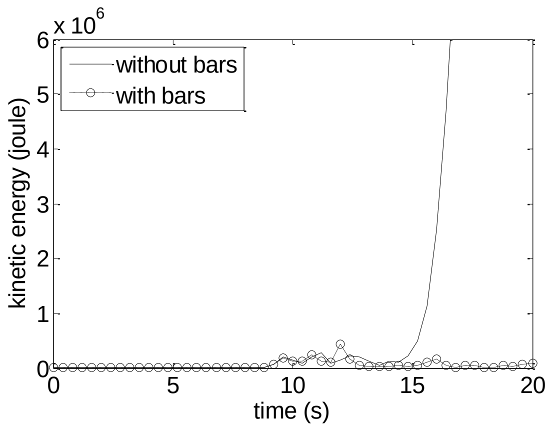
(c) sliding energy for Kocaeli Eartquake



(d) sliding energy for Düzce Eartquake



(e) Kinetic energy for Kocaeli Eartquake



(f) Kinetic energy for Düzce Eartquake

Fig. 17 Energy graphs with respect to time for $\beta = 3.5$ (Kocaeli earthquake) and 3.0 (Düzce earthquake)

graphs are plotted between zero and the time that the collapse initiates in order to see curves clearly. As it is obvious in graphs located at the last rows of Fig. 17, the kinetic energy of the minaret *w/o* bars increases drastically relative to the minaret *w/* bars when the overturning of the upper part of the minaret initiates. The increase in the sliding energy (Dissipated energy produced by the frictional forces) is limited and not able to prevent the overturning of the minaret. However, plastic deformation of lead bars causes substantial increase in the dissipation energy, so that the overturning of the minaret *w/* lead bars is prevented.

5. Conclusions

Minarets are tall and slender structures, which makes them interesting in terms of their seismic behavior under strong earthquake motions. Due to their slenderness, they are susceptible to earthquakes and wind loads. Historical minarets are masonry structures, which built up using cut limestone blocks or occasionally by using bricks. In this study, one minaret (M1 Minaret) of one of the charmest mosques of Turkey, Sultan Ahmed Mosque, popularly known as Blue Mosque is investigated under some registered earthquake motions.

Ottomans used forged iron connectors with lead to fix them to the upper and lower stones instead of using traditional mortar only. In doing so, they thought that they have obtained earthquake resistant structures. However, until now, this has not been shown by a research study.

To understand the behavior of the minarets, we should have intimate data about the structural system and the deteriorations due to harmful environmental effects, as well. As the time goes, the forged cast iron bars might be corroded. This causes the structural system of the minarets get weaker compared to the original strength which would result in collapse. Without knowing these details, the collapse of the minarets under the effect of earthquake or wind loads are misinterpreted.

Although there are lots of studies which investigated the masonry minarets, lots of them considered its structural system as an equivalent homogeneous media while some of them considered it as consisting of discrete elements. However, none of them considered the effect of the cast iron bar-lead mechanism on the behavior of the minarets under the earthquake loads.

This is the first study considering the effect of the cast iron bar-lead mechanism on the dynamical behavior of the minarets under the earthquake loads and it is seen that this mechanism plays a very important role on the dynamical behavior of the minarets.

The analysis is accomplished by using the software ANSYS/LS-DYNA in modelling and investigating the physical nonlinearity which arises from the plastic nature of the lead and geometrical nonlinearity which arises from changing contact status and large displacements of the minaret.

Investigation of the dynamic behavior of the minaret considering the relative motion of separate stones, frictional contact behavior and plastic deformation of lead bars reveals that the forged cast iron bars are very effective in increasing the energy loss and dissipating the earthquake energy. Thus, it can be concluded that the vertical connectors must be taken account in restoration and retrofitting processes in order to increase and/or preserve the earthquake resistance of historical minarets.

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