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Seismic vulnerability and preservation of historical masonry monumental structures

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Abstract. Seismic damage and vulnerability of five historical masonry structures surveyed after the 1999 Kocaeli and Duzce, Turkey earthquakes are discussed in this paper. The structures are located in two neighboring cities that have been struck by five very large ($M_s \geq 7.0$) earthquakes during the 20th century alone. Older masonry mosques with arches and domes and their masonry minarets (slender towers) were among the most affected structures in this highly seismic region. While some of the religious and historical structures had virtually no damage, most structures suffered significant damage or collapsed. In the city of Bolu, for example, approximately 600-year-old Imaret, 500-year-old Kadi, 250-year-old Sarachane, and 100-year-old Yildirim Bayezid mosques suffered substantial structural damage after the 1999 earthquakes. Another historical mosque surveyed in Duzce partially collapsed. Most common factors contributing to deterioration of historical structures are also presented. Furthermore, a brief overview of issues associated with analysis and modeling of historical masonry structures is provided.

Keywords: seismic damage; historical Turkish mosques; masonry; deterioration; earthquake

1. Introduction

During the 20th century, the 1944 Gerede-Bolu ($M_s = 7.3$), 1957 Abant ($M_s = 7.0$), 1967 Adapazari ($M_s = 7.1$), and August 17 ($M_s = 7.8$) and November 12 ($M_s = 7.4$) 1999 earthquakes occurred along the North Anatolian fault and hit the cities of Bolu and Duzce in Turkey (with respective populations of 84,500 and 56,600, in 2000). These and other smaller earthquakes caused thousands of casualties and collapse of scores of structures including many that can be considered religious and architectural heritage. As presented in this paper, for example, the 1999 earthquakes resulted in collapse of at least three 500- to 100-year old minarets, which are slender tower structures built next to a mosque structure. Recent studies have investigated the structural vulnerability of concrete and masonry minarets in Turkey and masonry structures in the Mediterranean region (El-Borgi *et al*. 2008, Syrmakezis *et al*. 2008, Sezen *et al*. 2008, Pagnini *et al*. 2011, and Ural *et al*. 2012). Given the high seismicity of the region, similar future destructive earthquakes are likely to cause damage in historical structures if they are not strengthened to resist such large earthquakes.

This paper presents environmental and other factors playing a role in deterioration of historical structures. The deteriorated structures may be able to carry typical gravity loads, however they are

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more susceptible to damage and failure when subjected to seismic loads. Architectural and structural characteristics of historical structures depend largely on the knowledge and aptitude of the designer and availability of local construction materials at the time of construction. For example, mostly brick or stone masonry and rarely timber have been used in historical monumental structures in Turkey.

Historical and modern structures are and should be treated differently even if they have similar or same structural load carrying system. Accordingly, significant effort is needed to preserve and protect the symbolic or architectural features of historical structures. However, sometimes the load carrying system of the historical structure does not get the necessary attention or protection it deserves because, for instance, the load carrying components may be hidden. It is obvious that symbolic or architectural components can not be supported if the structural system deteriorates and loses its strength, stiffness and deformation capacity to efficiently carry gravity and other external loads including earthquakes. This is especially true in certain countries like Turkey, where frequent strong earthquakes are common.

2. Deterioration of historical structures

The main factors contributing to deterioration, failure and potential collapse of historical structures are briefly summarized below (Dogangun and Sezen 2006, Sezen and Dogangun 2009). Damage may be triggered or exacerbated by:

(1) Surface or rain water runoff. If the roof structure, including domes and drainage system, are not maintained properly, grass or fungus may grow and weaken the structural materials. Timber roof and walls are particularly vulnerable to such damage. Furthermore, water accumulated on or penetrated into structural members may cause cracks due to freezing and thawing. The material strength and load resisting capacity of structural members may, in turn, decrease.

(2) Soil settlement and relative movement of foundation. Properties of the soil under the structure may not always be uniform. If the foundation and soil are subjected to different loading conditions, or if part of soil is saturated, relative settlements and cracks are expected in the structure. The location of settlements can be identified from the direction and distribution of cracks developed in the structure.

(3) Deficiencies in the load carrying structural system. The structure should be able to resist all loads that are likely to be applied during its lifetime. For example, structures designed to carry mainly gravity loads frequently fail during strong earthquakes as they may not have effective lateral load carrying structural systems. For example, one of the most magnificent historical structures in Turkey, Hagia Sofia in Istanbul, was not able to carry its dome when it was initially constructed in 537AD. The 31-m diameter dome was the largest at that time, and it collapsed in 558 by pushing the walls outward following an earthquake in 557. A second smaller diameter and taller dome was constructed, yet it also partially collapsed during the 10th and 14th centuries. The great architect Sinan added support walls later in the 16th century, and the structural system was further strengthened during the 19th and 20th centuries (Cakmak *et al.* 1995 and Sahin and Mungan 2005).

(4) Insufficient material strength. In most cases, high quality materials are selected and used in important monumental and religious structures. Strong stone materials are used in majority of historical monumental structures. This is one of the reasons why they survive many natural hazards and different harsh weather and environmental conditions. Layers of clay or other impure materials inside stone blocks may eventually lead to wearing, spalling or cracking. In stone masonry

structures, the properties of the mortar significantly influence the strength of the entire structural component such as a load bearing wall. Deterioration of mortar binding the stone blocks, especially poor quality mortar including mud or low quality lime, can reduce the strength and stiffness of the wall considerably.

Bricks are also successfully used in historical structures. Incidentally, it is reported that the earliest bricks dating back to 7500 BC were found in Çayönü, southeastern Turkey. During brick making process, typically the higher the temperature is, the stronger the brick blocks are. Poorly baked and weaker bricks lose their strength as their area and volume gradually decrease through scaling, wear and tear, and spalling off. As timber is more susceptible to humidity and temperature variations, if timber structures or components are not maintained properly, they may decay and lose their load carrying capacity at a much faster rate. In order to have a structural system to carry loads for centuries, the construction materials should retain their strength as they go through freezing-thawing cycles, humidity and temperature variations, and other harsh climate and environmental conditions.

(5) Detailing problems. Certain structural or non-structural details not considered during design or construction stages can lead to damage. For example, in some historical stone masonry structures, iron or steel clamps and dowels are used to reinforce and connect individual cut stone blocks (Dogangun *et al*. 2007, 2008). The clamps are supposed to be covered by proper detailing so that their corrosion could be prevented. In regions of high snow fall or precipitation, steeper roof slopes will reduce the amount of rain or snow accumulation on the roof. Leakage and freezing of water can then cause damage. Similarly, if some simple measures are not taken to prevent water leakage, for instance, around the window frames, the frames and surrounding walls can be damaged as the leaked water freezes and thaws.

(6) Other problems. Historical structures can be subjected to various environmental and loading conditions depending on their use and geographic location. Loading from continuous traffic and heavy trucks can lead to vibrations and excessive loads on foundations because the streets and other structures in historical cities are not designed for modern day traffic. Similarly, the use or occupancy of the structure may change and create larger unexpected loads. Parts of older structures are sometimes used as storage, in which the magnitudes of loads are usually much higher.

Other local and environmental effects, such as acid rains, may adversely affect construction materials. Acid rains are usually created by reaction of rain water with sulfur or nitrogen compounds in the air, and are harmful to surface of materials. Even stone blocks may disintegrate when subjected to acid rains.

Most of the factors presented here result in gradual deterioration of materials or the load carrying structural system, which can be prevented as the damage progresses and becomes visible in many cases. On the other hand, structural damage, failure or total structural collapse occurs suddenly during moderate or strong earthquakes. Thus, it is essential to evaluate the capacity of existing historical structures and to retrofit them before an expected earthquake strikes. Strengthening of structural system will consequently help protect non-structural and architectural components of the structure during an earthquake.

3. Earthquake damage observed in surveyed historical mosques

Two recent strong earthquakes caused widespread damage in modern structures as well as historical, religious, and monumental structures in Turkey. The Kocaeli (M_w7.4) and Duzce (M_w7.2)

Table 1 Surveyed historical mosques in Bolu and Duzce

Name	Year	Damage	Location (coordinates)	
			North	East
Imaret	14th century	Moderate	40°43.852′	31°36.635′
Kadi	1499	Heavy	40°43.901′	31°36.459′
Sarachane	1750	Light	40°43.935′	31°36.513′
Yildirim Bayezid	1804	Light	40°44.040′	31°36.576′
Duzce Merkez	1912	Heavy	-	-

earthquakes occurred on August 17 and November 12, 1999, respectively. Damage observed in five historical mosques and their minarets are presented and seismic vulnerability of similar masonry structures is discussed. Imaret (or Şemsi Ahmet Paşa), Kadi, Sarachane and Yildirim Bayezid mosques are in the city of Bolu. Their coordinates are shown in Table 1. Lateral seismic loads were resisted by relatively thick unreinforced stone masonry walls in these four mosques. Duzce Merkez mosque is located in downtown Duzce, and had stone columns in addition to load bearing masonry walls. Some of these historical structures were repaired after the earthquakes. Rehabilitation schemes and their effectiveness are also discussed.

3.1 Imaret (Şemsi Ahmet Paşa) mosque

The Imaret mosque is one of the oldest structures in the region. The building complex next to the mosque was destroyed during previous earthquakes. The current mosque structure was rebuilt and had to be retrofitted several times (Kenthaber 2006, Archive 2006). Probably as a result of learning from previous earthquakes, the walls of the current structure are relatively thick (1 m) and the number and sizes of the openings in the walls are relatively small in order not to reduce the lateral

(a) (b)

Fig. 1 Imaret mosque: (a) minaret collapsed during the 1999 earthquakes and (b) after the minaret is rebuilt

(a) (b)

Fig. 2 (a) Vertical wall crack observed after the 1999 earthquakes and (b) repaired cracks in the Imaret mosque

load carrying capacity of the walls on the perimeter of the structure. The mosque does not have a dome but has a timber roof. Its plan dimensions are approximately 14 m by 12 m. The load bearing walls of the mosque and its minaret were constructed using stone blocks and small bricks bounded by a thick layer of mortar. The mortar between the bricks is typically as thick as the bricks. Four layers of brick and a layer of brick and stones were consistently used in the walls.

Old brick masonry minaret collapsed and Imaret mosque was closed after the 1999 earthquakes due to cracks in the walls (Sezen *et al*. 2003). The collapsed unreinforced masonry minaret was rebuilt (Fig. 1) and the large cracks in the walls were repaired by injecting mortar inside the cracks. Some of the vertical and diagonal cracks in the east and north walls were 2 m or longer (Fig. 2).

3.2 Kadi mosque

The main prayer hall of the Kadi mosque has a square floor plan with approximately 13 m inside dimensions. As shown in Fig. 3, walls on the south side of the structure form a five-sided polygon,

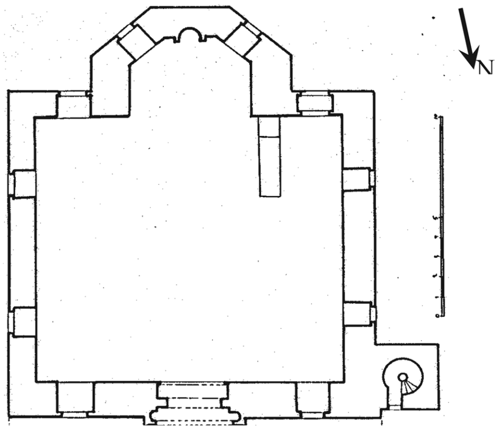

Fig. 3 Kadi mosque floor plan

more like an apse in older church structures. Typical thickness of the stone masonry walls is approximately 1.5 m. The square base of the circular masonry minaret in the northwest corner was constructed integrally with the mosque walls. It was reported that the original structure had a dome, however the current structure has a timber roof (Kenthaber 2006, Archive 2006).

The Kadi mosque sustained substantial damage during the 1999 earthquakes and had to be closed after the earthquakes. Severe cracks and stone dislocations were observed at several critical locations. The wall damage was also exposed inside the structure as the wall covers and plaster fell down at those critical locations. Damaged walls on the south and west side of the mosque are shown in Fig. 4. Damage was mostly concentrated below or above the windows. The reduced wall area along the vertical section through the windows was stressed more, causing considerable damage. Note that two key stones on top of the top window are missing while another one barely stays in place (Fig. 4).

Several cracks formed through the mortar and stone blocks on the sides and above the main entrance door during the earthquakes (Fig. 5). The stone masonry minaret collapsed right above its base because the minaret base was integral with minaret walls (Fig. 3) and was quite stiff compared to the cylindrical minaret body. The Kadi mosque recently went through a retrofit program. The walls were repaired and a new minaret with a more modern appearance was constructed (Fig. 6(b)).

Fig. 4 Damage to southwest walls of Kadi mosque (outside and inside views)

Fig. 5 Entrance of Kadi mosque showing failed minaret

Steel clamps were used to tie together the stone blocks on each side of the diagonal crack in the wall shown in Fig. 6(a).

3.3 Sarachane mosque

The main mosque building has approximately 10 m square usable floor plan. Four load bearing walls on the perimeter of the mosque are approximately 1 m thick. Walls are constructed using a


(a) (b)

Fig. 6 (a) Repaid wall and (b) recently constructed minaret


Fig. 7 Sarachane mosque and its undamaged minaret

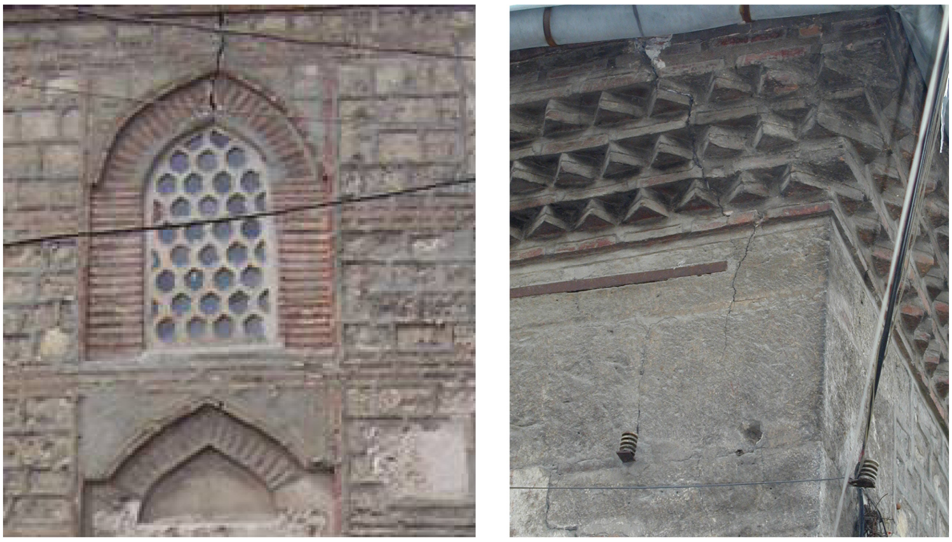

Fig. 8 Cracks developed in walls of Sarachane mosque

combination of stone units, rubble, brick and mortar (Kenthaber 2006, Archive 2006).

The 1999 earthquakes caused very limited damage to the mosque and there was no visible damage to its minaret (Fig. 7). Some large cracks were observed in the walls at locations similar to those observed in other mosques discussed in this paper. Fig. 8 shows examples of couple such cracks; one immediately above a window and another in a corner near the roof. Plaster spalled off at several locations inside the walls. The cracks seen in Fig. 8 were still visible in 2006, indicating that the mosque or minaret was not repaired or strengthened since the 1999 earthquakes.

3.4 Yildirim Bayezid mosque

The Yildirim Bayezid mosque was originally built in 1382 and was burned down in the 19th century (Kenthaber 2006, Archive 2006). A new structure was constructed after the fire, and it was severely damaged during the 1944 Gerede-Bolu earthquake ($M_s = 7.3$). Subsequently, the structure was rebuilt (Fig. 9). The plan view of the current mosque is shown in Fig. 10. The top of the square main prayer hall is covered by a large dome. The square bases of two circular unreinforced stone minarets are constructed monolithically with the eastern and western walls near the entrance.

The mosque was damaged during the 1999 earthquakes and was closed for a period of time. The shops under the mosque were back in business a few weeks after the November 12 earthquake. On the south side of the mosque, portion of the walls above and below the windows were subjected to larger shear stresses (compared to solid wall sections) during the strong ground shaking. Higher shear demand in those parts of the relatively thick walls created serious cracks and openings between the stone blocks (Fig. 11).

3.5 Duzce merkez mosque

The mosque was initially constructed in 1912. It was damaged and rehabilitated after the May 26, 1957 Abant earthquake ($M_s = 7.0$). The gravity and lateral seismic loads are resisted by unreinforced

Fig. 9 Yildirim Bayezid mosque after the 1999 earthquakes

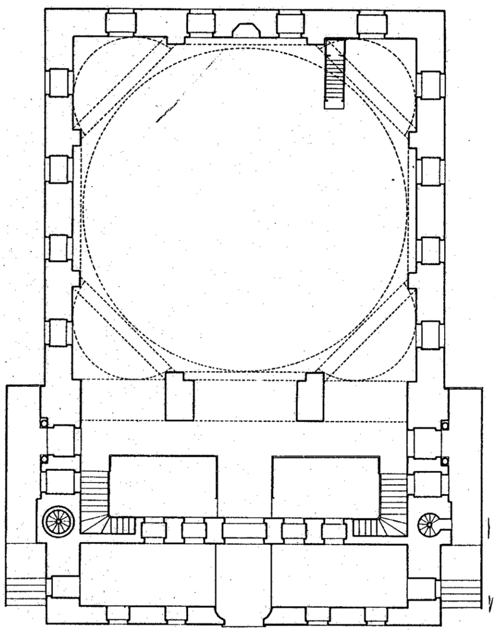

Fig. 10 Plan of Yildirim Bayezid mosque

stone masonry walls as well as four very tall square stone columns in the middle of the structure. A large portion of side walls on the east and west side of the structure collapsed during the November 12, 1999 earthquake (Fig. 12(a)). The main entrance door was exposed as a result of collapse of the secondary structure at the entrance. Square stone columns in the middle of the mosque were twisted during earthquake (Fig. 12(b)). This suggests that demands on the interior columns were high

Fig. 11 Cracks in south walls of Yildirim Bayezid mosque

(a) (b)

Fig. 12 Damage in the Duzce Merkez mosque after the November 12, 1999 earthquake

during the earthquake. It should be noted that failure of one of the interior columns would lead to collapse of the decorated roof of this historical mosque. Part of the mosque near the entrance and walls along the shorter side had less damage compared to the other parts of the mosque.

The mosque was retrofitted and re-opened in 2004 (Fig. 13). It appears that window openings in the lower story level were too large and there were too many windows in the upper floor level in the collapsed structure. This considerably reduced the lateral resistance of longer exterior walls in the east-west direction. Apparently similar window sizes and a placement scheme were also adapted in the recently retrofitted structure (Fig. 13). Unreinforced stone minaret also collapsed couple meters above its base (Fig. 12(a)). It should be noted that the base of the stone minaret was attached to the mosque wall. On the other hand, there was no constraint or support just above the square minaret base where relatively slender cylindrical minaret body failed. Two new minarets were constructed as part of the recent retrofit work (Fig. 13).

Fig. 13 Duzce Merkez mosque after retrofit (Duzcetanitim 2008)

4. Structural analysis and modeling issues

Several researchers developed three-dimensional finite element (FE) models and analyzed historical masonry structures similar to those presented in this paper. Celik *et al*. (2008), Gedik and Celep (2008), Massanas *et al*. (2004) analyzed mosques in Istanbul, Turkey. Celep *at al.* (2008) analyzed a mosque in Filibe (Plovdiv), Bulgaria and Apostolska *et al*. (2008) analyzed a church in Macedonia. Similarly. Kaya *et al.* (2004) performed dynamic analyses of FE models of the Suleymaniye mosque in Istanbul. Kaya *et al*. used four different boundary conditions and four different combinations of material properties. The analysis results were compared with ambient vibration test results. The researchers selected a final model with vibration frequencies closest to those obtained from the vibration tests. This study shows how difficult it is to develop a model that best represents the actual material properties and boundary conditions in a historical masonry mosque. Similarly, Beyen (2008) and Durukal *et al.* (2003) attempted to characterize dynamic properties of mosques in Istanbul using the ambient vibration and actual earthquake motion records.

Availability of powerful comprehensive FE computer programs has made it easier to perform detailed nonlinear dynamic analysis in recent years. We decided not to model and analyze the mosques presented here. This is mainly because even very detailed models and analyses may not necessarily predict the actual behavior accurately. The analysis results are as good as the models used and the assumptions involved. However, such analyses would undoubtedly provide insight into understanding of overall structural response and structure's collapse potential, and help identify structural members more susceptible to damage. On the other hand, small variations in selected input parameters can affect the predicted results significantly. Some of the analysis and modeling difficulties are briefly described below.

- Existing material properties need to be determined. Several different unique materials might have been used in the structure. Strength and stiffness of bricks or stones and strength of mortar or other binding materials need to be determined by testing material samples collected from the structure. Even then, it is extremely difficult to predict the strength, stiffness, and deformation capacity of a 1 m thick old masonry wall. For example, Cakmak *et al.* (1995) studied the mortar materials in detail using a number of preliminary microstructural, mineralogical, and chemical tests to support the choice of effective mechanical properties in their finite element models and analysis.

- Appropriate boundary conditions need to be determined and used in the model. Continuous masonry walls may not have strong footings to warrant fixed supports, and soil-structure interaction may significantly affect the structural response.
- As for any other structure, local site effects need to be known and suitable input ground motions need to be selected or generated (Berilgen 2007).
- Sufficient number of nodes and finite elements are needed for a reasonable model. In some cases, thousands of elements may be needed for an accurate analysis.
- Specified damping ratio greatly influences the dynamic analysis results. It is difficult to predict the damping ratio for a structure with thick brick or stone masonry walls.
- Nontraditional members such as arches and half and full domes are used in most historical structures. Interaction between components, for instance, effect of minaret or small domes attached to the main structure needs to be considered.

It is discouragingly expensive to instrument many historical masonry structures, conduct ambient vibration tests, or record actual infrequent earthquake motions to obtain structural frequencies. Also, performing detailed material tests is not practical most of the time. Even if such data is available, nonlinear dynamic analysis of a full-scale FE model still has limitations. Instead, the authors recommend using generic simplified models to evaluate historical masonry structures. One such model was presented in Gulkan *et al.* (2008). Along with the analysis results from such a model, damage observed in recent earthquakes, i.e. cracks immediately above or below the windows in a wall, can be used to assess the vulnerability of historical masonry structures.

5. Conclusions

Five historical masonry mosques were surveyed in a couple of relatively small cities struck by the 1999 Turkey earthquakes. Wide ranging factors contributing to deterioration of historical structures are presented, and structural damage observed in five mosques and implications are discussed. Since 1999, one partially collapsed mosque (Duzce Merkez) and its minaret were reconstructed. The walls of two mosques were repaired and their collapsed minarets were also reconstructed (Imaret and Kadi). Very limited or no repair was done in the remaining two mosques with noticeable cracks documented during the survey. Rather than repairing the visible damage caused during recent earthquakes, a comprehensive strengthening program is needed to protect the architectural heritage in future earthquakes in this highly seismic region of Turkey.

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